Retrofitting Airbus A320 to work on Liquified Natural Gas

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Master of Science Thesis

TU Delft
Delft University of Technology

Challenge the future

Retrofitting Airbus A320 to work on Liquified Natural Gas

By

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in partial fulfilment of the requirements for the degree of

Master of Science
in Aerospace Engineering

at the Delft University of Technology,
to be defended publicly on Monday September 23, 2019 at 09:30 AM.

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Acknowledgements

I would like to thank my supervisors, dr. Arvind Rao and dr. ir. Roelof Vos for their support, ideas and invaluable advice along the course of this thesis. Special thanks to Arvind for his motivation and encouragement.
I would also like to thank my committee: dr. Arvind Rao, dr. Botchu Jyoti, ir. Nando Timmer and dr. ir. Roelof Vos.
Finally special thanks my family for their support, patience and encouragements.

Abstract

The aviation sector is growing every year with a steady pace of 5%. This increase leads to more challenges, especially the one concerning the release of greenhouse gas emissions in the atmosphere causing global warming. In the current state, in order to control the warming of the climate, the global greenhouse gas emissions need to be significantly reduced. With the rise of traveling by airplanes and consequently the rise in number of aircraft, more emissions will be generated thus more detrimental climate effects.

With this expected growth, the greenhouse emissions can only rise in the future unless new innovative aircrafts are designed such as electrical aircrafts. However these are more than a decade or two away. One way to make an impact in the near future on reducing the greenhouse emissions of the airplanes is to switch the fuel from kerosene to Liquefied Natural Gas (LNG). LNG is natural gas cooled to -161.5 °C, where it reduces its volume by over 600 times. LNG is much cleaner for the environment compared to kerosene. It is cheaper than kerosene and more abundant. On top of that, in the next years the differences in price between jet-A Fuel and LNG will increase even more due to depletion of oil.

This study looks into the possibility and benefits of the retrofitting conventional aircraft to work on LNG. Existing airplanes' engines are able to work on natural gas instead of kerosene with minor modification. Thus current aircraft can be easily retrofitted to work on LNG without any external adjustments on the airplane's body. The only addition needed is a cryogenic tank to store the LNG and keep it at the required temperature. Cryogenic tanks have large volume and cannot be fitted in the wings of conventional aircrafts, therefore they either need to be stored in the cargo bay or externally in the wing pods. Nonetheless since most of the airlines rarely use all the cargo bay, a few unused containers can be replaced with cryogenic tanks.

To prove the benefits of using LNG fuel on current aircraft configuration, the Airbus A320 is chosen as the baseline for this thesis. A320 is the most used airplane in the commercial aviation, and in this respect can have the highest impact. In this master thesis the Airbus A320 is retrofitted to work on LNG and the two configuration are compared in terms of emissions and direct operating cost.

First a cryogenic tank design was presented, in which a heat transfer analysis was done to calculate the insulation thickness that results in an acceptable boil-off rate. In addition, a stress analysis was performed in order to find the thicknesses of the internal and external tank materials. Then the cryogenic tank was incorporated into the preliminary aircraft design program, Initiator, and is used to generate and analyze both aircraft.

Finally two aircraft were generated using the Initiator, one working on kerosene and the other on LNG. The two aircrafts are geometrically identical; the LNG Aircraft has a slightly larger OEM due to the cryogenic tanks, however this was compensated by the lower fuel mass needed, and thus the two aircraft have similar MTOM. The two aircraft were compared in terms of emissions and direct operating cost. The LNG achieved a 24% CO_2 reduction and 69% NO_x reduction compared to the kerosene for the same mission. In addition to that, LNG configuration showed a potential reduction of 17% in direct operating cost.

List of symbols

Symbol	Unit	Definition
$\dot{m}$	[Kg/s]	Mass flow rate
T	[N]	Thrust
R_{out}	[m]	External radius of the cryogenic tank
R_{in}	[m]	Internal radius of the cryogenic tank
t	[m]	thickness of a layer
L_{cyl}	[m]	Length of the cylindrical part of the tank
V_{LNG}	[m^3]	Volume of LNG inside the tank
P	[MPa]	Pressure
ΔP	[-]	Difference in pressure
σ	[MPa]	Stress
σ_y	[MPa]	Yield Strength
$T\_$	[°K]	Temperature
Q	[W]	Heat input
m	[Kg]	Mass
c_v	$\left[\frac{J}{Kg.K}\right]$	specific heat capacity at constant volume
ρ	$[\frac{Kg}{m^3}]$	Density
h	$\left[\frac{W}{m^2K}\right]$	Convection coefficient
k	$\left[\frac{W}{m^2K}\right]$	Conduction coefficient
Pr	[-]	Prandtl number
γ	$[\frac{m^2}{s}]$	Kinematic viscosity
α	$[\frac{m^2}{s}]$	thermal diffusivity
β	$[\frac{1}{K}]$	expansion coefficient
D	[m]	Diameter of the cylindrical part of the tank
g	$[\frac{m}{s^2}]$	Standard gravity
$\overline{Ra_D}$	[-]	Rayleigh number
$\overline{Nu_D}$	[-]	Nusselt number
V_c	$[\frac{Km}{hr}]$	Cruise speed
t_{cruise}	[hr]	time of the cruise phase
B_{off}	[Kg]	Boil-off of the LNG during the flight
V_{off}	[m^3]	Volume of the boil-off
C_{m_α}	$[\frac{1}{rad}]$	Longitudinal stability derivative $(\frac{\partial M}{\partial \alpha})$
W	[N]	Weight
S	[m^2]	Surface area
L	[N]	Lift
D	[N]	Drag
X_{np}	[m]	X coordinate of the neutral point
X_{cg}	[m]	X coordinate of the center of gravity

Abbreviations

Acronym	Definition
LNG	Liquified Natural Gas
SFC	Specific Fuel Consumption
Al	Aluminum alloy
ULD	Unit Load Device
CG	Center of Gravity
DOC	Direct Operating Cost
MTOM	Maximum Take Off Mass
OEM	Operating Empty Mass
VT	Vertical Tail
HT	Horizontal Tail
CFRP	Carbon Fiber Reinforced Polymer
LFL	Lower Flammability Limit
LDI	Lean Direct Injection
MAC	Mean Aerodynamic Chord
PU	Polyurethane

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1
Introduction

The aviation sector is on constant growth with around 5% per year and this growth is expected to continue for the next few decades. With this expansion, the number of commercial aircrafts is expected to double by 2036 [1] . Roughly the number of aircraft in service doubles every 15 years. Figure 1.1 shows the expected growth of Airbus aircraft fleet for the next two decades.

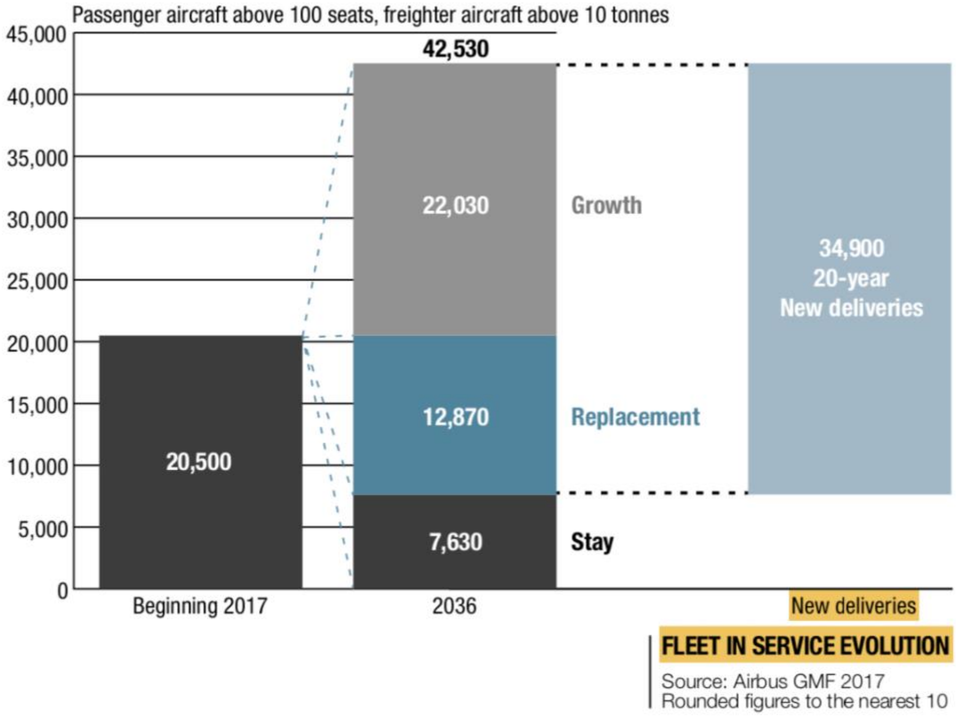


Figure 1.1: Airbus fleet in service between 2017 and 2036

While more people will be able to benefit from this growth to travel around the globe; in the absence of any mitigation, the greenhouses emissions from airplanes will increase significantly, aggregating the global warming with an adverse impact on human health and air quality and extinction of plants and animals.

These negative effects are well known in the aerospace industry, and there are already established national and international goals for reducing the emission per passenger. The European Commission Flightpath 2050 has a target of reducing the CO_2 emissions per passenger Kilometer by 75%, 90% reduction of NO_x and 65% of the perceived noise level compared to the capability of conventional aircraft from the year 2000 [2]. Figure 1.2 shows the projected CO_2 emissions up to year 2050 with and without improvements made for aircraft emissions.

One can see clearly that even with fleet renewal and operational improvements, the projected CO_2 emissions is way larger than the carbon neutral growth line. The green section, showing the improvement due to a fuel change and technology development, constitutes the biggest chunk of CO_2 emissions improvements, and thus it is necessary for reducing the level of CO_2 emissions to a carbon neutral growth. In consequence, for a carbon neutral growth, the aircraft's fuel needs to be changed to one that produces significantly less emissions, or to move to an electrical aircraft. However fully electrical propulsion for manned aircraft is still in its infancy, and large-scale commercial applications are regarded as two decades away. [3]

In this respect, LNG aircrafts are not only a better choice than the kerosene ones, but it is an essential element for a carbon neutral growth, until new electric aircraft become ready for commercial use.

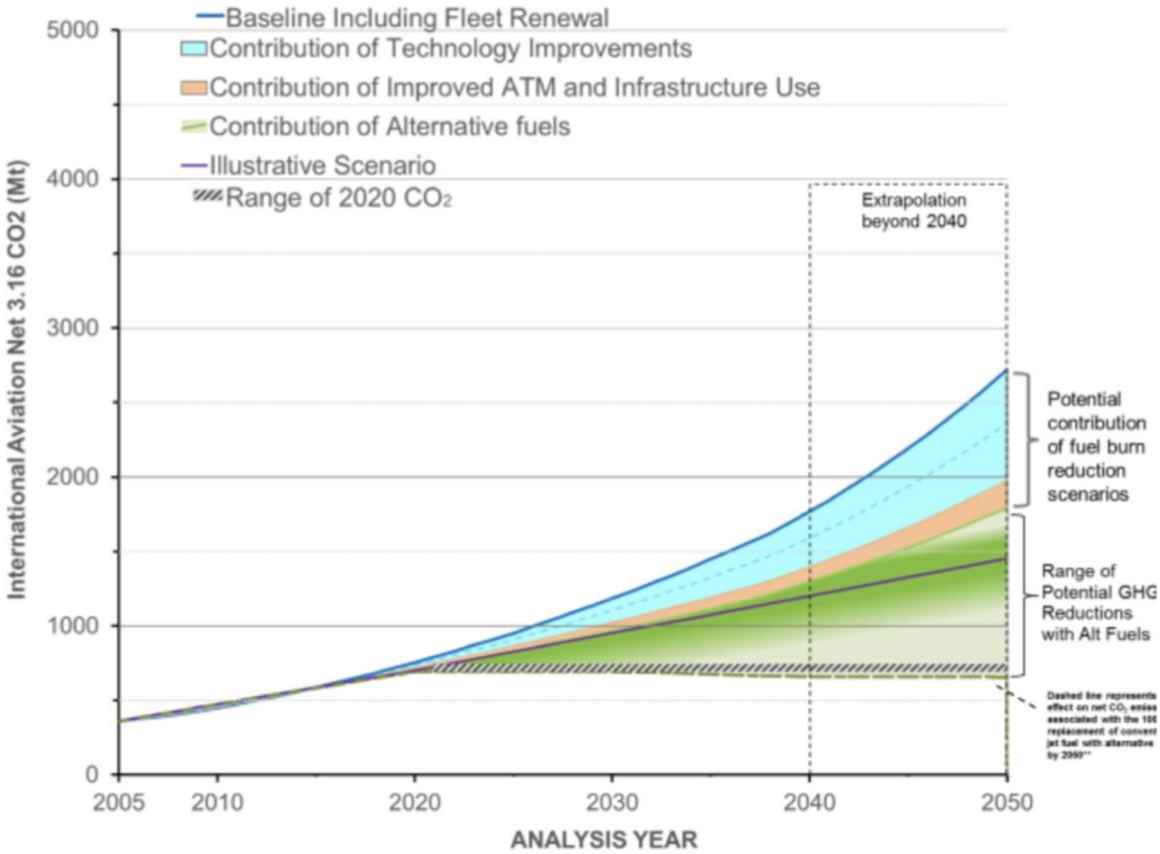


Figure 1.2: Carbon emissions grow until 2050 without improvement and with technology improvement. [4]

An interim solution, that can reduce greenhouse emissions per passenger Kilometer and can accommodate for the increase in number of aircraft, is to retrofit current airplanes to be able to work on natural gas instead of kerosene.

Natural gas is notably cleaner than jet-A Fuel, it's combustion produce far less CO_2 and NO_x . Natural gas is cheaper then jet-A Fuel and more abundant. The cost benefit of using natural gas as alternative fuel will only amplify in the years ahead, since crude oil is depleting and is expected to last up to 2050. While natural gas is more available, and new wells are being found continuously, which should result in a constant price.

In addition to that, natural gas has a higher calorific value per mass then jet-A fuel, which results in less fuel weight for the same mission. However natural gas occupies considerably more volume. To be able to use it on airplanes, natural gas should be stored as Liquefied

Natural Gas (LNG) in cryogenic tanks. Liquefying natural gas shrink its volume by over 600 times. The cryogenics tanks have large volume and cannot fit within the wings of current airplanes, thus the tanks needs to be placed within the fuselage, replacing few of the cargo containers, and possibly in the aft body.

The best part is the ease of retrofitting the current aircraft. Aircraft can be modified to work on LNG without external geometry changes. A cryogenic tanks needs to be added, and the combustor of the engines needs to be altered in order to accept gaseous fuel. Airbus A320 is one of the most used commercial aircraft and it can be retrofitted in a short period of time. That is the reason why it was chosen for this thesis.

1.1 Historical background of LNG aircraft.

Aircraft operating on LNG are not a new idea. In the past, several studies were done and even few aircraft flew on LNG. In 1980, Beech successfully flew a Beech Sundowner aircraft operating on Liquid methane [5].

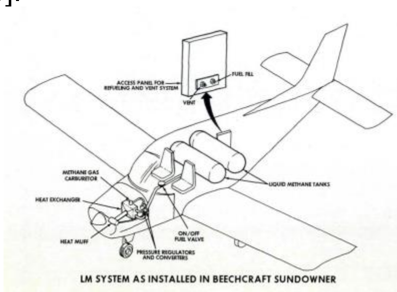


Figure 1.3: Beech Sundowner aircraft.

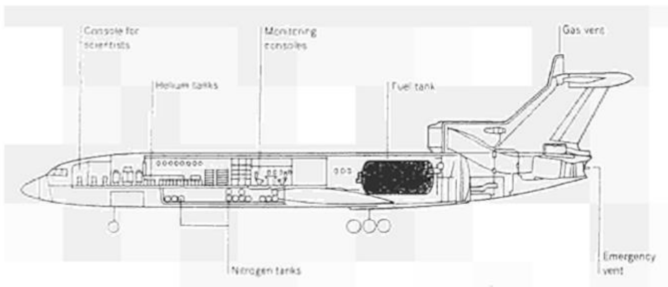


Figure 1.4: Tupolev TU-155 [6].

The Tupolev TU-155 , had one of its three engines working on LNG or Liquid Hydrogen, made several demonstration flights to the international airports of Moscow, Bratislava, Nice, Berlin and Hannover. The aircraft accumulated more than 100 flight hours. The TU-155 tests showed the real possibility of developing and operating aircraft on LNG.

There were several studies done on liquid natural gas as an alternative fuel, NASA [7], AIR-LNG [8], CLIPAIR [9] , all of which showed the feasibility and benefits of using LNG over Jet-Fuel.

The study of Methane Fuel For Subsonic Transport Aircraft, by NASA [7], found that methane is competitive as an alternative fuel in all major performance factors such as direct operating cost, gross weight, initial cost and energy utilization. The cryogenic tanks for liquid methane were found to be producible by present methods using an all welded structure of 2219 aluminum. Several cryogenic tank location were considered from external pod tanks, integral wingbox tank, and tanks within the fuselage. And The best fuel tank locations was found to be fore and aft of the cabin in the fuselage. The requirements for airport facilities were studied, such the liquefication, storage, processing and distribution system. It concluded that liquid methane can be safely used as aircraft fuel as long as appropriate standards for its handling are followed.

The study by AIR-LNG [8], the Jet-LNG program, considered multiloab tanks fitting in LD6 containers within the cargo bay, and it showed that the program can be implemented in a time frame of 3-6 years on existing aircrafts, by adding the LNG equipment, without altering the full functionality of kerosene operations, but simply allowing LNG to burn in partial or full replacement of kerosene

What can be concluded from the previous studies, is that an LNG aircraft is feasible, and is beneficial not only for the environment but also for reducing the operating costs for the airlines. In addition to that, current aircraft can be easily and quickly retrofitted to work on LNG without any change to the external geometry, but with little modifications to the engine, mainly the combustor, and some other fuel systems changes.

1.2 Initiator

Initiator[1] is a software tool that works within the MATLAB environment and serves as an aircraft preliminary design tool. The Initiator combines empirical models with numerical models to give reliable analysis results.

The program consists of several modules and parts, and it is able to generate aircraft configuration based on certain requirements fulfilling a specific mission. The different modules are :

- Sizing modules: They create an initial preliminary sizing of an aircraft based on a set of top-level requirement. They result in a first estimation of the aircraft geometry, weights, propulsion and performance.
- Analysis modules: use the aircraft geometry generated by the sizing modules, and analyze it to find a more accurate weight estimation, aerodynamic and propulsion performance.
- Design modules: Add or change the aircraft design. It Has method for the cabin design, landing gears design.
- Work-flow modules: Has the design convergence loop, and the plot tool, report writer.

The program starts with extracting data from a database reference aircraft, then it estimates the Maximum Take-Off Mass, where the fuel weight estimation is based on fuel-fraction method [10]. Then the required thrust and wing size are computed based on a user-specified set of top-level aircraft requirements , and on performance requirements from regulations (FAR/CS 25). Then, using the wing loading and weight information , the “GeometryEstimation” module creates a first estimate of the aircraft geometry. The wing are sized to meet the wing loading, the fuselage is sized to meet the required cabin floor to hold the payload, and The engines are sized based on the calculated thrust and from database.

Based on this geometry the weight and aerodynamic properties are estimated. The weight estimation is based on Raymer [11]. The aerodynamic properties, stability and control derivative, C_L and C_D, forces and moment, are found by the “AVLVLM” module which is a vortex-lattice method [12]. Afterwards, the engine is sized. The resulting analysis results in terms of Operating Empty Mass, the drag polar, and the Specific Fuel Consumption are fed back to the first module, which uses this input to recompute the MTOM.

[1] Initiator : A software tool developed by TUDelft students at the Flight Performance and Propulsion department.

In a second loop, the fuel fraction method is discarded and replaced by a more accurate analysis of the mission. The "Mission Analysis" module is sensitive to changes in center of gravity, and uses the trimmed drag polar.

In the final loop, the empirical methods to predict the fuselage weight and the wing weight are replaced by two more advanced methods. The fuselage weight estimation module relies on various combinations of critical loads (inertial, aerodynamic, taxi). Based on these load cases, the primary structural components (skin panels, frames, stringers) are sized and their weight is estimated, this method is developed by K. Schmidt [13]. Similarly, the weight of the wing is estimated based on gust loads or maneuver loads, whichever prevails, this method is developed by A. Elham [14]. Both the fuselage weight estimation method and wing weight estimation method rely on the results of the aerodynamic analysis, as well as an estimation of the mass distribution.

Initiator works in two ways:

- Top-level requirements and aircraft configuration: Initiator can be used as a tool to perform preliminary sizing and analysis of the design.
- Fully defined aircraft geometry: the sizing process is skipped and the aircraft can be analyzed directly.

Thus it is very hard to generate the exact aircraft as Airbus A320-200. Hence to make sure the generated aircraft is similar to the real one, as much of the A320 characteristics should be inputted to the program. For example, these inputs are the external dimensions of the aircraft, the wing characteristic such as taper ratio, span, root chord, airfoil’s type. Other particular inputs are the engine thrust, position, length, diameter, the horizontal tail and vertical tail data, the landing gears, etc. All these data are written in the *.xml file of the aircraft. Initiator can then find the aerodynamic performance and the weight estimation of the aircraft.

The outputs that are of interest to this thesis are the mission’s fuel mass, the harmonic range, and the mission’s emissions in terms of CO_2, H_2O and NO_x. In addition to that, the maximum take-off weight and the direct operating cost are of interest.

Initiator is capable of designing and analyzing most conventional aircrafts, using typical Jet Fuel. However, it is limited to generating fuel tank only within the wings, and working only with kerosene. Since the wing tanks cannot accommodate the LNG, cryogenic tanks need to be created in the cargo bay within the fuselage, and LNG needs to added as a fuel.

1.3 Thesis Goal

The goal of this thesis is to modify Initiator to be able to work with LNG as an alternative fuel, and to generate cryogenic tanks within the fuselage, so that any conventional aircraft can be used with LNG. Once this is done, an A320-LNG configuration is generated, and the aim is to study the benefits of using LNG instead of Jet fuel in terms of the greenhouse gas emissions and operating costs.

The end result of this project is to confirm the benefits of moving towards LNG, and the ease of retrofitting the current operating aircrafts. Furthermore, by altering Initiator to works with LNG, any type of conventional aircrafts can be generated and studied.

In a nutshell, the project is focused on transforming the Airbus A320 into an A320-LNG, that operates on LNG instead of kerosene, and study the benefits of using LNG in terms of emissions and mission fuel cost.

1.4 Thesis approach

First an Airbus A320-200 was generated in Initiator, and compared to the real A320 in order to validate that Initiator is capable of recreating the A320-200. Then the Initiator was modified to accept LNG fuel and to generate cryogenic fuel tanks within the fuselage. The cryogenic tanks were designed and sized based on the available internal geometry of the specific aircraft.

Furthermore a heat transfer analysis was performed on the tank, in order to select the insulating material and its required thickness, such that it provides acceptable boil-off rate while keeping the tank's weight at a minimum. The tank's materials were chosen to meet the structural forces while keeping the tank's weight to a minimum.
Once the LNG was implemented in Initiator, two A320-200 aircrafts for the same mission were generated, one working with kerosene and the other on LNG. These two aircraft were afterwards compared in term of greenhouse emissions and operating cost.

1.5 Thesis outline

The thesis will incorporate the following Chapters:

- Chapter 1: Introduction.
- Chapter 2: LNG emissions, and engine Specific Fuel Consumption.
- Chapter 3: Tank design in terms of shape, boil-off rate and weight.
- Chapter 4: Initiator necessary inputs, modifications, and added modules.
- Chapter 5: Design mission and available options.
- Chapter 6: Results and comparison of A320 and A320-LNG.
- Chapter 7: Conclusion and Recommendation.

2
Liquified Natural Gas

LNG stands for liquefied natural gas, where the natural gas at a temperature of −161.5°C and atmospheric pressure becomes liquid [15]. Once liquid, LNG takes 600 times less volume than when it is gas. Thus mainly liquefying natural gas is done for transportation and storage reasons. On airplanes, there is very limited space for storing the high volume natural gas. Therefore natural gas needs to be stored as LNG in cryogenic tanks on-board of an airplane.

Compared to the typical Jet-A fuel, LNG has several benefits. Natural gas is more abundant, cheaper and cleaner then the kerosene. Natural gas will still be available after the depletion of crude oil. Figure 4 shows the reserves and resources of both fuels [16].

PROVED RESERVES	OIL TWh	GAS TWh
Austral-Asia	66	159
Africa	188	152
Latin America	172	75
North America	95	95
Europe	23	51
Eurasia	207	635
Middle East	1,195	776
WORLD TOTAL	1,945	1,942

KNOWN RESOURCES	OIL	GAS
Conventional	TWh	TWh
Austral-Asia	81	194
Africa	124	96
Latin America	90	84
North America	169	233
Europe	46	61
Eurasia	266	820
Middle East	258	278
TOTAL Conventional	1,034	1,766
Non conv. Oil sand/shale	3,981	
Non conv. Gas shale/hydrates		13,110
TOTAL RESOURCES	5,015	14,876

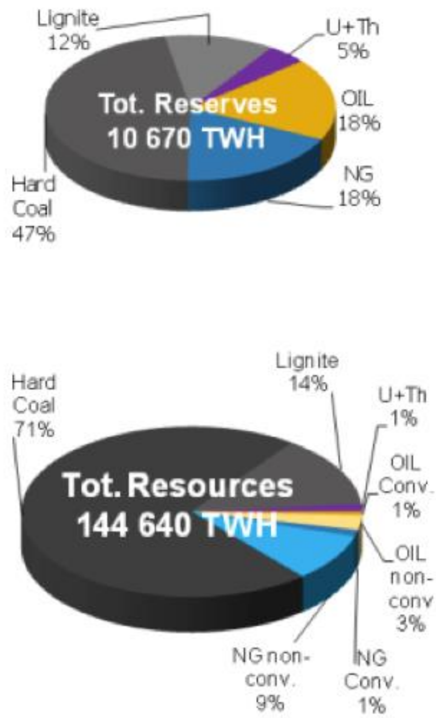


Figure 2.1: Reserves and resources of oil and gas.

Figure 2.1 shows that the known resources of natural gas are 3 times more than that of crude oil. Besides that, the crude oil's price keeps fluctuating and is expected to increase in the future. On the other hand, natural gas prices have been stable and are expected to stay much lower than that of the oil.

In order to find the price of the LNG, the cost of liquefication of natural gas, the transportation and storage costs needs to be added. These extra cost are approximated from [17].

The table below compares the prices of Jet-A and LNG based on the average prices from the year 2018.

Table 2.1 Fuel price comparison

	Jet-A Fuel	LNG	Difference(%)
Price [18], [19]	$2.02\ (\frac{\$}{gal})$	Natural gas: $3.33\ (\frac{\$}{MMBtu})$	-
Liquefication cost $(\frac{\$}{MMBtu})$ [17]	-	6	-
Transportation cost $(\frac{\$}{MMBtu})$ [17]	-	0.3	-
Storage cost $(\frac{\$}{MMBtu})$ [17]	-	0.82	-
Total price	$2.02\ (\frac{\$}{gal})$	$10.45\ (\frac{\$}{MMBtu})$	-
Energy Price $(\frac{MJ}{\$})$	65.32	101.04	54.68
Price per MJ $(\frac{\$}{MJ})$	15×10^{-3}	9.9×10^{-3}	-34

Thus currently LNG has 54.68% more energy per dollar. In another way, LNG is 34% cheaper per MJ compare to Jet-A. Figure 2.2 below shows the price projection of the natural gas and Jet Fuel. It can be seen clearly the price difference is expected to increase in the future.

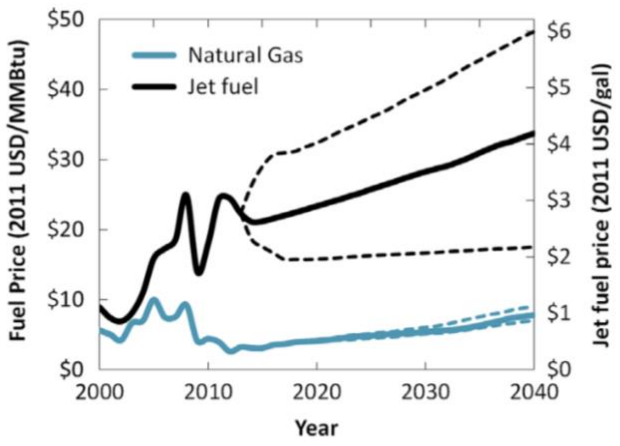


Figure 2.2: Jet fuel vs Natural gas price projection [17]

Taking for example the price for year 2025:

- Natural Gas cost : $6\ (\frac{\$}{MMBtu})$
- Jet-A fuel : $3.2\ (\frac{\$}{gal})$

These equates too :

- LNG price : $80.38\ (\frac{MJ}{\$})$
- Jet-A fuel : $40.22\ (\frac{MJ}{\$})$

By 2025, LNG is estimated to cost half the price of the kerosene for the same energy density.

2.1 Safety

LNG is not explosive or flammable in its liquid state. In order to be ignited, LNG must be vaporized, mixed with between 5% and 15% air and needs to come in contact with an ignition source. [20]

In an unconstrained open-air environment, the cold gas vapor will condense most of the water in the surrounding air forming a white vapor cloud. If unhindered, the cloud will drift in the direction of the wind, further mixing with the air and picking up heat from both the ground and the air as it moves. As the vapor cloud warms up, it will become lighter than air and rise into the atmosphere where typically it will gradually disperse without ignition. At the center of the cloud, the air quantity is too low for ignition; at the outer limits of the cloud the air quantity is too high for ignition. If the limited flammable portion of a natural gas vapor cloud in an unconstrained environment met an ignition source, it would burn but not explode.

2.2 LNG combustion emissions

LNG is taken as 100% of methane CH_4, for all the performance and emission calculation performed in this report.
The Complete Stoichiometric Ideal Fuel-Air Combustion of methane is:

$$1C_xH_y + \varepsilon\left(X_{O_2}O_2 + X_{N_2}N_2 + X_{CO_2}CO_2 + X_{Ar}Ar\right) \rightarrow N_{CO_2}CO_2 + N_{H_2O}H_2O + N_{N_2}N_2 + N_{Ar}Ar \quad (2.1)$$

Where:

X_i : mole fraction of species i;
N_i : number of moles of species i;

$$\varepsilon = \frac{x + y/4}{X_{O_2}}; \quad (2.2)$$

The air composition can be estimated by [16] [17]:

$$X_{O_2} = 0.209476; X_{N_2} = 0.780840;$$
$$X_{CO_2} = 0.000319; X_{Ar} = 0.009365;$$

$$\Rightarrow \quad \varepsilon = \frac{1 + 4/4}{0.209476} = 9.5476;$$

$$\Rightarrow \quad 1CH_4 + (2O_2 + 7.455N_2 + 0.00345CO_2 + 0.089Ar) \rightarrow 1.003045\ CO_2 + 2H_2O + 7.455N_2 + 0.089\text{Ar}$$

The molar mass:

$$M_{CH_4} = 16.0426\ \left(\frac{Kg}{kmol}\right)$$
$$M_{O_2} = 44.1435\ \left(\frac{Kg}{kmol}\right)$$
$$M_{H_2O} = 36.3056\ \left(\frac{Kg}{kmol}\right)$$

⇨ Thus 1 Kg CH_4 → 2.75 kg CO_2 + 2.263 kg H_2O

However the combustion of methane is not ideal, and other harmful compounds are formed. One of the main resulting product is Nitrogen oxide NO_x .

NO_x :

NOx formation depends on several sources and factors, and cannot be easily calculated. The major sources of NO_x formation during combustion are, [23]- [24]:

- Nitrogen(N_2) in air:

- Thermal NO_x
- Prompt NO_x : Prompt NO_x reactions occur within the flame and are usually negligible when compared to the amount of NO_x formed through the thermal NO_x mechanism.

- Nitrogen in fuel: Natural gas practically does not have fuel nitrogen.

The Major factors influencing NO_x formation:

- flame temperature
- air excess
- residence time in flame

NO_x production in gas turbines mostly occurs during fuel injection [25] . The NO_x formation rate depends on the local flame temperature and the residence time of the gas mixture. Non-uniform fuel-air mixture causes local hot spots that contribute to NO_x production.

NO_x production can be minimized significantly if combustion is performed in either fuel-rich or fuel-lean conditions. Also, the gas mixture residence time must be reduced to near stoichiometric conditions. Burning rich in combustion chamber causes NO_x reduction, but at the expenses of fuel consumption. On the other hand Lean combustion reduces NO_x formation while reducing fuel consumption.

One concept for lean combustion is the Lean Direct Injection (LDI) combustor which create a lean mixture, which in combination with an efficient mixing process, reduces peak flame temperature and thus NO_x production. Since the flammability limit for methane is wider than for kerosene, combustion can take place at lean conditions, potentially reducing NO_x emissions in comparison with a conventional kerosene combustor. The lean mixture can be accomplished by mixing fuel and air at a low equivalence ratio [25]. The main difference between LDI or Multi-Point LDI (MPLDI) from conventional combustor, is that MPLDI takes most of the air in the front end with the fuel before they are burned, while the conventional combustor takes only around one third of the air in the front. Therefore, the mixture of MPLDI is essentially lean. It burns at a lower temperature and produces less NOx. Also efficient mixing process in the MPLDI combustor also produces less CO.

It is hard to calculate exactly the NOx reduction as it depends on the combustor used and on the combustion technique. However a rough estimate can be done based on several references. Based on [16] LNG produces 87% less NO_x per MJ compared to kerosene. Also from [24]- [26], when low NO_x burners and Flue Gas Recirculation are used in combination, these techniques are capable of reducing NOx emissions by 60 to 90 percent.
From [27], LNG has approximately 66% less NO_x emissions compared to kerosene. This reduction can be increased by operating LDI combustor or low NO_x burners.
Thus for the rest of the report, a conservative estimate of 66% NOx reduction per MJ is taken for the LNG compared to kerosene. Thus LNG is assumed to produce $0.1105\left(\frac{g}{MJ}\right)$ of NO_x.
The table below compares the emissions of kerosene and LNG.

Table 2.2: Emissions of 1 Kg of LNG and kerosene.

	CO_2 (Kg)	H_2O (Kg)	NO_x (Kg)
Kerosene (1Kg)	3.16	1.24	0.014
LNG (1Kg)	2.75	2.263	0.005
Difference (%)	-12.97	82.5	-64.3

For the same energy produced of 1 (MJ) of both fuels, the emissions is compared in the table below:

Table 2.3: Emissions of 1 MJ of LNG and kerosene.

	CO_2 (g)	H_2O (g)	NO_x (g)
Kerosene (1MJ)	73.44	28.82	0.325
LNG (1MJ)	54.97	45.24	0.1105
Difference (%)	-25.15	56.97	-66

2.3 LNG Specific Fuel Consumption at cruise

The engine is assumed to run at the same efficiency using LNG as kerosene. So they have same energy output per second (MJ/s) . Form Elodie Roux [28], for the CFR56-5A3 engine, the specific fuel consumption at cruise $\mathrm{SFC} = 1.69\ \mathrm{e} - 5\ (\frac{\mathrm{Kg}}{\mathrm{N.s}})$.
The thrust at cruise is 22241 (N). Since the specific fuel consumption is defined by:

$$SFC = \frac{\dot{m}}{T} \tag{2.3}$$

⇨ $\dot{m}_{cr} = SFC_{cr} \times T_{cr} = 1.69\mathrm{e} - 5 \times 22241 = 0.3758729\ (\frac{\mathrm{Kg}}{\mathrm{s}})$

While the total energy is found from equation (2.4):

$$\text{Total energy} = \dot{m}_{cr} \times colorific\ value_{kerosene} \tag{2.4}$$

⇨ $\text{Total energy} = 0.3758729 \times 43.031 = 16.174\ (\frac{\mathrm{MJ}}{\mathrm{s}})$

Since the engine is assumed to have same efficiency for working with the kerosene and LNG, the total energy is the same.

⇨ $\dot{m}_{LNG} = \frac{\text{Total energy}}{colorific\ value_{LNG}} = \frac{16.174}{50.03} = 0.323\ (\frac{\mathrm{Kg}}{\mathrm{s}})$

⇨ $SFC_{LNG} = \frac{0.323}{22241} = 1.454\mathrm{e} - 5\ \left(\frac{\mathrm{Kg}}{\mathrm{N.s}}\right) = 0.516\ (\frac{\mathrm{lb}}{\mathrm{lbf.h}})$

Table 2.4: Cruise Specific fuel consumption comparison

	Jet-A fuel	Methane	Difference (%)
$\mathrm{SFC_{cr}}\ (\frac{\mathrm{lb}}{\mathrm{lbf.h}})$	0.6	0.516	-14

So this SFC_{LNG} value should be used in the Initiator to account for the higher calorific value that the LNG has, and ultimately the less fuel needed.

3
Tank Design

The main purpose of the cryogenic tank is to store and keep the natural gas in its liquid state, that is at $-161.5℃ \text{ and } 1 \text{ bar}$. When the heat from outside of the tank reaches the LNG, some of the latter will evaporate so that the temperature of the LNG stays constant. This is also known as boil-off of LNG.

For the A320-LNG, three key factors control the volume available for storing LNG. These factors are the tank's geometry, the location of the tank, and the boil-off rate.

3.1 Tank location and geometry

The tank's design takes into consideration the least amount of modification on current A320 in order to transform it to LNG aircraft. So the easiest choice with least modification is to fit the cryogenic tanks in the cargo bay, either within the LD3-45W containers or to replace some of them.

The best configuration that has the highest volume to weight ratio is a cylindrical tank or spherical one, since these distribute the stress the best.

The tank is made of two Aluminum alloy layers, and between them an insulation layer. The internal Aluminum layer takes care of the pressure loads, the external layer carries the weight of the tank and the fuel, and the insulation layer takes cares of minimizing the heat input into the tank. The cross section of the suggest tank is depicted in the figure below:

Figure 3.1. Cross section view of the cryogenic tank.

The dimensions of the ULD LD3-45W are used as a starting point to generate LNG tanks that fits within the ULD. The outer diameter of the tank is fixed to height of the LD3-45W, which results in an outer radius R_{out} of 0.57m.
With the different thicknesses, this leaves an internal radius of:

$$R_{in} = R_{out} - t_{Al2090} - t_{insulation} - t_{Al2024}\ ; (m) \tag{3.1}$$

This is the internal radius of the tank that is available for LNG. The tank consists of a cylindrical part and 2 half cup sphere at both ends. The figure below shows the 2D side view of the tank:

Figure 3.2. 2D Side view of the tank

Looking at the volume of internal of the tank:

$$V_{LNG} = \pi \times L_{cyl} \times {R_{in}}^2 + \frac{4}{3} \times \pi \times {R_{in}}^3 ;\ (m^3) \tag{3.2}$$

Form the equation above, and since Rin is fixed by the outer radius and by the different materials thicknesses, the only variable that influences the volume available for the fuel is the length of the cylinder, L_{cyl} . So in order to fit more fuel, the only solution is to extend the tank's length.
To best use the available volume of the cargo and the LD3-45W, two tanks next to each other along the fuselage length are fitted in an LD3-45W as shown in the figure below:

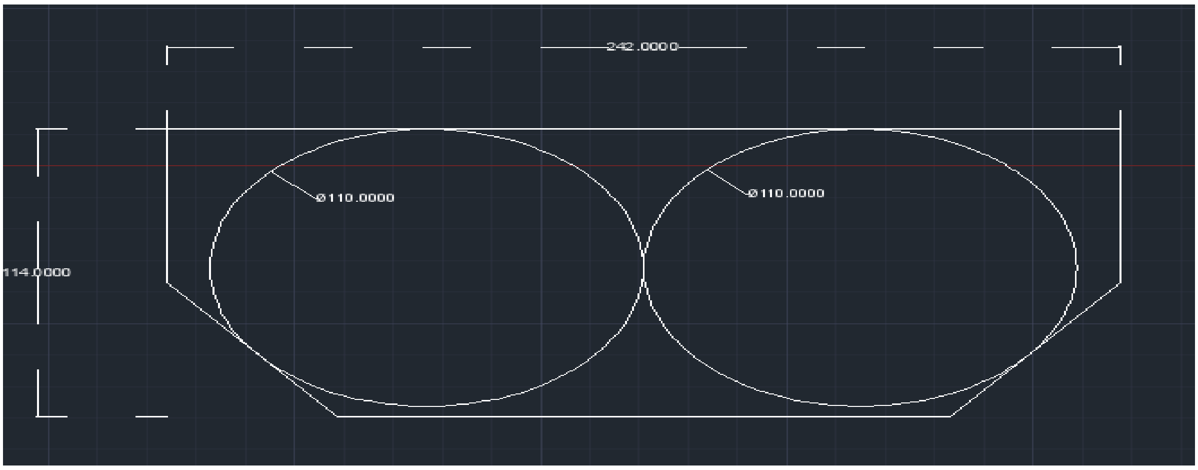


Figure 3.3: LD3-45W and tanks front view.

From the figure above, fitting the two tanks next to each other along the fuselage length, will reduce a little bit the outer radius to 0.55 m instead of 0.57 m. Figure 3.3 and 3.4 below give a view of how the tanks are positioned in cargo bay.

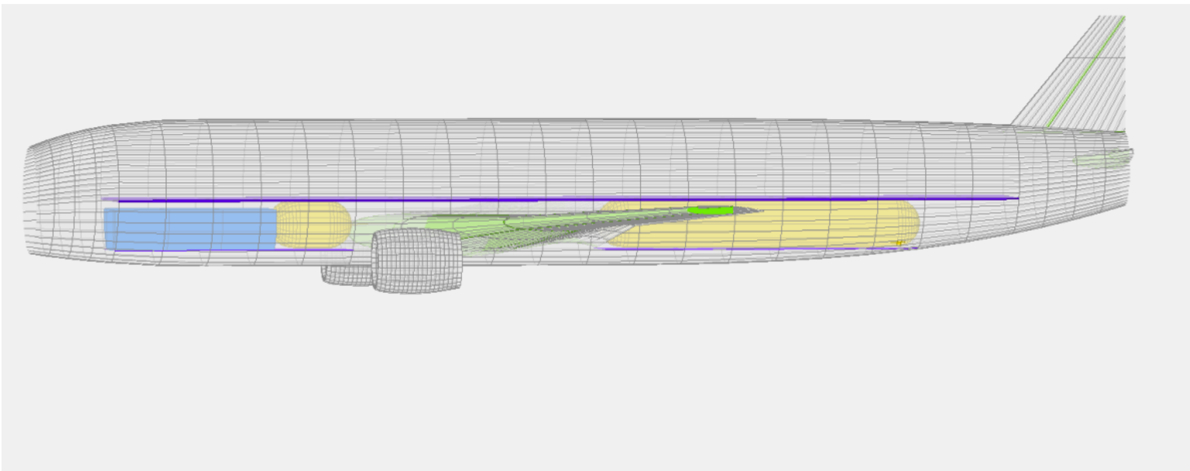


Figure 3.4: Side view of the LNG tank in the cargo bay

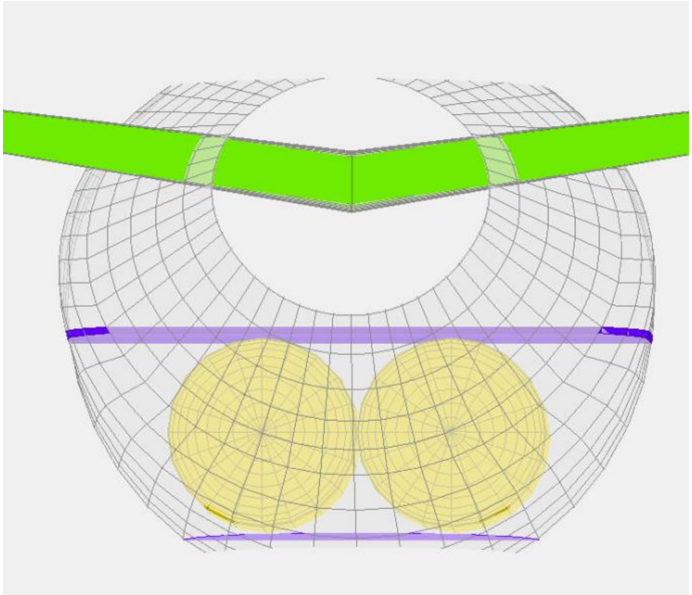


Figure 3.5: Rear view of the tanks

To better use the available space, and increase the tank capacity, the tanks diameter is slightly increased to utilized all the space between the upper and lower floor. This increases the external tank's radius to 0.67 m, while leaving a 10 cm around the tank for the tank's support.

3.2 Materials choice, their thickness and stress analysis

3.2.1 Material choice

The other factor in the design of the tank is the Aluminum layer that is in touch with the LNG, it should be able to withstand the low temperature, prevent leakage of the cryogenic fuel and withstand the pressure difference due to the altitude. The material needs to have favorable properties even at low temperature. These properties are ductility at cryogenic temperatures, as well as weldability, formability, stress corrosion resistance, and high fracture toughness and resistance to flaw growth. Al 2219 is one material suited for this application. However since the weight is crucial on airplanes, Al 2090 has higher yield strength and lower density, which results in lower weight. The most noticeable feature of alloy 2090-T81 is that its yield strength, ultimate strength, and elongation and the fracture toughness increase as temperature decreases. Al 2090 excellent weldability and cryogenic properties make it suitable for cryogenic tank structure. [29]

While the outer layer of Aluminum, it should be able to hold the weight of the tank and the fuel. Since it's not in contact with the LNG, the weldability and corrosion resistance and excellent cryogenic properties are not critical. Al 2024 has high strength at room temperature and sub-zero temperatures, and it commonly use in aircraft and aerospace structures. Al 2024 is chosen for the external tank layer.

The insulation layer must prevent the heat from reaching the LNG ,in order to minimize the boil-off the fuel. For cryogenic use, 3 different choices are available:

- Multilayer insulation : generally used in spacecrafts. However it requires high vacuum to operate properly , which makes the system heavy. In addition, the result of losing vacuum during flight could be catastrophic. [30]
- Aerogels: are extremely light materials composed mostly of air, while possessing excellent insulation qualities. They require less thickness, which increases the internal

volume available for LNG. They are durable and flexible even at low temperature. They are hydrophobic, offering good resistance to moisture. In addition they have a low thermal expansion coefficient, so there is minimal differential movement of the insulation system. Cryogel-Z is one suitable aerogel material for the cryogenic tank.
- Insulation foam: Have slightly higher thermal conductivity then the other 2 options, but require no vacuum. Polyurethane foam (PU) has low thermal conductivity, is light and has good resistance to thermal cycling [31]. PU has a good balance between weight, mechanical strength and insulation properties. Also, Polyurethane foam are widely used in the gas liquefication industry.

The Cryogel-Z seems to offer the best properties, however the Polyurethane foam is chosen for this study as the insulation material since it is wildly used in cryogenic application and thus a lot of experience with it is present, which makes it a safer choice.
Nevertheless Cryogel-Z is used for comparison as alternative choice in appendix E.

3.2.2 Stress analysis and required thickness

The main stress that needs to be evaluated is the hoop stress due to the pressure difference at cruise altitude. At the cruise altitude of 11278 km, the outside pressure is 5 times less than the pressure at sea level. The outside ambient pressure, P_∞, at cruise altitude can be found from:

$$P_\infty = P_0\, e^{-h/h_0}\,; \tag{3.3}$$

with P_0 =1 bar; h_0 = 7 at sea level;

⇨ $P_\infty = 0.1997$ bar.

So, the hoop stress, σ_o, is found from:

$$\sigma_o = \frac{\Delta P \times R}{t}\;;\;\;(\text{MPa}) \tag{3.4}$$

with $\Delta P = P_{in} - P_{out}$; R: radius, t: layer thickness and P_{in} = 1 bar;

Furthermore, taking a safety factor of 1.5 for design of the tank, the maximum allowed stress is the yield strength of the material, σ_y, divided, by the safety factor.
To find the thickness of each of the Aluminum layer, we apply the analogy above.
Starting with the external layer, Al 2024 has a yield strength of 324 MPa, at 298 $_o$K. [29]
Since the external layer holds the weight of the tank and the fuel:

$$\text{P}_{\text{tank}_{ext}} = \frac{W_{tank} + W_{fuel}}{2\times\pi\times r_{out}\times L_{cyl}}\;;(\text{Pa}) \tag{3.5}$$

Using equation (3.4):

⇨ $\text{t}_{\text{tank}_{ext}} = \frac{\text{P}_{\text{tank}_{ext}}\times R_{out}}{\frac{\sigma_{y2024}}{1.5}}\;;(\text{m})$

Applying equation (3.1):

⇨ $\text{R}_{in} = 0.4487\;;\;(\text{m})$

Now for the internal layer, Al2090-T81 has a yield strength of 559 MPa, at 111.65 $_o$K. [29]

Using $\Delta P = \text{P}_{\text{in}} - \text{P}_{\text{out}} = 1 - 0.1197 = 0.8003$ (bar),

⇨ $\text{t}_{\text{tank}_{in}} = \frac{\Delta P\times R_{in}}{\frac{\sigma_{y2219}}{1.5}}\;;\;(\text{m})$

So the optimal thickness of different layers is summarized in the table below:

Table 3.1: Tank's materials and thickness

Material	Thickness (mm)
Al2090-T81	0.93
Foam	100
Al2024-T4	0.0032

However one of the certification requirement of an cryogenic tank, the "REQ_ATA28-01" states: The tank shall be able to withstand the maximum pressure due to 72 hour normal heat flux at the tank's maximum fuel capacity without venting or exceeding the maximum operating pressure. The ambient temperature during the 72 hours period shall be 25 degrees Celsius. NPFA4.3.5 [32]
So the internal layer needs to withstand a higher pressure difference due to the no boil off condition. For an ideal gas:

$$P \times V = n \times R \times T = m \times R_{specific} \times T \quad (3.6)$$

Where : T: temperature in degrees Kelvin , R the ideal gas constant ,

$$R_{specific} = R_{CH_4} = \frac{R}{M_{CH_4}} = \frac{8.315}{16.04} = 519 \left(\frac{J}{Kg.K}\right)$$

Where M_{CH_4}: is the molar mass of methane.

For an Isochoric process:

$$\Delta Q = m \times c_v \times \Delta T \quad (3.7)$$

With:

- Q: rate of heat transfer to the LNG.
- m: mass of LNG in the tank.
- c_v: specific heat capacity at constant Volume.

LNG is stored at -161.5 °C = 111.65 °K :

$$c_{v_{@111.65°K}} = 33.478 \left(\frac{J}{mol.K}\right) = \frac{33.478}{16.043} = 2086.8 \left(\frac{J}{Kg.K}\right) \text{ [33]}$$

⇨ $\Delta T = \frac{\Delta Q}{m \times c_v}$

From initiator, for one of the front tank, the rate of heat transfer to the LNG: Q = 236.52 [W]
For 72 hours:

⇨ $\Delta Q = 236.52 \times 72 \times 3600 = 61.306\ (MJ)$

To find m_{LNG}:

$$m_{LNG} = \rho_{LNG} \times V_{tank} \times usablefraction \quad (6.8)$$

Where:

$$V_{tank} = 2.5123\ (m^3)$$
$$\rho_{LNG} = 420\ \left(\frac{Kg}{m^3}\right) \text{ [15]}$$
$$usablefraction = 0.9869$$

⇨ $m_{LNG} = 1051.4\ \text{(Kg)}$

⇨ $\Delta T = \frac{\Delta Q}{m_{LNG} \times c_v} = 27.94$

⇨ $T_2 = T_1 + \Delta T = 111.65 + 27.94 = 139.59\ °K$

From [15], the vapor pressure of saturated liquid P_v , is found using the equation below

$$\log P_v = A + \frac{B}{T} + C \times \log T + D \times T + E \times T^2 \tag{6.9}$$

Where:

A, B,C,D,E = correlation constants for the chemical compound; and T = temperature, °K

- ⇨ $\log P_v = 22.573 - \frac{656.24}{T_2} - 7.3942 \times \log T_2 + 11.896 \times 10^{-3} \times T_2$
- ⇨ $\log P_v = 3.6729$
- ⇨ $P_v = 10^{3.6729} = 4708.9\ (mm\ oh\ Hg) = 6.278\ (bar)$
- ⇨ $\Delta P = P_{in} - P_{out} = 6.278 - 0.1197 = 6.1583\ (bar) = 0.6158\ (\text{MPa})$

The external layer needs to be sized to withstand a pressure difference of 6.2 bar.

- ⇨ $\text{t}\ \text{tank}_{ext} = \frac{\Delta P \times R_{in}}{\frac{\sigma_{y2090-T81}}{1.5}} = \frac{0.6158 \times 0.5196}{\frac{559}{1.5}} = 8.59 \times 10^{-4}\ (\text{m}).$

These calculation are for viewing purposes, Initiator was modified to calculate the required thickness based on the procedure above.

Furthermore, the minimum manufacturing thickness is $t_{min} = 0.002\ (m)$ [34]. And since,

$$\text{t}\ \text{tank}_{ext} < t_{min}, \text{ and t } \text{tank}_{in} < t_{min}$$

- ⇨ $\text{t}\ \text{tank}_{ext} = \text{t}\ \text{tank}_{in} = t_{min} = 0.002\ (m).$

3.3 Boil-off rate and thermal analysis

To minimize the boil-off rate of the LNG, the tank should be well insulated. The thicker the insulation layer the less the boil-off rate. However due to volume constraints, the insulation thickness should be a compromise between the reduction of boil-off rate vs. the increase of the weight of tank and the resulting available internal volume for storing the fuel.

Now that the dimensions are known, a heat transfer analysis on the tank is performed, in order to find the boil-off rate. Since the Aluminum alloys have a very high conduction coefficient, the conduction through these layers can be neglected and the resistant to conduction is assumed to be only done by the insulation.

So in short, there will be a natural convection between the air and the outer surface of the tank,

conduction through the insulation layer, and a natural convection between the LNG and the tank's inner surface.

Using the thermal resistance network concept , the resistances are represented in figure below:

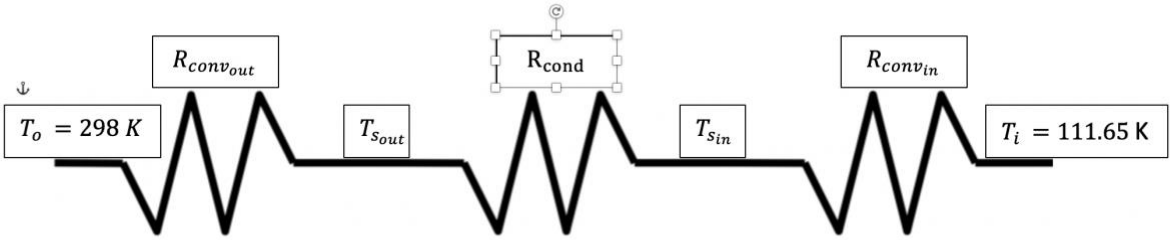


Figure 3.6 Thermal resistance network.

The unknowns in figure 3.6 are the interior and exterior surface temperature of the tank $T_{s_{in}}$ and $T_{s_{out}}$, and consequently the inner and outer convection coefficients. To find $T_{s_{in}}$ and $T_{s_{out}}$, and eventually h_{in} and h_{out}, a script was written in appendix [F] to find the values by trial and error. Two loops are written, for the first loop assume $T_{s_{in}} = T_i$. The loop then assign a value for $T_{s_{out}}$, calculate the convection coefficient h_{out} by applying equation 6.10.

$$h = \frac{k}{D} \times \overline{Nu}_D \text{ ; [35]} \tag{6.10}$$

The Nusselt number $\overline{Nu}_D$, can be found by assuming natural convection around a pipe, and using equation 6.11. The unknows in the equation is Ra_D.

$$\overline{Nu}_D = \left\{ 0.6 + \frac{0.387 \times Ra_D^{1/6}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2 \text{ ; [35]} \tag{6.11}$$

The Rayleigh number Ra_D, is found from equation 6.12, using the assigned value of $T_{s_{out}}$.

$$Ra_D = \frac{g \times \beta \times (T_s - T_\infty) \times D^3}{\gamma \times \alpha} \text{ ; [35]} \tag{6.12}$$

Then the external heat flux through the external layer $q_{conv_{out}}$ and the heat flux through the insulation layer q_{cond}, are found from equation 6.13 and 6.14 respectively.

$$q_{conv_{out}} = (T_o - T_{s_{out}})(2\pi r_{out} L_{cyl} h_{out}) \text{ ;} \tag{6.13}$$

$$q_{cond} = \frac{(T_{s_{out}} - T_{s_{in}})(2\pi L_{cyl} k_{foam})}{\log\left(\frac{r_{out}}{r_{in}}\right)} \text{ ;} \tag{6.14}$$

When the difference between the two, $\frac{(q_{conv_{out}} - q_{cond})}{\left(q_{conv_{out}} + q_{cond}/2\right)}$, falls within a small value, the $T_{s_{out}}$ is chosen.

With the know value of $T_{s_{out}}$, a second loop that iterate the $T_{s_{in}}$ is written. The convection coefficient h_{in} is found similarly to h_{out} by using equation 6.10-6.11-6.12. Then the internal heat flux through the inner layer $q_{conv_{in}}$ and the heat flux through the insulation layer q_{cond}, are found from equation 6.15 and 6.14 respectively.

$$q_{conv_{in}} = (T_{s_{in}} - T_i)(2\pi r_{in} L_{cyl} h_{in}) \text{ ;} \tag{6.15}$$

When the difference between the two, $\frac{(q_{conv_{in}} - q_{cond})}{\left(q_{conv_{in}} + q_{cond}/2\right)}$, falls within a small value, the $T_{s_{in}}$ is chosen.

These iterations are done in MATLAB, and there are located in the "getConvectionCoefficients.m" method and can be found in Appendix [F]. This method outputs h_{in} and h_{out}. This method adds several minutes to the convergence loop. It was found that small changes in the surface temperature $T_{s_{in}}$ and $T_{s_{out}}$, results in slight difference in h_{in} and h_{out} and thus a negligible difference in the boil off rate. So to save time and to make the program runs faster, it was decided to calculate h_{in} and h_{out} once by the method described above, and use the resultant h_{in} and h_{out} as fixed values for the calculation the heat input Q. So the program uses now:

- ⇨ $h_{in} = 124.8 \left(\frac{W}{m^2K}\right)$
- ⇨ $h_{out} = 2.8 \left(\frac{W}{m^2K}\right)$

Once h_{in} and h_{out} are found, the heat leakage into the tank can be calculated by applying the following equation:

$$Q_{cyl} = \frac{(T_{air} - T_{LNG})}{R_{equ}}; \qquad (6.16)$$

Where R_{equ} is the equivalent resistance for thermal resistance network in figure 3.6 :

$$R_{equ} = R_{conv_{out}} + R_{cond} + R_{conv_{in}}; \qquad (6.17)$$

$$R_{conv_{out}} = \frac{1}{h_{out} \times A_{out}}; \qquad (6.18)$$

with $A_{out} = 2 \times \pi \times R_{out} L_{cyl}$

$$R_{conv_{in}} = \frac{1}{h_{in} \times A_{in}}; \qquad (6.19)$$

with $A_{in} = 2 \times \pi \times R_{in} L_{cyl}$

$$R_{cond} = \frac{log\left(\frac{R_{out}}{R_{in}}\right)}{2 \times \pi \times L_{cyl} \times K_{foam}}; \qquad (6.20)$$

There is also the heat input from the two half sphere at the sides of the tank. It is similar to the cylindrical part, except the surface area.

$$R_{conv_{sphere_{out}}} = \frac{1}{h_{out} \times A_{sphereout}}; \qquad (6.21)$$

with $A_{sphere_{out}} = \pi \times R_{out}{}^2$.

$$R_{conv_{sphere_{in}}} = \frac{1}{h_{in} \times A_{in}}; \qquad (6.22)$$

with $A_{sphere_{in}} = \pi \times R_{in}{}^2$.

$$R_{cond_{sphere}} = \frac{\left(\frac{1}{R_{in}}\right) - \left(\frac{1}{R_{out}}\right)}{4 \times \pi \times K_{foam}}; \qquad (6.23)$$

The equivalent resistance is found from:

$$R_{equ_{sphere}} = R_{conv_{sphere_{out}}} + R_{cond_{sphere}} + R_{conv_{sphere_{in}}}; \qquad (6.24)$$

The heat input to the tank is found from:

$$Q_{tank} = \frac{(T_{air} - T_{LNG})}{R_{equ}} + \frac{(T_{air} - T_{LNG})}{R_{equsphere}}; \text{ (W)} \qquad (6.25)$$

Once Q_{tank} is found, the boil-off rate can be found from:

$$\dot{m} = \frac{Q}{\lambda}; \quad (6\text{-}26)$$

with $\lambda = 510\ (\frac{kJ}{Kg})$: Latent heat of vaporization of LNG. [15]

The resulting $\dot{m}$ is the boil-off rate and is given in $(\frac{kg}{s})$. To find the total boil-off mass for the whole flight, $\dot{m}$ is multiplied by the flight time. To account for the whole flight time in Initiator, the cruise speed Vc is used, and the cruise's time is approximate as $t_{cruise} = \frac{Range}{V_c}$; (hr)
In order to account for the take-off and landing, t_{cruise} is increased by half an hour.

⇨ $B_{off} = (t_{cruise} + 0.5) * 3600 * \dot{m}$; (kg)

⇨ $V_{B_{off}} = \frac{B_{off}}{\rho_{LNG}}$

Initiator works using a variable called "usableFraction", it is the fraction of the internal Volume of the tank that is available to store LNG, and is used to calculate the total fuel mass.

$$\text{usableFraction} = 1 - \left(\frac{V_{B_{off}}}{V_{tank}}\right);$$

This variable "usableFraction", is used to account for the boil-off of LNG during the flight.

3.4 Insulation thickness variation

Different foam thicknesses were studied, and their effect on the boil-off rate, the resultant pressure rise due to 72 hours of no boil-off rate, the tank's weight and the available fuel volume for LNG are examined. Three different thickness were studied, 0.1 (m), 0.15 (m) and 0.2 (m).

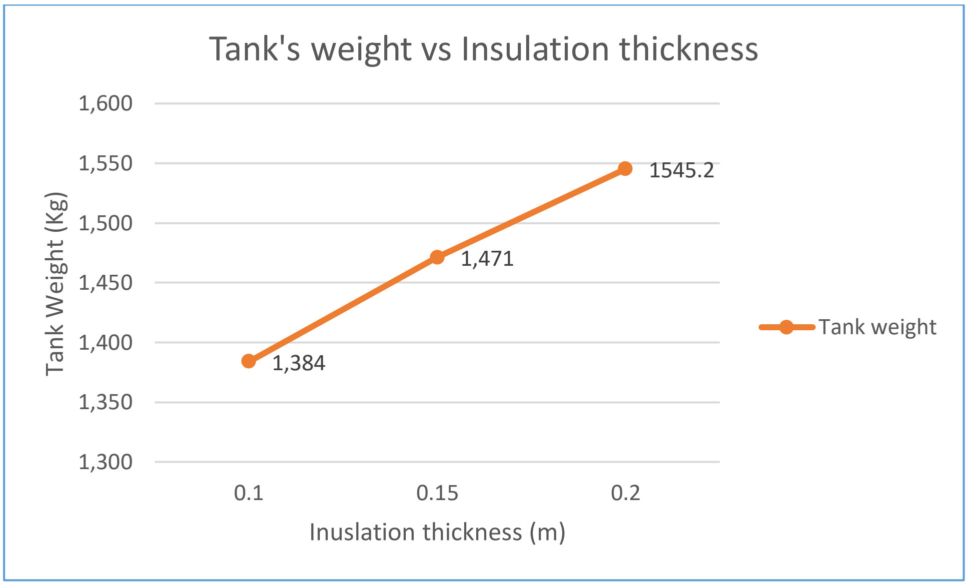


Figure 3.7: Effect of insulation thickness on tank's weight

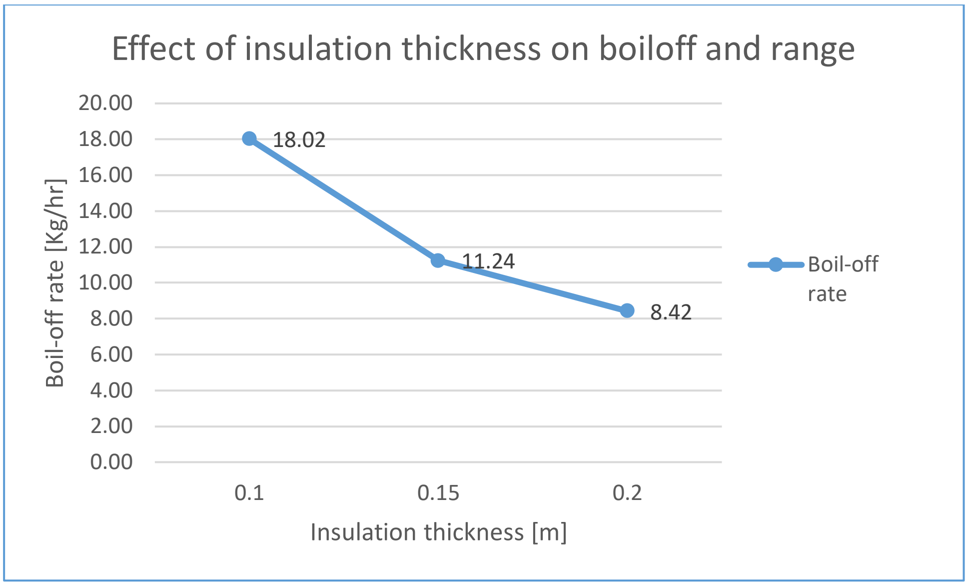


Figure 3.8: Boil-off rate vs Insulation's thickness

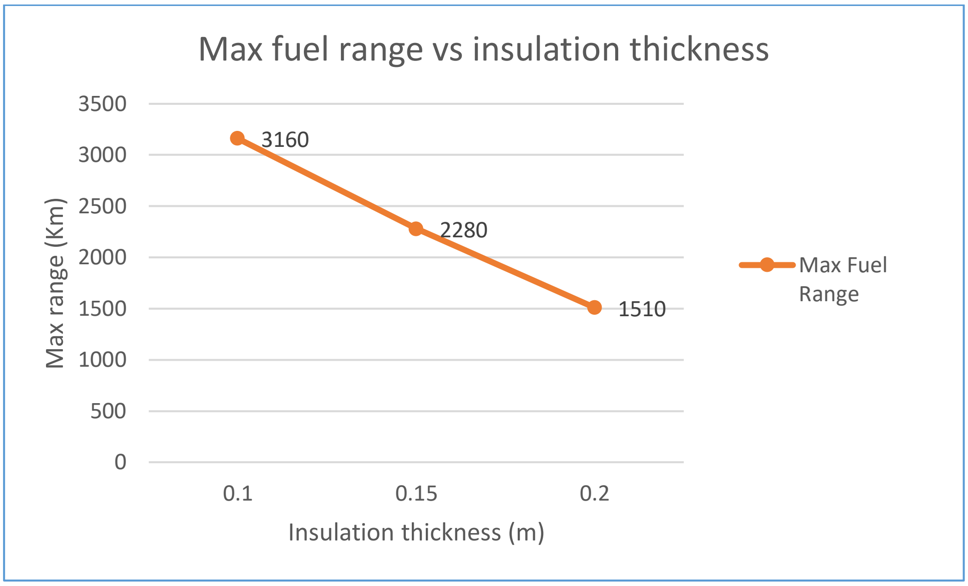


Figure 3.9: Maximum fuel range vs insulation thickness

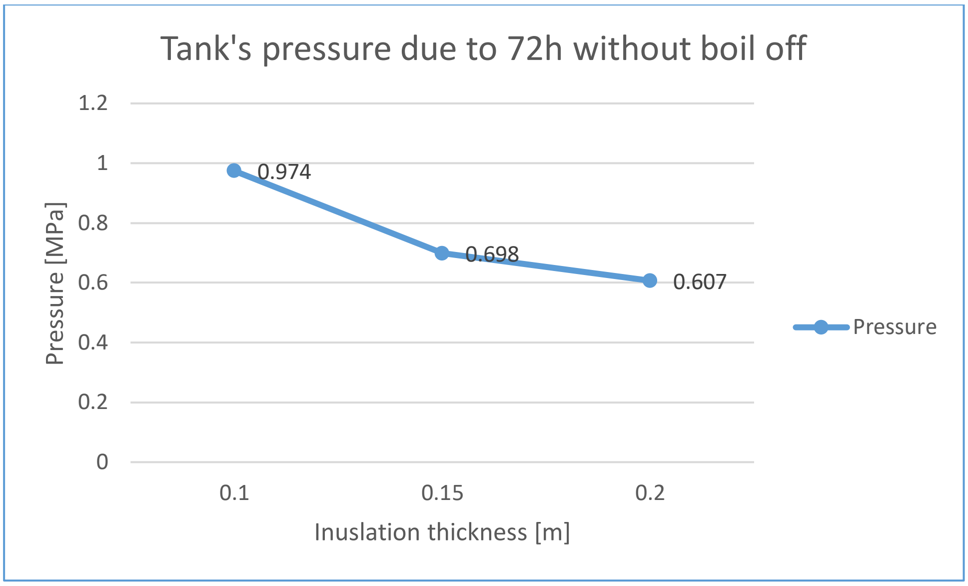


Figure 3.10: Tank pressure due to NPFA 4.3.5 vs Insulation thickness

Since longer range is more beneficial to the flexibility usage of the aircraft, the insulation that results in the maximum fuel range while having acceptable boil-off rate and pressure rise is chosen. So an insulation thickness of 0.1 meters was chosen for the design mission.

3.5 Other necessary modification for the LNG fuel system.

The main part in retrofitting the aircraft from kerosene to LNG is the cryogenic tanks. However other minor modification are needed. These modification are:

- The combustor needs to modified to accept gaseous fuel, and since the reduction of NO_x emission is crucial, the combustor should be replaced with an LDI combustor working with gaseous fuel.
- Fuel pipe: The fuel pipes needs to be insulated in order to minimize the two phase flow.
- A heat exchanger to vaporize the LNG before entering the combusting chamber.
- Feed tank to store the evaporated fuel before entering the engine. This is needed to sustain continuous fuel flow.
- A compressor, to raise the pressure of methane before entering the combustor.
- Several pumps, valves, and pressure sensors.

The LNG fuel system from DSE05 [34] is shown in the figure below as an example. The position of the engines and LNG tanks is different than this study, however the fuel system components is the same.

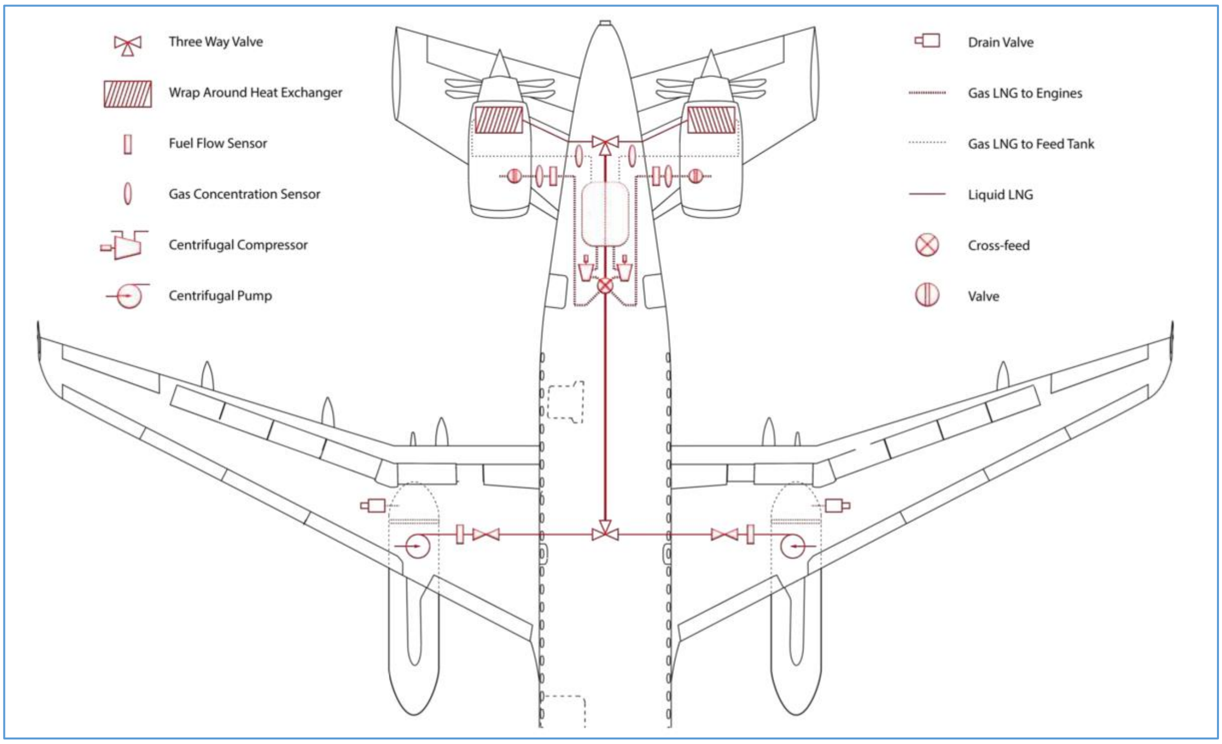


Figure 3.11 A320 LNG fuel system, from DSE05. [34]

Based on DSE05 [34], the LNG fuel system weight was found to be 70% heavier than the kerosene system. Since Initiator approximates the fuel system weight, for the LNG aircraft, the fuel system weight is taken as 1.7 times the estimated weight of the kerosene configuration.

4 Initiator

Initiator is used to design and analyze and compare both configurations, the A320-kerosene and A320-LNG. However before that, some inputs should be specified, and some modules need to be added or modified, especially for the LNG aircraft, since the current state of Initiator works only with kerosene, and only with fuel tanks in the wings.

So this chapter presents, and summaries all the required modification and additions made to the program.

4.1 A320-kerosene configuration

Before generating the A320 in the Initiator, some modification are done for the kerosene configuration, in order to make the configuration as close as possible to the Airbus A320.
These changes are listed below:

4.1.1 Number of ULD required to fit the luggage mass.

Initiator generates the maximum number of ULDs that fits within the cargo floor, and divides the required payload mass equally between all the ULDs. So no matter what is the payload, Initiator will always generates the maximum number of ULDs, and in the case of A320, 9 ULDs are generated. This is shown in the figure below.

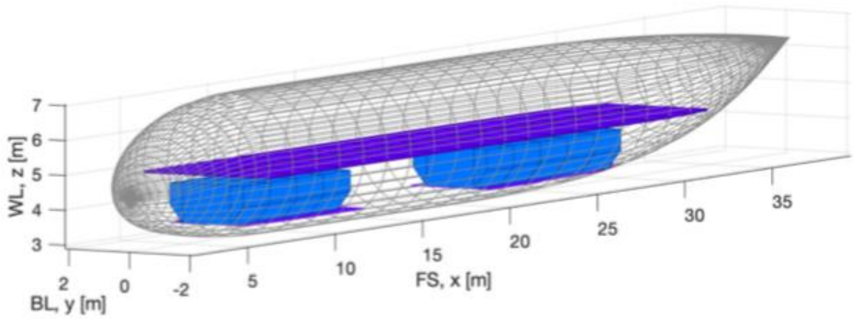


Figure 4.1: Default ULD positions

Also the resulting Cargo's CG is based on equal distributed mass in all the ULDs. This gives an inaccurate CG for the cargo.

In addition to that, for the LNG configuration , the unused ULDs are replaced with the cryogenics tanks. So the program was modified to generate the exact number of ULDs needed to fit the Cargo. These modification are done in the "calcMass.m" script which outputs the Mass and center of gravity of the Cargo.

Also a modification to "Generate.m" within the Cargo module is necessary. This script generates the ULDs, so it was modified to account for the exact number of ULDs and their positions.
For a 150 passengers, with a typical luggage allowance of 25 Kg, the cargo fits in 3 ULDs.
The figures below shows the modified version with the exact number of ULDs.

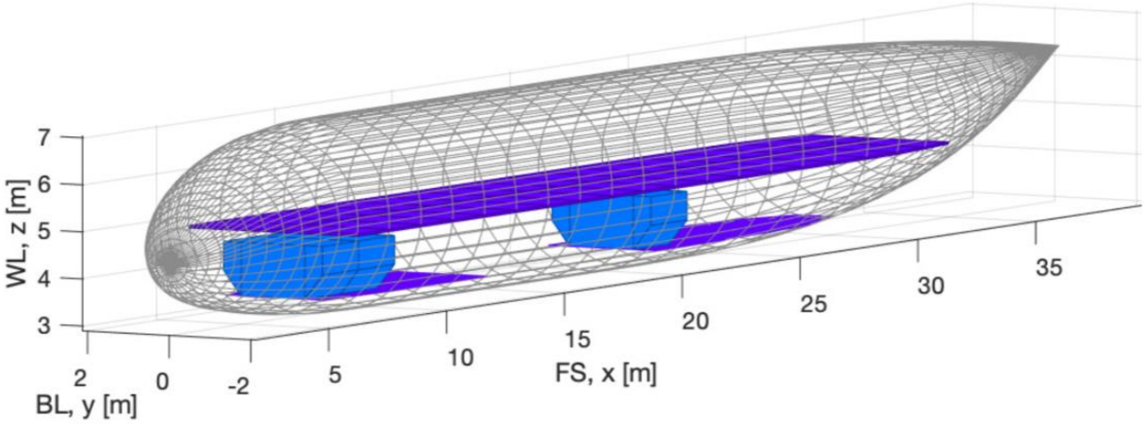


Figure 4.2: New exact ULD positions.

The new configuration with the exact number of ULD can be enabled by settings the 'exactULDs' [2] to true in the settings file. The default is set to false which is the old method that generates the maximum number of ULD that fits the cargo space.

4.1.2 ULD arrangement options.

Second, there are several ways that the exact number of ULDs can be positioned within the cargo bay. Four options were created. These options are shown in the figures below:

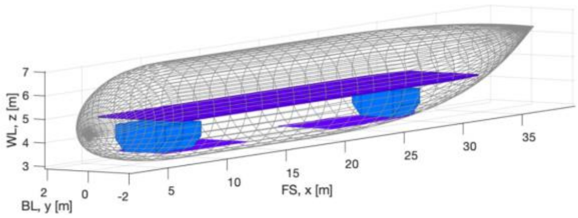


Figure 4.3: ULD option 1

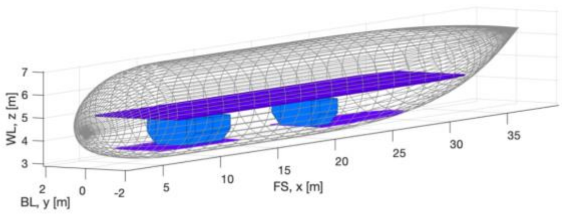


Figure 4.4: ULD option 2

[2] '-' : variable name in the setting file "Settings.m"

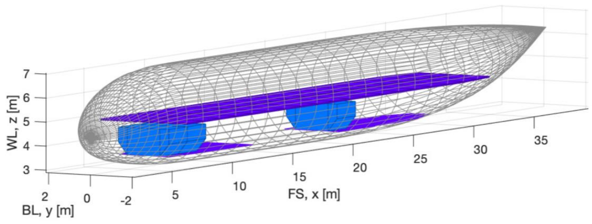


Figure 4.5: ULD option 3

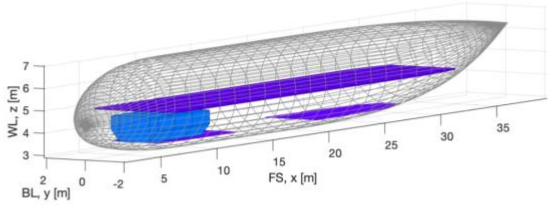


Figure 4.6: ULD option 4

Four different aircraft were generated with the options above. The different options resulted in different center of gravity and operational safety margin.

Table 4.1: Longitudinal stability vs ULD options.

	ULD option 1	ULD option 2	ULD option 3	ULD option 4
C_{m_α}	-2.73	-2.73	-2.9	-3.21
Safety margin(%)	51	51	55	61
X_{np} (m)	18.5	18.5	18.5	18.5
X_{cg}(MTOW) (m)	16.2	16.2	16.1	15.8
X_{cg}(OEM) (m)	16.5	16.5	16.5	16.5

From the table above, ULD option 4 has the highest longitudinal stability (smallest C_{m_α}) and the larger safety margin. So ULD option 4 is chosen as the default configuration, and is used to design and compare the A320-Kerosene and A320-LNG aircrafts for the rest of the report.
The user can specify which of the four ULD options wants to use by settings the 'ULDoption ' in the settings file to the desired option from 1 to 4.

4.1.3 Inputs for the kerosene configuration

This section describes the geometrical dimensions used to generates A320 as accurate as possible to the Airbus A320 from literature. Along with the dimensions, the position of different component such as the wing position, the engine positions, gear position, horizontal tail and vertical tail are specified. Also some performance and aerodynamics parameters are defined such as the SFC , CL_{max}.

Table 4.2: Initiator's Inputs for the A320-kerosene.

Variables	Value	Variables	Value
Passengers	150	Vertical stabilizer span	6.26 (m)
Range	1500 (Km)	Vertical stabilizer root Chord	5.83 (m)
Cruise Mach number	0.78	Vertical stabilizer tapers	0.303
Altitude	11278 (m)	Vertical stabilizer sweeps	34°
Take-Off Distance	2180 (m)	Vertical stabilizer twists	0°;0°
Landing Distance	1440 (m)	Vertical stabilizer dihedrals	0°
Loiter Time	30 (min)	Vertical stabilizer thickness Ratios	0.1;0.1
Diversion Range	500 (Km)	Vertical stabilizer spar Positions from root chord	0.2;0.7

$\left(\frac{L}{D}\right)_{max}$	18	Vertical stabilizer position x	29.8 (m)
SFC	0.6 $(\frac{\text{lb/h}}{\text{lbf}})$	Vertical stabilizer position z	1.66 (m)
FFStartUp	0.99	Number of engines	2
FFTaxi	0.99	Engine type	Turbo Fan
CL_{max} Landing	3	Engine bypass Ratio	6
CL_{max} Take-Off	2.56	Engine length	2.423 (m)
CL_{max} Clean	1.3	Engine diameter	1.829 (m)
Wing Aspect Ratio	9.39	Engine thrust at Take-off	117877 (N)
Fuselage length	37.57 (m)	Engine position x	11.19 (m)
Fuselage diameter	4.14 (m)	Engine position y	5.755 (m)
Wing span	33.91 (m)	Engine position z	-1.82 (m)
Wing root Chord	7.08 (m)	Main Gear number of rows	1
Wing section Positions	0;0.38;1	Main Gear number of wheels per row	2
Wing tapers	0.53;0.44	Main Gear tyre Diameter	1.27 (m)
Wing sweeps	23°;26°	Main Gear tyre Thickness	0.455 (m)
Wing twists	0°;-2°;-3°	Main Gear position x	17.71 (m)
Wing dihedrals	5.1°;5.1°	Main Gear position y	3.795 (m)
Wing thickness Ratios	0.16;0.12;0.1	Main Gear position z	-3.557 (m)
Wing spar Positions	0.15;0.6	Nose Gear number of rows	1
Wing position x	11.19 (m)	Nose Gear number of wheels per row	2
Wing position z	-1.08 (m)	Nose Gear tyre Diameter	0.828 (m)
Horizontal stabilizer span	12.45 (m)	Nose Gear tyre Thickness	0.254 (m)
Horizontal stabilizer root Chord	4.17 (m)	Nose Gear position x	5.07 (m)
Horizontal stabilizer taper	0.256	Nose Gear position z	-3.557 (m)
Horizontal stabilizer sweep	29°	settings	-
Horizontal stabilizer twists	0°;0°	Luggage Mass per passenger	25 (Kg)
Horizontal stabilizer dihedrals	8°	Number of passenger per square meter	1.5 (pax/m2)
Horizontal stabilizer thickness Ratios	0.1;0.1	‘MinimumCargoPackingEfficiency’	0.6
Horizontal stabilizer spar Positions from root chord	0.2;0.7	‘DefaultRelativeFloorZPosition’	-0.04
Horizontal stabilizer position x	31.8 (m)	‘exactULDs’	true
Horizontal stabilizer position z	0.84 (m)	‘ULDoption’	4

4.2 Airbus A320-200 validation

With these modifications, the Initiator is ready to generate a configuration working on kerosene as fuel, that meets the design mission of Airbus A320-200.

First an A320-200 is generated in Initiator that satisfies the design mission of the real Airbus A320-200. This is done in order to validate the capability of the program. The design mission for this validation is:

Table 4.3: Requirements for the validation design mission of Airbus A320-200

Range	5000 (Km)
Number of passengers	150 (2 class)
Payload Mass	15750 (Kg)
Cruise Mach number	0.78
Altitude	11278 (m)

The table below compares the real aircraft with generated one.

Table 4.4: A320-200 vs A320-Initiator.

	A320-200	A320-200-Initiator	Difference(%)
MTOM (Kg)	73500	68440	-6.88
OEM (Kg)	39733	35400	-10.91
OEM/MTOM	0.54	0.52	-4.32
Harmonic Range (Km)	5000	4780	-4.40
Mission Range (Km)	5000	5000	0.00
Mission Fuel Mass (Kg)	17940	17950	0.06
Payload (Kg)	15750	15090	-4.19
Payload/MTOM	0.21	0.22	2.89
Fuselage length (m)	37.57	38.5	2.48
Fuselage diameter (m)	4.14	4	-3.38
Wing span (m)	33.91	33.6	-0.91
T/W cruise	0.3084	0.3	-2.72
W/S (N/m2)	5890.8	5618.4	-4.62
L/D cruise	-	16.5	-
$SFC_{cruise}\ (\frac{lb}{lbf.h})$	0.6	0.6	0.00
MAC (m)	4.29	4.34	1.17
Wing area (m2)	122.4	119.5	-2.37
Horizontal tail area (m2)	31	24.53	-20.87
Vertical tail area (m2)	21.5	17.05	-20.70
X_{cg}(MTOW) (m)	16.56	17	5.07

From table 4.4, it can be seen that Initiator predicts MTOM within 7%,while slightly more the operating empty weight. This is mainly due to the underestimation of the Wing's mass that comes from the missing of high lift devices in Initiator and winglets.

The Harmonic range is within 4% , and the resultant mission payload is within 4%. Also Initiator predicts well the fuselage length ,diameter and wing span. These slight geometrical difference can be eliminated by running the program without the Design convergence loop. It will be emphasized later on.

The Thrust-to-weight ratio and the wing loading are well predicted. The Horizontal and vertical tail are less accurately predicted. However this difference is reduced when running the program without the Design convergence loop. This is done by running the Performance Estimation module. The program generates an exact geometrical aircraft from the characteristics data from table 4.2, and then analyze it. The results are shown in the table below.

Table 4.5: A320-200 vs A320-Initiator-Geometrical

	A320-200	A320-Initiator-Geom	Difference(%)
MTOM (Kg)	73500	65030	-11.52
OEM (Kg)	39733	32440	-18.36
OEM/MTOM	0.54	0.50	-7.40
Harmonic Range (Km)	5000	4700	-6.00
Harmonic Fuel Mass (Kg)	17940	16840	-6.13
Mission Range (Km)	5000	5000	0.00
Mission Fuel Mass (Kg)	17940	17730	-1.17
Payload (Kg)	15750	15750	0.00
Payload/MTOM	0.21	0.24	12.50
Fuselage length (m)	37.57	37.6	0.08
Fuselage diameter (m)	4.14	4.14	0.00
Wing span (m)	33.91	33.9	-0.03
T/W cruise	0.3084	0.285	-7.59
W/S (N/m_2)	5890.8	5583	-5.23
L/D cruise	-	16.1	-
SFC_{cruise} $(\frac{lb}{lbf.h})$	0.6	0.6	0.00
MAC (m)	4.29	4.35	1.40
Wing area (m_2)	122.4	126.5	3.35
Horizontal tail area (m_2)	31	32.23	3.97
Vertical tail area (m_2)	21.5	23.5	9.30
X_{cg}(MTOW) (m)	16.56	15.8	-4.59

From table 4.5 it can be seen that the aircraft geometry i.e., the fuselage length, fuselage diameter, wing span are identical to the Airbus A320-200. The area of wing and horizontal and vertical tail are much closer to the real aircraft then the converged configuration. However the in MTOW and OEM are larger than the converged aircrafts.

So the results above shows that Initiator is capable of generating an Airbus A320-200, and the results difference falls within acceptable margins.

4.3 Modifications necessary for the LNG configuration

In the Initiator, an aircraft is defined by a combination of parts such as : Cargo, Engine, Fuselage, Wing, Landing Gear, etc.

So the way the program calculates the fuel is by checking if the part has a fuel tank, if so Initiator expect from the part to have 3 methods that output the necessary tank's characteristics.

The main methods required for a fuel tank in any part are :

- A script to generate the Tank's geometry in terms of 3D Cartesian coordinates, labelled "getFuelTankGeometry.m" .
- A script to find the center of gravity of the tank, labelled "getFuelTankCG.m" .
- A script to find the available volume for the fuel within the tank, labelled "getFuelVolume.m" .

However in the current state of the Initiator, the only part that has a method to generate a fuel tank is the "Wing" part. So these three scripts were created for the "Fuselage" part, below is a brief explanation of how the methods work, and the full scripts are available in Appendix [F].

i. getFuelTankGeometry.m

This method generates the 3D Cartesians coordinates of the external of the tank, then these coordinates are used to plot the cryogenic tank.

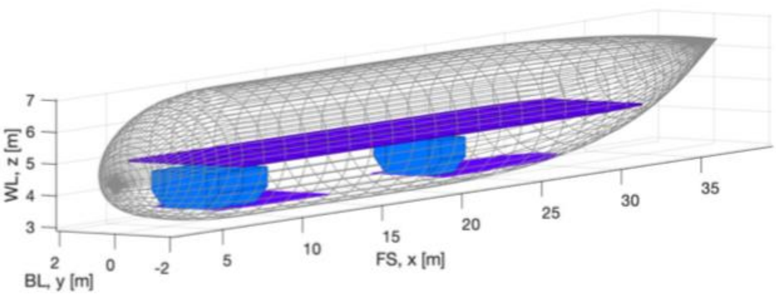


Figure 4.7: ULD option 4.

The outer diameter of the tank is defined as the distance between the upper and lower floor minus 10 centimeters to allow room for fuel pipes and cables.
Then the method takes the positions of the ULDs from the "Cargo" part, from "calcMass.m" function :

```
[~,~,XTankStartFront,XTankStartRear] = obj.CargoBay.calcMass;
```

This gives the start and the end point of both the frontal tank as well as the rear tank.
The front tank starts at the end of the last ULD and ends at the end of the frontal lower floor. And the rear tank runs from the last ULD until the end of the rear lower floor, as show in the figure below:

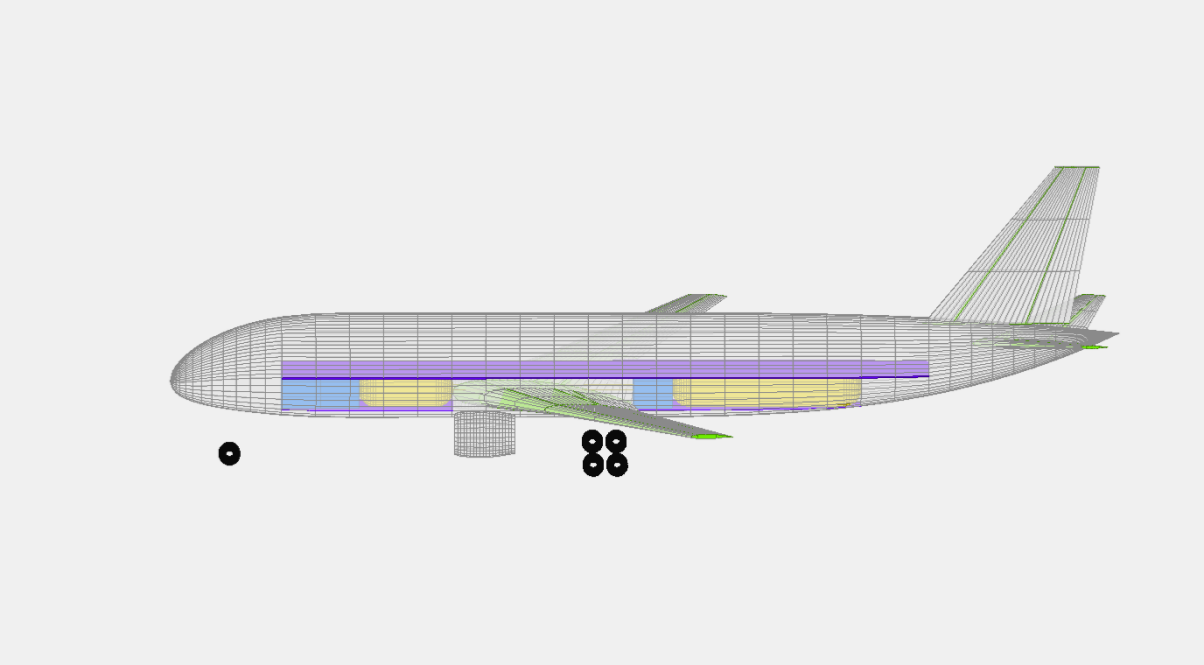


Figure 4.8: LNG tanks configuration. ULDs(blue) and cryogenic tanks(yellow) layout.

Two tanks are positioned next to each other along the fuselage for maximum fuel capacity, like the figure below:

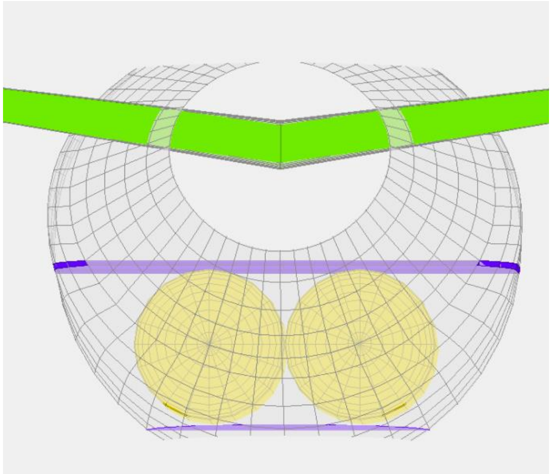


Figure 4.9: Rear sectional view of the cryogenic tanks.

So the output of "getFuelTankGeometry.m" method is the [X, Y, Z] coordinates of the external tanks' geometry. The coordinates are used to plot the tanks.

i. getFuelTankCG.m

This method calculates the center of gravity of the fuel tanks, and output the resultant as 3D coordinates.

ii. getFuelVolume.m

This method calculates the internal volume of the tanks where LNG is stored. Based on the outer radius and the different tank material thickness, it calculates the internal tank's radius and thus the internal volume.
The outer radius as mentioned before is fixed based on the distance between the upper and lower floor, and the insulation thickness's to 0.1 meters.
Whereas the thicknesses of the internal Aluminum layer is calculated based on the maximum

pressure that the tank needs to withstand and the external Aluminum layer's thickness based on the weight of the tank and the fuel while taking a safety factor of 1.5. These thicknesses are read from the "getFuelTankWeight.m" method.

So the output of this method is the volume capacity available for storing cryogenic fuel in [m^3]. In addition to these required scripts, two other methods were added:

- A method for finding the boil-off rate from the cryogenic tanks, and consequently outputting the allowable fraction of the tank's volume that can be filled with LNG. The module is called "getBoiloffrate.m"
- The second method calculates the weight of the cryogenic tank, based on the materials used and on an acceptable boil-off rate. This was explained in the tank design section. The module is titled "getFuelTankWeight.m".

The two methods are described briefly below, and can be found in Appendix [F].

iii. getBoiloffrate.m

Based on the method explained in chapter 3, section 3.3, this script calculates the boil-off rate of the LNG in ($\frac{\mathrm{Kg}}{\mathrm{h}}$). It determines the heat leakage to the inside of the tank, and thus the boil-off rate. The result is then used to determine the fraction of the internal volume of the tank that is available for storing LNG.

iv. getFuelTankWeight.m

Since the LNG tank is much heavier then kerosene tanks, and since the weight of the tank to the fuel weight ratio is between 10% and 20%, it cannot be ignored.

So this script calculates the weight of the cryogenic tanks based on the materials used and the required forces that they need to withstand. This was presented in the tank design chapter section 3.2 "Materials thickness and stress analysis".

The output of this method is the total mass of the fuselage tanks in kilograms. This result is added to the final fuel system weight.

These 5 modules are the minimum requirement for generating a cryogenic tank within the fuselage.

4.3.1 Other modifications needed for LNG aircraft.

Further modifications to the existing modules in the Initiator are needed in order to be able to generate and study an LNG aircraft. This section describes briefly those adjustments. The added code can be found in Appendix [G].

i. Generating fuel tank only in the required part.

Initiator was always generating wing's tanks and in the LNG case, it resulted in fuel tank in the wing and in the fuselage. So if 'LNGfuel' is selected, the program generates cryogenic tanks in cargo bay within the fuselage. If not , the program works like before with the fuel tanks in the wings.

ii. Model the LNG fuel and tanks weight distribution.

The fuel weight is modelled as linear distribution of weight point along the tank's length. This weight distribution is only available for the wing tank, so it should be added in case of the fuselage tank. So the weight of the LNG fuel and tanks is modelled as a point distribution of individual tanks, similar to the ULDs.

iii. Usable tank volume for storing fuel.

In the case of kerosene, the maximum portion of the wings' tanks volume available for storing the fuel is defined by a fixed setting called 'UsableFuelVolume' equal to 1. In the LNG case , the "usuableFraction" is calculated based on the boil-off of the LNG.

iv. The cryogenic fuel system weight.

Since the cryogenic system needs extra parts such insulated pipes, extra pumps, heat exchanger and feed tank, their weight needs to be added . So the cryogenic fuel system is assumed to weight 70% more than the kerosene fuel system, based on DSE05 [34].

v. Add the mission's fuel weight to the correct part.

The program was always adding the mission's fuel mass to the Main Wing. So the program was modified to writes the fuel mass to the fuselage in case of Fuselage tank, and if not then the fuel mass is written to the Main Wing like before.

vi. Add the emissions of the Methane.

Since Initiator worked only with kerosene fuel , the emissions from the combustion of Methane needs to be added. For LNG the amount of CO_2, H_2O and NO_x emitted in kg per kg of fuel burned are added.

vii. Convergence criteria for the LNG configuration.

In order for an aircraft modules to converge, few criteria needs to satisfied. Two of the convergence criteria are having enough tank volume to fit the required fuel mission, and enough cargo space to fit the required cargo. Initiator modifies the aircraft's geometry in two conditions, one if the required cargo does not fit, then the fuselage is extended until the cargo can fit. The second geometrical change is for the wings, if the fuel does not fit, the wings are extended.

Since the LNG's volume needed might not fit within the typical length of A320's fuselage, one solution to that is to extend the fuselage. So in a similar way to the wing part, the program is modified to extend the fuselage if the required mission's LNG fuel does not fit. This can be enabled by setting 'DesignConvergenceFuselageTankFitting' to true in the settings. So "LNGTankScalingFactor" was added as a criteria to the convergence loop, now this must be satisfied so that the configuration can converge. The figure below depicts the activity diagram for the fuel convergence loop.

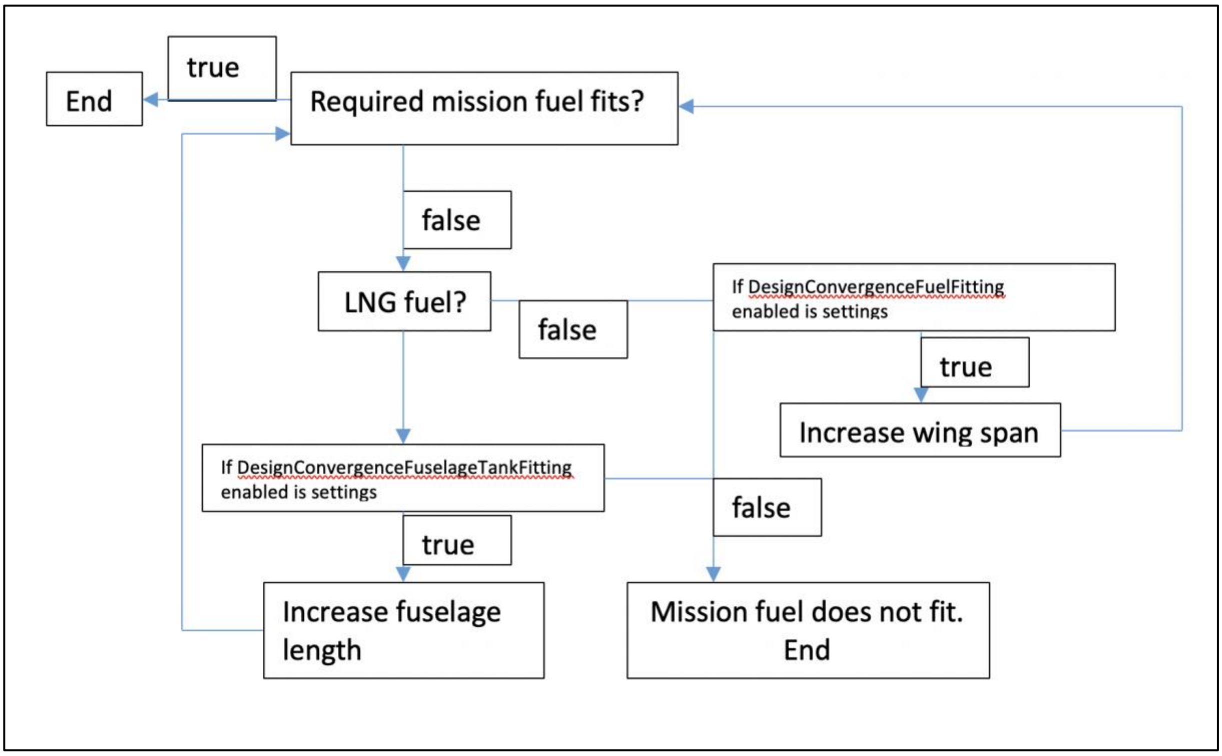


Figure 4.10. Fuel convergence loop

It should be noted, that for the LNG configuration the 'DesignConvergenceFuelFitting' setting should be set to false in the settings file, so that if the fuel does not fit, only the fuselage will be extended and not the wing span.

viii. Method to plot the cryogenic tanks.

Since a cryogenic tank was added to the fuselage; it needs to be added to the plotting module. So a method to draw the cryogenic tank is added to the plot module and the report module.

ix. General program settings.

In this file, all the settings that were added to the Initiator are defined. For the LNG, several new variables need to be defined in the 'settings.xml' file. All the added variables are listed in the table below:

Table 4.6: LNG variables added to "settings.xml".

Name	Default Value	Description
LNGfuel	false	Use LNG fuel in cryogenic tanks within the fuselage
AftLNG	false	Generates an additional tank in the aft of the fuselage
TanksALL	false	Generates a whole cryogenic tank that runs across the fuselage between the ULDs, including through the wing box.
exactULDs	false	Generates the exact number of ULDs that fits the required luggage mass.
ULDoption	4	Choose between 4 ULD positions within the cargo bay.

DesignConvergenceFuselageTankFitting	false	Extend the fuselage if the mission's fuel does not fit
FuselageLengthIncreaseForFuelTank	0.05	Extend the fuselage length by a factor of (this value) for each iteration when 'DesignConvergenceFuselageTankFitting' is set to true.

x. Direct Operating Cost.

A cost Estimation module was added to the Initiator, while writing this report. The cost estimation module estimates the costs of the aircraft designed. What is of interest to this thesis is the DOC, since it includes the mission fuel price. The module assumes the fuel to be JET-A FUEL, with the density to be $6.84\ (\frac{\text{lb}}{\text{gal(US)}})$, and a fuel price of $4\ (\frac{\$}{\text{gal(US)}})$.

So to take account for the LNG, it's density and price are added to the module in the required units. LNG has a density of $420\ (\frac{\text{Kg}}{\text{m}^3})$, this is equal to $3.505\ (\frac{\text{lb}}{\text{gal(US)}})$. From [29] the forecast price of LNG in 2025 will be double that of the Jet fuel in terms of energy density $(\frac{\text{MJ}}{\$})$. Thus LNG price of $1.191\ (\frac{\$}{\text{gal(US)}})$ is used.

4.3.2 Additional inputs for the LNG configuration

The LNG configuration uses all the inputs of the kerosene configuration from table 4.4, and in addition to that some additional inputs are required for LNG.

Table 4.7: Addition inputs for A320-LNG

Variables	Value	Description
Fuselage fuelTank	true	Generates fuel tank in the fuselage.(Set in in the aircraft input xml file)
Settings	-	Variable in the common settings file
LNGfuel	true	Set to true to use LNG as fuel
AftLNG	false-true	Set to true to generate a tank in the aft of the aircraft
FuelDensity	420 (Kg/m3)	The density of the fuel
FuelHg	5003 (*10^4 J/Kg)	Heating value of the fuel
SFC	0.516 ((lb/h)/lbf)	Specific fuel consumption at cruise
FTMMT	0.002 (m)	Minimum manufacturing thickness for the Aluminum alloys.

4.3.3 ULD options for the LNG aircraft

Similar to the kerosene configuration explained in section 4.1.2 , it was added the possibility to position the ULDs in 4 different configuration. The same options are available for the LNG aircraft. The figures below shows the 4 options along with the LNG tanks.

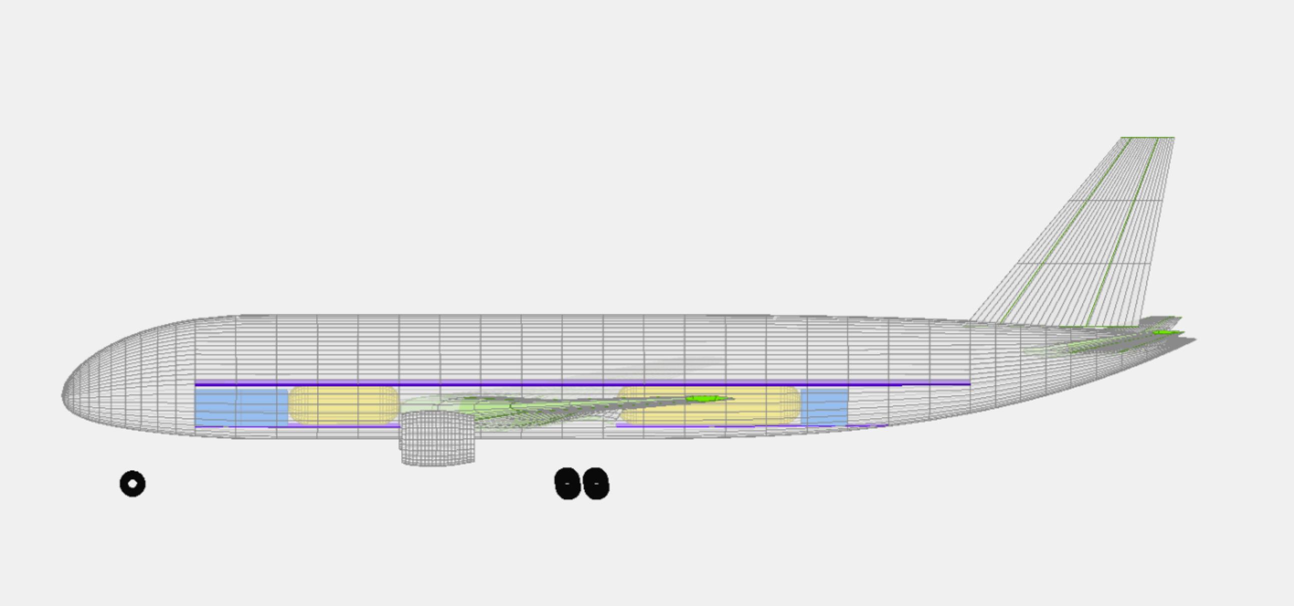


Figure 4.11. ULD option 1

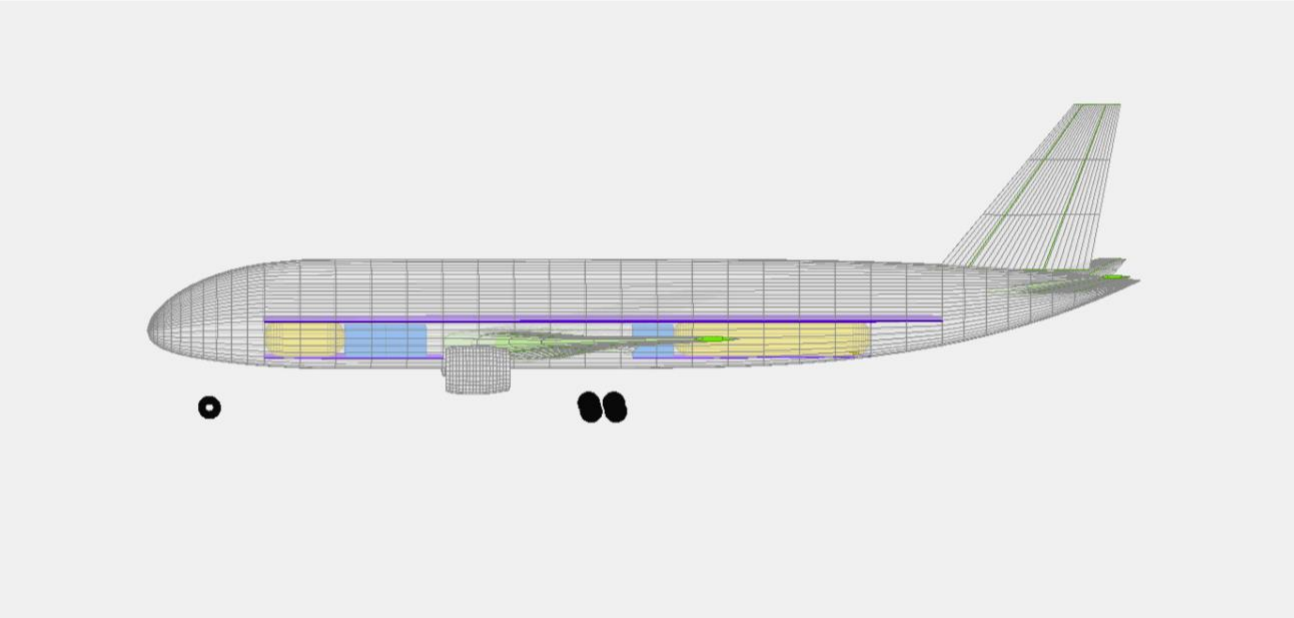


Figure 4.12. ULD option 2

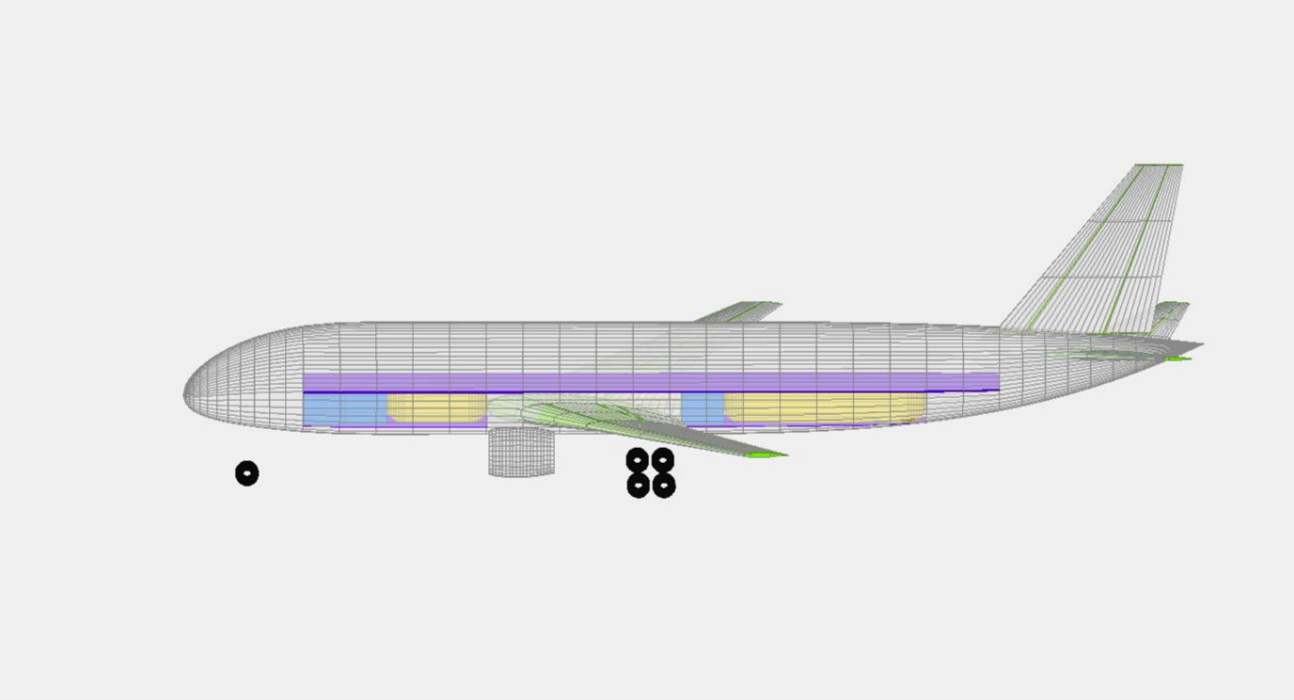


Figure 4.13. ULD option 3

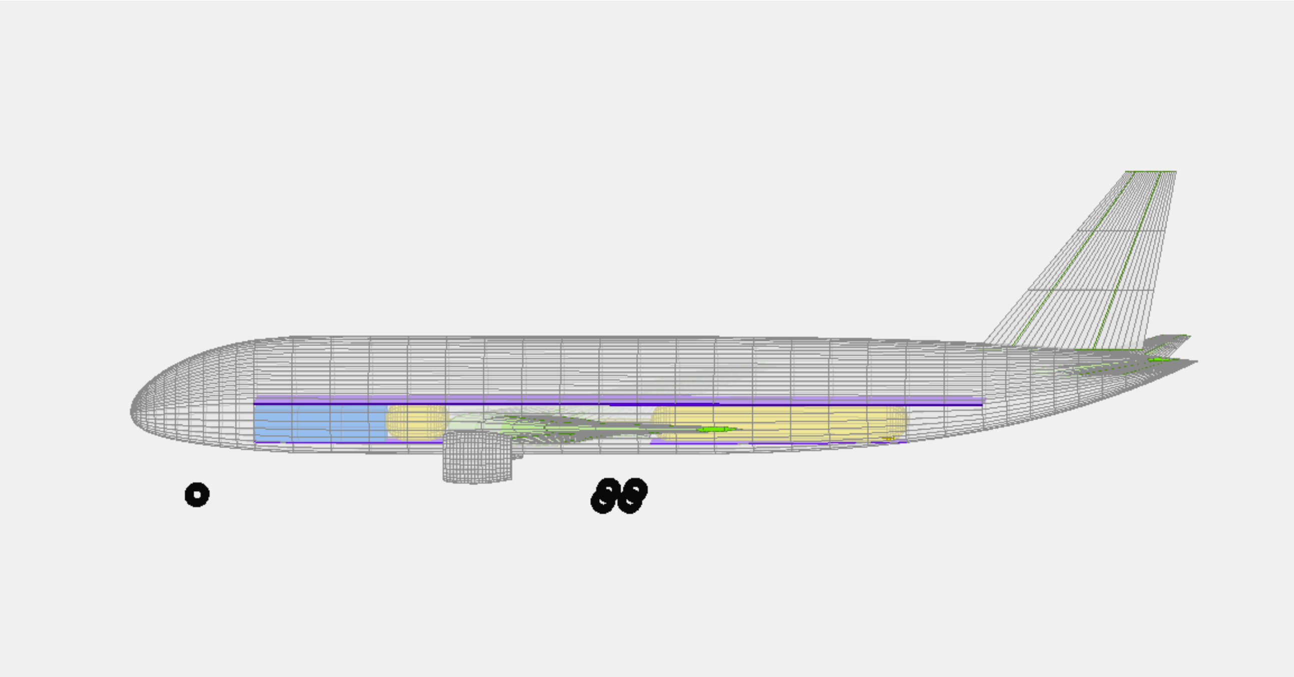


Figure 4.14. ULD option 4

These 4 options were tested for the converged aircrafts, for the geometrical configurations and LNG aircrafts with and without aft tank. The tables below compares the 4 option for each different type of generated aircrafts.

Table 4.8: Comparison of ULD options for LNG-Geometrical configurations.

	ULDoption= 1	ULDoption=2	ULDoption=3	ULDoption=4
C_{m_α}	-2.48	-2.18	-2.29	-2.32
SM (%)	47	41	43	44

X_{np} (m)	18.5	18.5	18.5	18.5
X_{cg}(MTOW) (m)	16.4	16.7	16.6	16.5
X_{cg}(OEM) (m)	16.5	16.6	16.6	16.7

Since the cryogenic tanks will be stationary, and to allow the loading and unloading of the ULDs taking into consideration the cargo doors on the Airbus A320, shown in the figure 4.15, option 1 was disregarded as a feasible option for the A320-LNG.

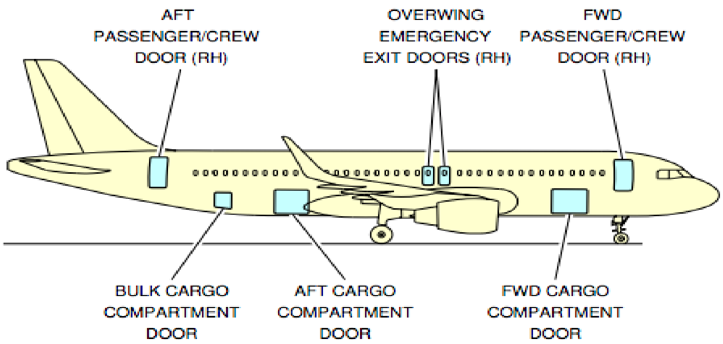
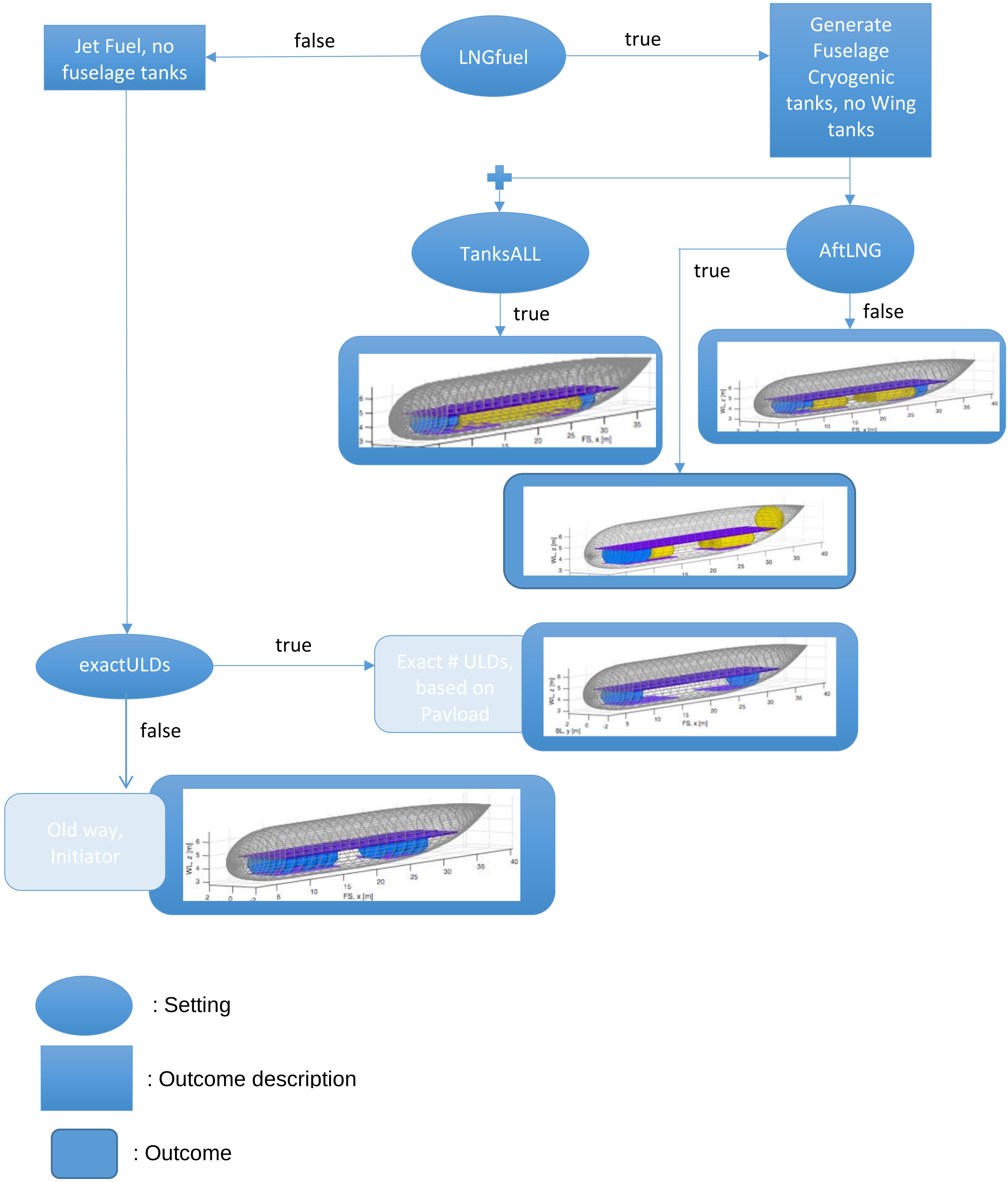


Figure 4.15 Airbus A320 doors. [36]

From the tables 4.8, ULD option 4 was chosen for the design mission comparison, since it is the best choice based on the longitudinal stability, and the safety margin.
So option 4 is used for the final comparison for all configurations, both for the kerosene and the LNG configuration.

4.4 Modified Initiator flow diagram

Below is the flow diagram of the Initiator program:



5
Design Mission

The kerosene and LNG configurations will be designed to carry 150 passenger for a range of 1500 Kilometers. This range is chosen, since on average A320 is used for flights of around 1481 Km, and 75 percent of flights around the world are less then 1984 Km [34] - [37], as can be seen in the figure below. Figure 5.1 represents the average flight distance based on over 16500 routes where Airbus A320 is being used.

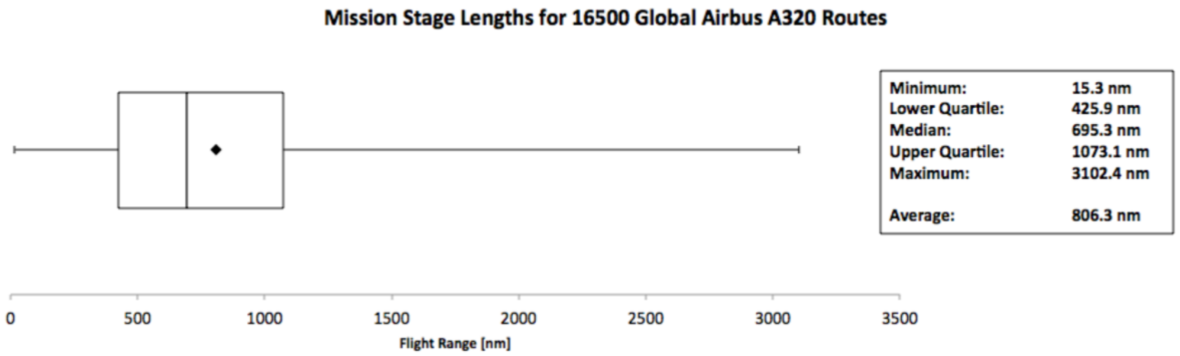


Figure 5.1 Average Stage Range for 16500+ Airbus A320 Routes. [34]

In addition looking at figure 5.2, it represents the flight distance between Amsterdam and most of the capitals within Europe. The flight distance ranges from 347 Km to 2167. So a design range of 1500 Km covers most of the flights within Europe.

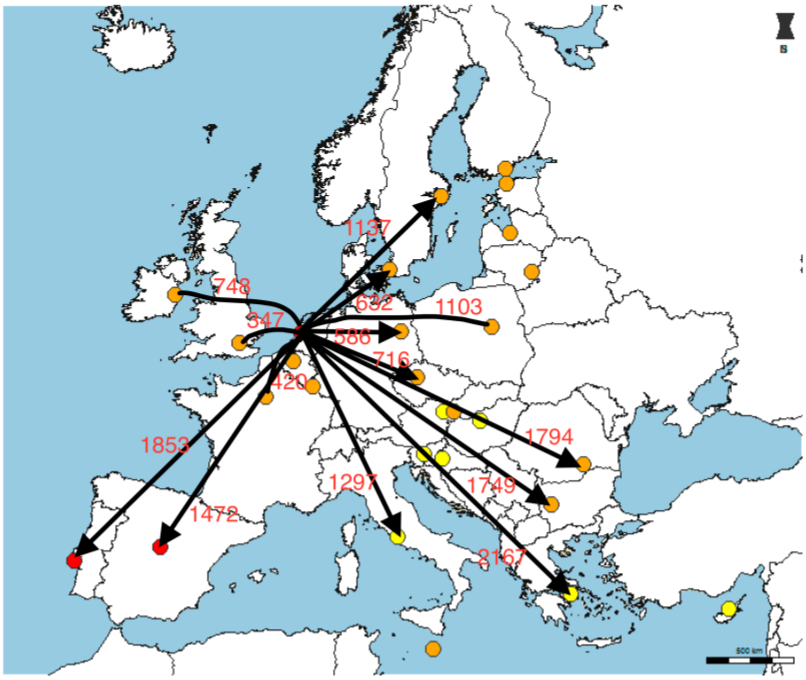


Figure 5.2 Flight distance from Amsterdam to most capitals within Europe in Km.

The table below describes the design mission requirements, while the full mission's input can be found in table 4.2 .

Table 5.1: Design mission requirements.

Range	1500 (Km)
Number of passengers	150 (2 class)
Mass per Passenger	80 (Kg)
Luggage Mass per Passenger	25 (Kg)
Payload Mass (passengers + luggage)	15750 (Kg)
Cruise Mach number	0.78
Altitude	11278 (m)

5.1 Designed aircraft for the mission

First an A320-kerosene configuration and an A320-LNG configuration are generated. The table below shows the resulting characteristics of both aircrafts.

Table 5.2: A320-kerosene vs A320-LNG converged.

	A320-kerosene	A320-LNG	Difference(%)
MTOM (Kg)	54000	54450	0.83
OEM (Kg)	31470	32780	4.16
Harmonic Range (Km)	1320	1210	-8.33
Mission Fuel Mass (Kg)	7190	6520	-9.32
Mission Luggage mass per passenger (Kg)	22.3	21	-5.83
Reserve fuel Mass (Kg)	1950	1700	-12.82
Max Passenger Range (Km)	3274	1923	-41.26

Max Passenger fuel mass (Kg)	10530	9680	-8.07
Max Fuel Range (Km)	7580	1760	-76.78
Max Fuel Range's fuel mass (Kg)	18820	6790	-63.92
Max Fuel Range's Luggage mass per passenger (Kg)	-	19.3	-
Fuel System (Kg)	108	147.4	36.5
Fuselage length (m)	38.4	38.4	0.00
Fuselage diameter (m)	4	4	0.00
Wing span (m)	32.2	32.5	0.93
T/W_{cruise}	0.28	0.296	5.7
L/D_{cruise}	16.6	16.7	0.60
CO_2 emissions (Kg)	13317.4	9975.72	-25.1
H_2O emissions (CO_2 equivalent) (Kg)	1067.2	1736	62.67
NO_x emissions (CO_2 equivalent) (Kg)	2186	680.53	-68.87
Tank front (Kg)	-	453.6	-
Tank rear (Kg)	-	653.4	-
Tank weight (Kg)	-	1107	-
Tank Volume (m_3)	-	16.2	-
Boil-off flight (Kg)	-	33.7	-
Tank P_v (MPa)	-	1.04	-
Insulation thickness (cm)	-	10	-
Al-in thickness (cm)	-	0.2	-
Al-out thickness (cm)	-	0.2	-
Wing area (m_3)	109.7	112.1	2.19
MAC (m)	4.16	4.21	1.20
Horizontal tail area (m_3)	19.14	22.36	16.8
Vertical tail area (m_3)	13.3	15.55	16.92
X_{np} (m)	20.6	20.8	0.97
X_{cg}(MTOM) (m)	17.1	17.2	0.58

From the table above, it can be seen that the LNG's Operating Empty Mass is slightly larger than the kerosene aircraft, this is due to the extra Cryogenic tanks' weight. While the Maximum Take-off Mass of both aircrafts is within 1% of each other. The added weight of the cryogenic weight is offset by the mission fuel mass, which is 9% less than the kerosene.

The big difference is in the emissions during the mission. For the same mission, the LNG aircrafts emits 25% less CO_2 mass, and 69% less NO_x, while producing 63% more H_2O.

From table 5.2, it can be noted that the mission range is completed by both aircrafts but with less luggage mass then the requirements. LNG aircraft complete the 1500 Km mission with a luggage mass of 21 Kg per passenger instead of the required 25 Kg, while the Kerosene has a luggage mass of 22 Kg. Another way to look at it is through the Harmonic range, which is the range that the aircraft can fly with the required Payload Mass ,which is equal to 150 passenger times 80 kg for the passenger's weight and 25 Kg of luggage each.
So for this comparison, The kerosene has a 8% higher harmonic range.

One thing can be noticed from table 5.2, is that the LNG aircraft has a maximum Fuel capacity “MaxFuelMission” of 6790 Kilograms, while having a higher Maximum passenger Fuel Mass of 9680 Kg. This can be interpreted, that the range of the aircrafts is limited due to the small available fuel volume, and not by the MTOM. This also results in Maximum range for the LNG aircraft of 1760 Km with a luggage mass of 19 Kg per passenger “MaxFuelMission Luggage mass per passenger”.

The cryogenic tanks takes all the available space in the Cargo bay. So one way to increase the range is by adding a small tank in AFT on the aircrafts. This is shown in figure 5.3.

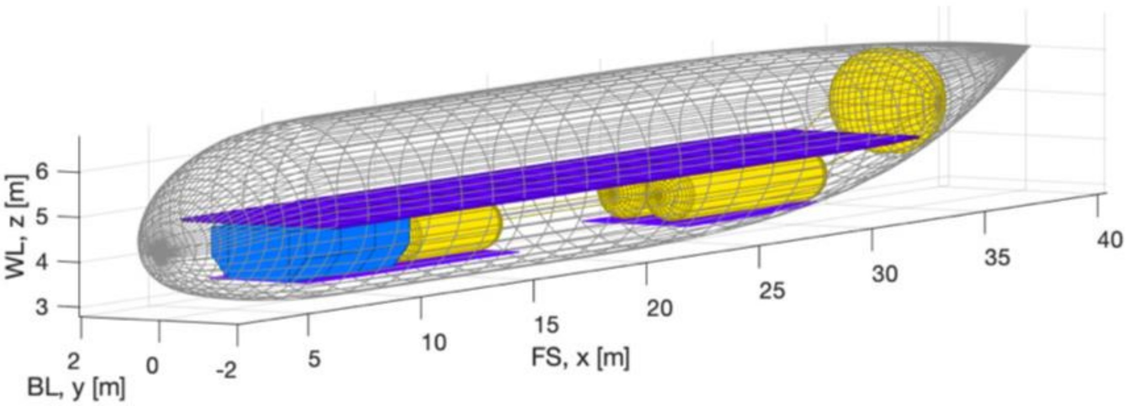


Figure 5.3: LNG aircraft with aft tank.

The tank is positioned latterly, to optimize the tank’s volume within the available space.
The Aft tank option can be enabled by setting ‘AftLNG’ to true in the “settings.xml” file.
Now an LNG aircraft with AFT tank is generated for the same design mission. The table below compares the LNG aircraft with an AFT tank with the Kerosene configuration.

Table 5.3: A320-kerosene vs A320-LNG-AFT, both converged.

	A320-kerosene	A320-LNG-Aft	Difference(%)
MTOM (Kg)	54000	54710	1.3
OEM (Kg)	31470	33110	5.2
Harmonic Range (Km)	1320	1180	-10.6
Mission Fuel Mass (Kg)	7190	6500	-9.6
Mission Luggage mass per passenger (Kg)	22.3	20.7	-7.17
Reserve fuel Mass (Kg)	1950	1680	-16.07
Max Passenger Range (Km)	3274	3207	-2.05
Max Fuel Range (Km)	7580	3190	-57.92
Max Fuel Mission (Kg)	18820	9330	-50.43
Max Fuel Mission Luggage mass per passenger (Kg)	-	1.8	-
Fuel System (Kg)	108	178.6	65.54

Fuselage length (m)	38.4	38.5	0.26
Fuselage diameter (m)	4	4	0.00
Wing span (m)	32.2	32.6	1.24
T/W_{cruise}	0.28	0.29	3.57
L/D_{cruise}	16.6	16.9	1.81
CO_2 emissions (Kg)	13317.4	9952.5	-25.27
H_2O emissions (CO_2 equivalent) (Kg)	1067.2	1710.1	60.24
NO_x emissions (CO_2 equivalent) (Kg)	2186	675.3	-69.1
Tank front (Kg)	-	452.3	-
Tank rear (Kg)	-	652.5	-
Tank Aft (Kg)	-	247.7	-
Tanks' weight (Kg)	-	1352.5	-
Tank volume (m_3)	-	22.3	-
Boil-off flight (Kg)	-	40.5	-
Tank P_v (MPa)	-	1.04	-
Insulation thickness (cm)	-	10	-
Al-in thickness (cm)	-	0.2	-
Al-out thickness (cm)	-	0.2	-
Wing area (m_3)	109.7	112.9	2.92
MAC (m)	4.16	4.22	1.44
Horizontal tail area (m_3)	19.14	22.6	18.08
Vertical tail area (m_3)	13.3	15.71	18.12
X_{np} (m)	20.6	20.8	0.97
$X_{cg(}$MTOM) (m)	17.1	17.6	2.92

From the table above, it can be seen that by adding an AFT tank, the aircraft has now a "Max Fuel Range" of 3190 Km compared to 1760 Km for the first LNG configuration.

So with a aft tank, the aircraft can fly any mission combination between 1180 Km range with 25 Kg of luggage mass per person to a mission of 3190 Km range with 1.8 Kg Luggage per person. So for the rest of the results comparison, all LNG aircrafts will be generated with aft tank.

5.2 Geometrically Identical aircrafts

One important thing that can be seen from the tables 5-2 and 5-3, is that the Fuselage length and diameter, the wing span, the area of the wing and the area of the horizontal and vertical stabilizer are slightly different than the dimensions specified in the xml input files, and thus different from the Airbus A320. This is due to the way Initiator works, the Design Convergence loop sizes the aircraft for the optimal configuration that satisfies the design mission.

Since the aim of the thesis is to retrofit the current A320 with least possible changes , especially to the external geometry, a trick is to run the Performance Estimation module in Initiator without the design convergence loop. This will make sure to use the exact geometry specified, and study the performance of this geometrical defined aircraft.

For the rest of the report, the aircraft above will be called "-converged" aircraft, and the geometrical identical aircrafts will be called "-Geometrical". The table below shows the results of 3 geometrical identical aircraft, one with kerosene and the other two with LNG with and without an aft tank.

Table 5.4: Geometrical identical aircrafts A320-kerosene vs A320-LNG vs A320-LNG-AFT

	A320-kerosene	A320-LNG	A320-LNG-Aft	Diff(%): (LNG-AFT vs kerosene)
MTOM (Kg)	53810	53380	53710	-0.19
OEM (Kg)	30680	31190	31490	2.64
Harmonic Range (Km)	1400	1330	1330	-5.00
Mission Fuel Mass (Kg)	7640	6820	6850	-10.34
Mission Luggage mass per passenger (Kg)	23.3	22.4	22.5	-3.44
Reserve fuel Mass (Kg)	2060	1770	1780	-13.59
Max Passenger Range (Km)	3093	2477	3170	2.49
Max Passenger Fuel Mass (Kg)	11130	10180	10220	-8.18
Max Fuel Range (Km)	7080	2390	3160	-55.37
Max Fuel Mission (Kg)	19970	8450	10020	-49.82
Max Fuel Mission Luggage mass per passenger (Kg)	-	11.5	1.3	-
Fuel System (Kg)	112	167.4	186	66.07
Fuselage length (m)	37.6	37.6	37.6	0.00
Fuselage diameter (m)	4.14	4.14	4.14	0.00
Wing span (m)	33.9	33.9	33.9	0.00
T/W_{cruise}	0.284	0.284	0.284	0.00
L/D_{cruise}	15.1	15.1	15.1	0.00
CO_2 emissions (Kg)	14697.8	11113.5	11176.9	-23.96
H_2O emissions (CO_2 equivalent) (Kg)	1165.9	1724.4	1720.7	47.59
NO_x emissions (CO_2 equivalent) (Kg)	2514.4	780.1	783.1	-68.85
Tank front (Kg)	-	227.4	227.4	-
Tank rear (Kg)	-	966.2	966.2	-
Tank Aft (Kg)	-	0	190.5	-
Tank weight (Kg)	-	1193.6	1384	-
Tank Volume (m_3)	-	20.20	23.96	-
Boil-off flight (Kg)	-	36.16	41.63	-
Tank P_v (MPa)	-	0.974	0.974	-
Wing area (m_3)	126.5	126.5	126.5	0.00
MAC (m)	4.35	4.35	4.35	0.00

Horizontal tail area (m_3)	32.23	32.23	32.23	0.00
Vertical tail area (m_3)	23.5	23.5	23.5	0.00
X_{np} (m)	18.5	18.5	18.5	0.00
X_{cg}(MTOM) (m)	15.8	16.5	16.8	6.33

From table 5.4, it can be seen that all 3 generated aircrafts has identical external geometry. The geometrical aircrafts are a better option for this thesis since the aim is to study the benefits of transforming the Airbus A320-200 to LNG aircraft while maintaining the external geometry.

6
Study Results and comparison

Two aircrafts, one working on kerosene and the other on LNG, were generated satisfying the design mission requirement presented in chapter 5, table 5.1. The two aircrafts can be seen in the figure below:

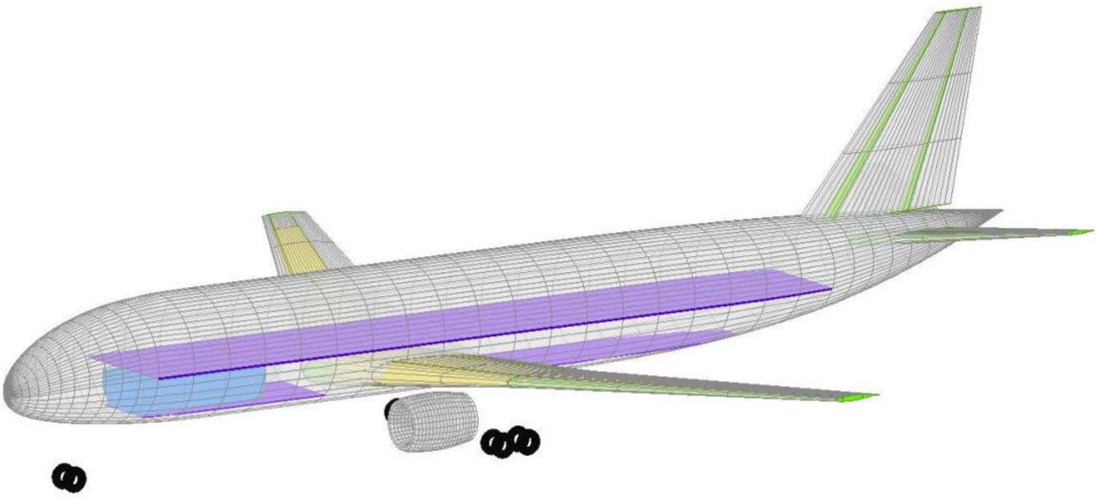


Figure 6.1. A320-kerosene. ULDs in blue, and fuel tank in yellow

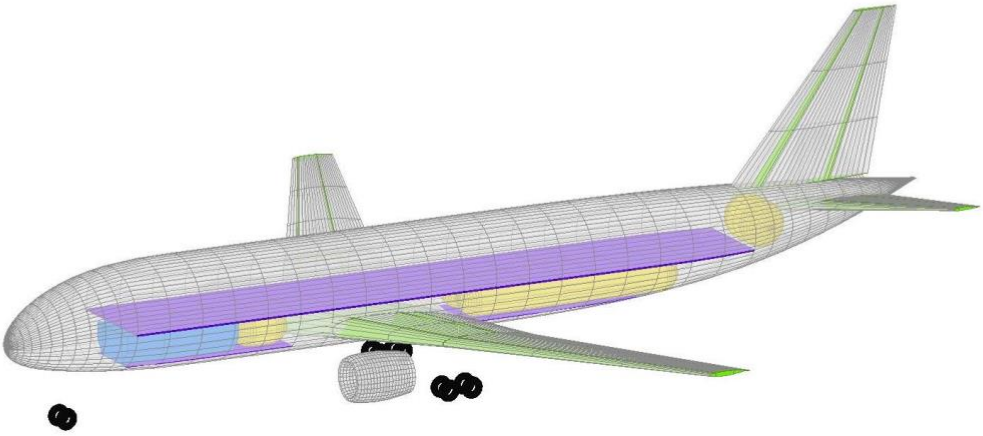


Figure 6.2. A320-LNG-Aft. ULDs in blue, and fuel tank in yellow

Both configuration have the same geometry, the LNG aircraft has two front, two rear and one aft tank.
The cryogenic tanks has the following characteristics:

Table 6.1: Cryogenic tank design characteristics.

Al 2090 thickness (m)	0.02
Al 2040 thickness (m)	0.02
Insulation thickness (m)	0.1
Total Tanks weight (Kg)	1384
Total Tanks volume (m3)	23.96
$\frac{\text{Tanks weight}}{\text{Fuel weight}}$	0.14
Boil-off flight (Kg)	41.63
Tanks' pressure after 72h of no boil-off (MPa)	0.974

The table below displays the main results for the two aircrafts.

Table 6.2: Design mission results.

	A320-keorsene	A320-LNG-Aft	Difference(%) LNG vs kerosene
MTOM (Kg)	53810	53710	-0.19
OEM (Kg)	30680	31490	2.64
Mission's fuel mass (Kg)	7640	6850	-10.34
Luggage mass per passenger (Kg)	23.3	22.5	-3.44

Max passenger Range (Km)	3093	3170	2.49
Max passenger Range mission's fuel mass (Kg)	11130	10220	-8.18
Luggage mass per passenger for the Max passenger Range mission (Kg)	0	0	0
Max Fuel Mass (Kg)	19970	10020	-49.82
Max Fuel Range (Km)	7080	3160	-55.37
CO_2 emissions (Kg)	14698	11177	-24
NO_x emissions (CO_2 equivalent) (Kg)	2514	783.1	-68.85
H_2O emissions (CO_2 equivalent) (Kg)	1166	1721	47.6
Mission Boil-off (Kg)	-	41.63	-
DOC ($\frac{\$}{\mathrm{nm}}$)	25.06	20.84	-16.8

Figure 6.3 and figure 6.4 displays the payload-range diagram of both aircraft. It can be seen that both configuration complete the design mission with less than the required luggage mass. The A320-Kerosene complete the 1500 Km range mission with 150 passenger with 23.3 Kg luggage mass per passenger. The A320-LNG complete the mission with a luggage mass per passenger of 22.5 Kg.

However the maximum possible range with 150 passenger is 2% larger for LNG aircraft; it is the "Max passenger Range" in table 6.2. A320-Keorosene can achieve a range of 3093 Km with 150 passenger with no luggage mass. While the A320-LNG can achieve 3170 Km range with no luggage mass. However since the required fuel mass "Max passenger Range mission's fuel mass" is larger than the tank capacity "Max Fuel Mass", the maximum possible range for the LNG aircraft with 150 passengers is 3160 Km, equal to the "Max Fuel range", with 1.3 Kg luggage mass per passenger. From this, it can be deduced that the A320-LNG's range is limited by the cryogenic tank's capacity and not by the MTOM.
The full design report from the Initiator can be found in appendix I for the A320-kerosene, and appendix J for the A320-LNG. The report contains the loading diagram, V-n diagram, components masses, Center of gravity, loading diagram, Drag polar, aerodynamics properties at cruise, and the dimension and properties of the Wing and fuselage and VT and HT.

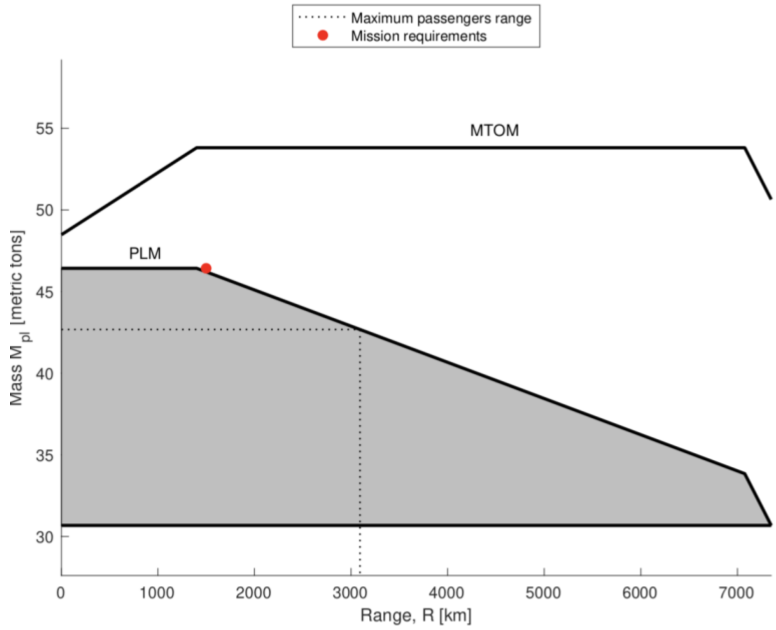


Figure 6.3. Payload-Range of the kerosene configuration

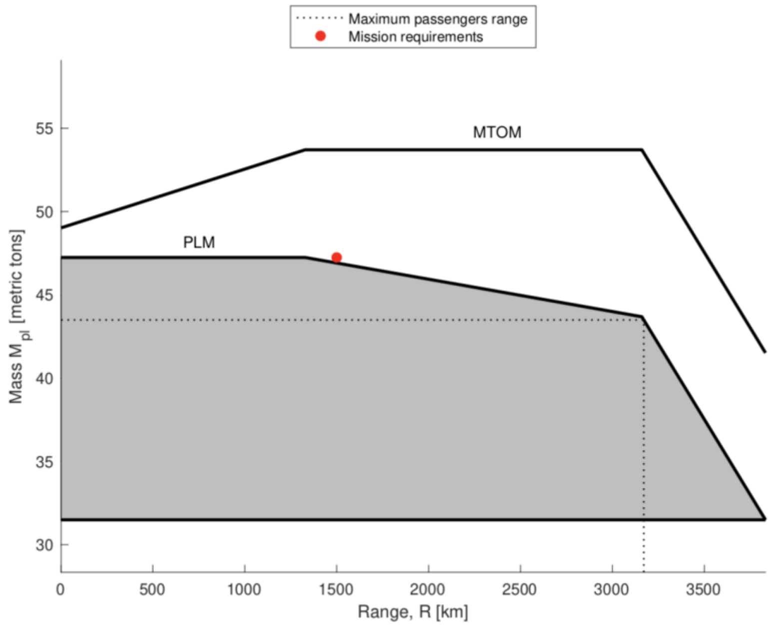


Figure 6.4. Payload-Range of the LNG configuration

Furthermore the LNG configuration has a 2% higher operating empty mass due to the additional weight of the cryogenic tanks. However this is compensated by a 10% reduction in the mission's fuel mass needed ,and ultimately the maximum take-off mass of the LNG aircraft is the same as the Kerosene aircraft.

The major benefit of LNG aircraft is the comparable lower emissions. A320-LNG produce 3521 (Kg) less CO_2 , that is a 24% reduction from the A320-kerosene. Also it reduces NO_x emissions by 69% which equates to 2154 (Kg) . However LNG produces 47.6% more H_2O ; the negative effect of water, i.e. contrails, can be reduced by lowering the cruise's altitude.

The other big factor is the direct operating cost. LNG reduces the DOC by 16.8%. This reduction is due to the lower price of LNG compared to kerosene, and does not account for the CO_2 taxes. So a larger DOC is to be expected.

6.1 Various mission ranges

Several design mission ranges were studied, in order to look at the effect of range on the emissions and direct operating cost. The figures below compares the kerosene and the LNG for the various ranges.

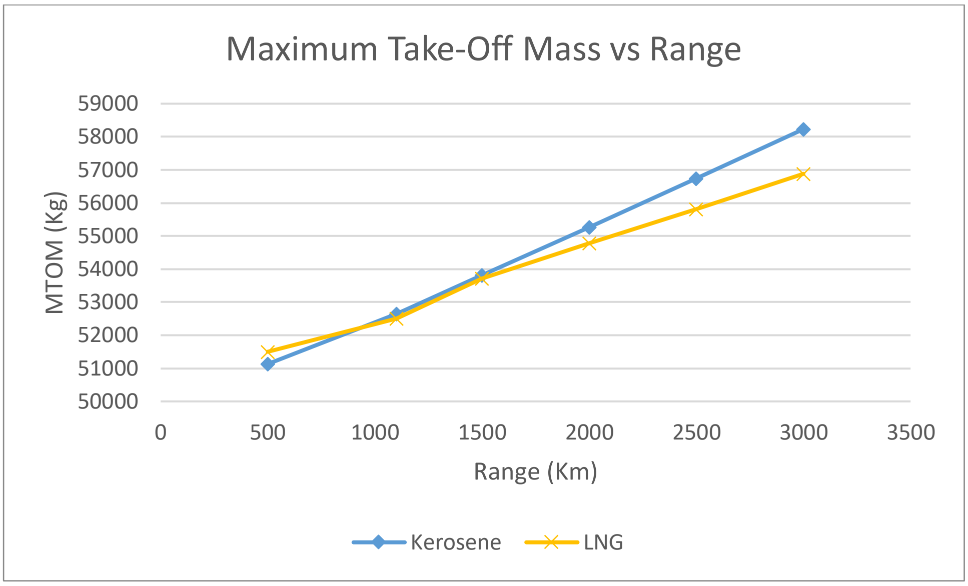


Figure 6.5 MTOM vs range for A320-kerosene and A320-LNG aircraft.

The MTOM of the A320-LNG is slightly larger for range smaller then 1000 Km. For range between 1000 and 1500 Km , both aircraft have similar MTOM. However for range over 1500 Km the LNG aircraft MTOM is lower, and the difference increases with increasing range.

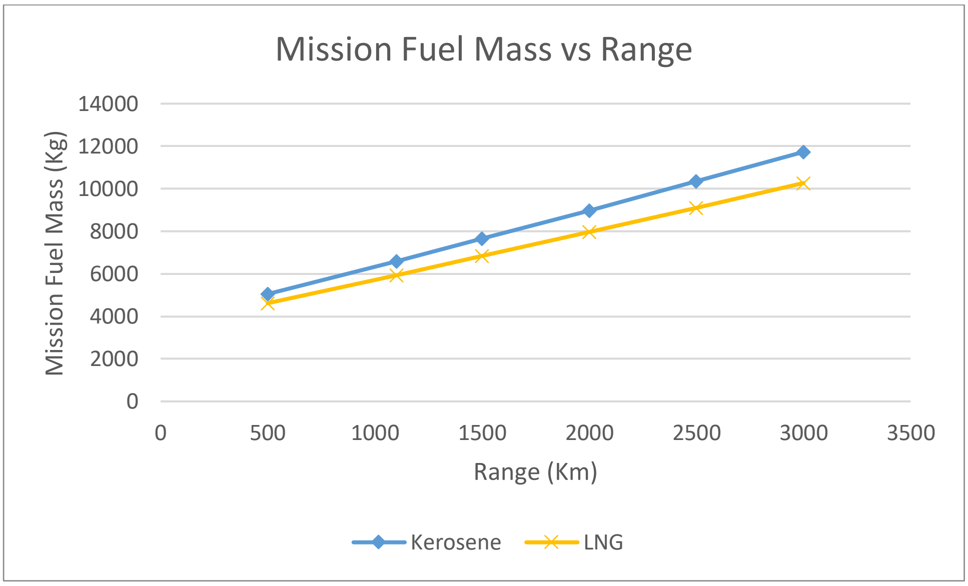


Figure 6.6 Mission fuel mass vs range for A320-kerosene and A320-LNG aircraft.

The mission fuel mass difference between both aircraft increases with increasing range.

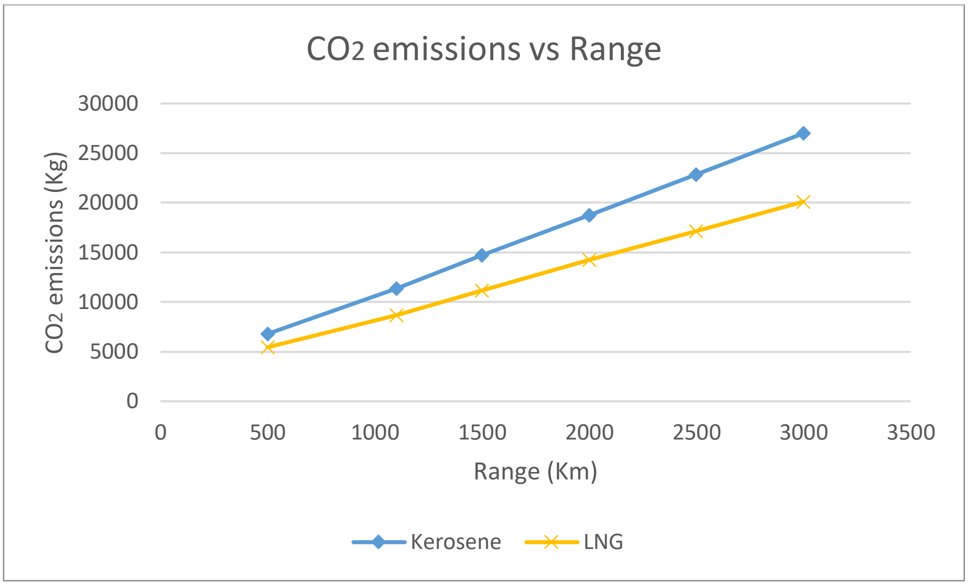


Figure 6.7 CO_2 emissions vs range for A320-kerosene and A320-LNG aircraft.

The CO_2 reduction of the A320-LNG compared to A320-kerosene increase with increasing range.

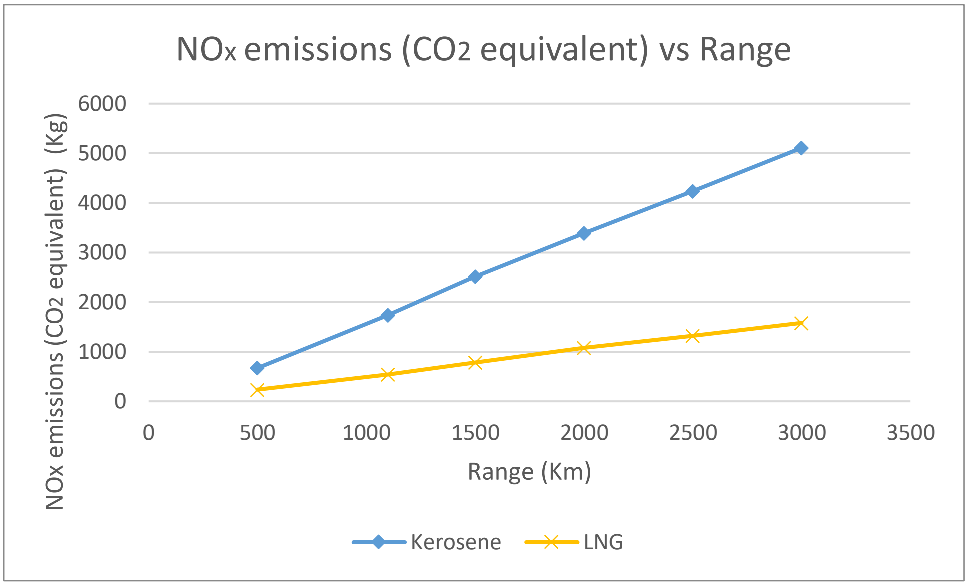


Figure 6.8 NO_x emissions (CO_2 equivalent) vs range for A320-kerosene and A320-LNG aircraft.

The NO_x (CO_2 equivalent) difference significantly increases with increasing the mission range.

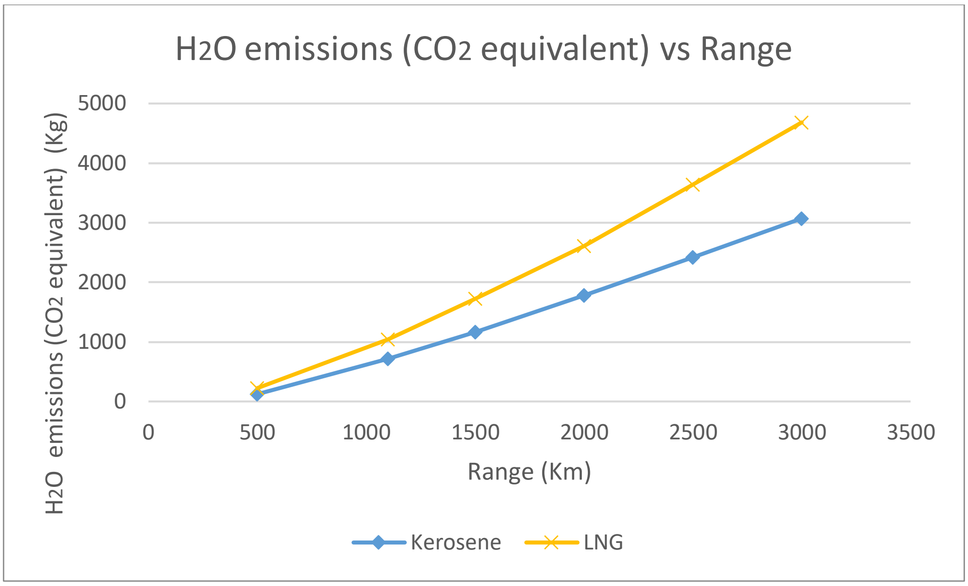


Figure 6.9 H_2O emissions (CO_2 equivalent) vs range for A320-kerosene and A320-LNG aircraft.

The H_2O emissions (CO_2 equivalent) difference is more significant at higher ranges.

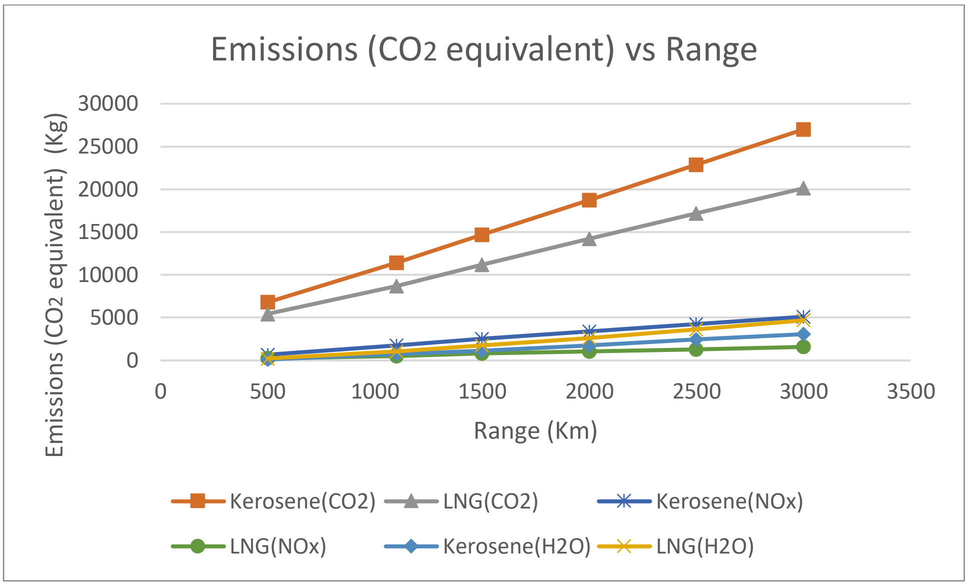


Figure 6.10 CO_2, NO_x, H_2O emissions vs range for A320-kerosene and A320-LNG aircraft.

Figure 6.10 plot all the emissions, to show the scale of each compound, CO_2 emissions and reduction is much larger than the NO_x and H_2O.

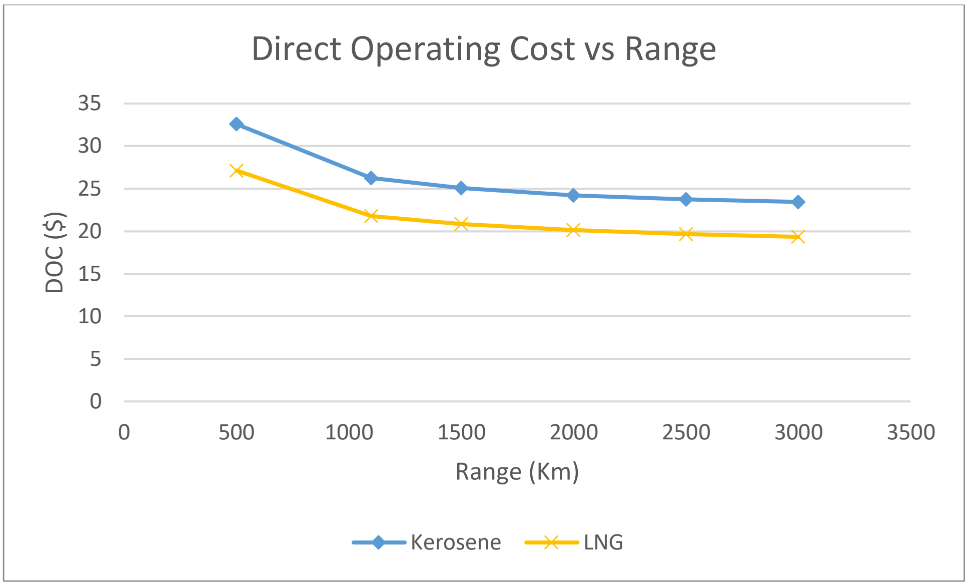


Figure 6.11 Direct Operating Cost vs range for A320-kerosene and A320-LNG aircraft

The direct operating cost shows almost constant difference between the LNG and Kerosene with ranges. However for the for range smaller than 1000 Km a sharp increase in the DOC is observed. While for range larger than 1000Km , minimum change in DOC is seen.

So the LNG aircraft shows favorable reduction in CO_2 and NO_x for all range. Furthermore this reduction is increased with increasing the mission range. The direct operating cost difference between the aircraft is barely influenced by the mission range. While The MTOM of LNG is slightly larger for shorter ranges, less then 1000 Km, then similar MTOM is observed for both aircraft for range between 1000 and 1500, and over 1500 the MTOM of the LNG aircraft becomes smaller than the kerosene, this is due the increase in difference of the mission fuel mass with ranges.

7
Conclusion

The study was set out to determine the cost and environmental benefits of replacing kerosene with LNG on single aisle aircraft, mainly Airbus A320. The main challenge in this transformation is the storage of the cryogenic tanks within the current A320 geometry. In order to make the retrofitting as easy as possible, the geometry of the aircraft was unchanged. So the LNG tank were located in the cargo bay replacing some of ULDs. In addition to that, in order to increase the range capability of the aircraft, an additional tank was created in the aft of the aircraft. The tanks have cylindrical shape with two half-cup sphere at the side.

The tank is made of three layers, two Aluminum Alloy layer, in between them foam insulation. The layer that is in contact with LNG is Al2090, while the outer layer is Al2024, and the insulation foam is Polyurethane.

The insulation thickness controls the boil-off rate. The various thicknesses were found from stress analysis taking a safety factor of 1.5. A heat transfer analysis was performed to determine the boil-off rate of LNG.

The cryogenic tank was implemented in Initiator, and the program was modified to accept LNG as a fuel, and to generate cryogenic tanks in the cargobay within the fuselage. Using the Initiator, two configurations were generated satisfying a mission range of 1500 Km with 150 passengers. These configurations are A320-Kerosene and A320-LNG.

The LNG configuration showed very promising results, it achieved a 24% CO_2 reduction, 69% less NO_x and 17% savings in DOC compared to the kerosene configuration. These constitutes a huge reduction in greenhouse emissions that benefits not only the environment, but also the airlines; since they will benefit from the CO_2 taxes cut, in addition to the 17% less DOC that is due to the lower LNG prices.

These results combined with the ease of retrofitting the aircraft from working on kerosene to LNG, make this project very promising, and the airlines and aircraft's manufacturers should be encouraged to make the switch. This is necessary as a short-term solution to accommodate for the projected aviation growth.

The Initiator is capable now of working with different aircraft operating on LNG, or even other fuels that uses cryogenic fuselage tanks. These aircrafts are not limited to the A320. So in this way, other students can design and analyze different aircrafts that needs to satisfy different requirements, for example longer range, more passengers or more cargo, and will be able to benefit from using LNG.

7.1 Recommendation

A number of recommendation are given for further improvement:

- Study the feasibility of using CFRP instead of the Aluminum alloy layer, which can result a significant weight reduction, and possibly thinner layer, which results in an increase in the internal volume of the tanks ,and thus more fuel can be stored which increase the maximum range of the aircraft.
- Use of different insulation type, such that Cryogel-Z which reduces the thickness of insulation needed for an acceptable boil-off rate, and thus increasing the available fuel volume.
- Appendix [E] shows how to change the tank's material. And as an example, Cryogel-Z was used instead of the Polyurethane.

Thus it is recommended to look for tank's materials that results in thinner required layers, and thus increases the internal volume of the tank available for storing the LNG. In the A320-LNG case, the available volume is more crucial than the weight of the tank, since the maximum range of the aircraft is limited by the space available and not by the maximum take-off mass of the aircraft.

7.2 Operational flexibility

There are several possibilities of retrofitting the Airbus A320. Few of them are mentioned below:

a) Keep the kerosene system : As the aircraft is being retrofitted, and since the kerosene fuel system is already available in the aircraft, and the engine is capable of working with both fuels; the airline can decide to keep the kerosene system. This gives them the possibility of either extending the range of the aircraft by filling more kerosene, or carry the reserve fuel as kerosene in the wing. This results in more available volume for storing the mission's LNG, since the reserve fuel constitutes 25% of the total fuel. Thus it extends the maximum range of the aircraft operating on LNG. This can be considered viable since very rarely do airlines use the reserve fuel.

b) Low cost airlines: Most passengers carry only hand luggage with them on low cost airlines, while only few paying extra for carrying a check-in luggage. Thus low cost airlines can extend the fuel tanks by replacing 2 more ULDs like in figure 8.1 .
For a hand luggage of 10 kg per person and a total check-in luggage of 1500 Kg (or 60 bags of 25Kg) , this LNG configuration can achieve a range 2850 Km. Or a maximum passenger range with hand luggage only (no check-in luggage) of 3628 Km.

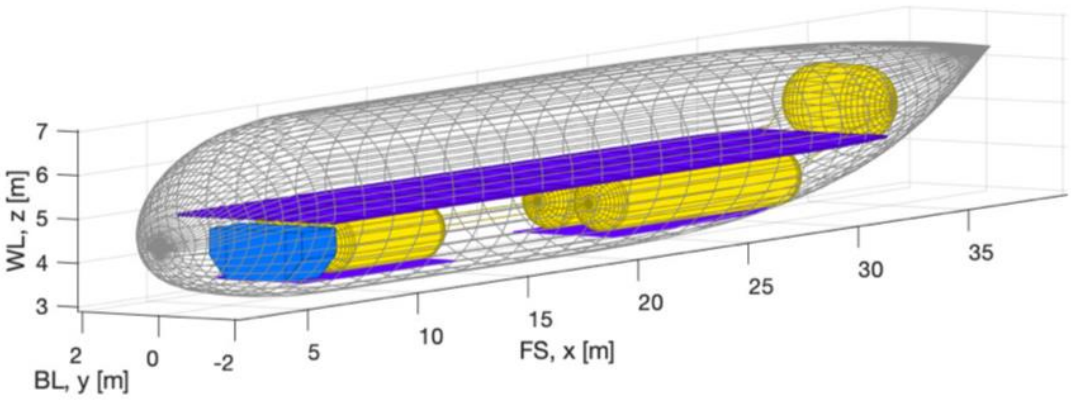


Figure 7.1: A320-LNG-AFT 1 ULD

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Appendix A
LNG thermal Properties

- Thermal conductivity: K_{CH_4} = A +BT +CT2;
  A = 722.72; B = -144.42e-2; C = - 76.36e-4; T = 112K;
  ⇨ K_{CH_4} = 465.18 [μcal/s.cm.K] = 0.19 [W/m.K]; [15]

- Dynamic viscosity: $\log(\mu_{CH_4}) = A + \frac{B}{T} + CT + DT^2$;
  A = -11.67; B = 499.3; C = 8.125e-2; D =-226.3e-6; T =112K;
  ⇨ $\log(\mu_{CH_4}) = -0.9474$
  ⇨ $\mu_{CH_4} = 0.113\ [centipoise] = 0.000113\ \left[N.\frac{s}{m^2}\right]$; [15]
- Liquid density of CH4: $\rho_L = AB^{-(1-T_r)^{2/7}}\ [g/cm^3]$
  A = 0.1611; B = 0.2877; T = -161.5 oC;
  ⇨ ρ_{CH_4} = 0.42 $[g/cm^3]$ = 420 $[Kg/m^3]$; [15]

- Heat capacity of liquid CH_4: $c_p = A + BT + CT^2 + DT^3$;
  A = 1.23; B = -10.33e-3; C = 72e-6; D = -107.3e-9; T = -161.5 oC;
  ⇨ $c_{p_{CH_4}} = 0.824\ [cal/g.°C] = 3449.9217\ [J/Kg.K]$; [15]

- Coefficient of Thermal Expansion of Liquid CH_4: $\beta_L = a\,(1 - T/T_c)^m$;
  a = 1.809e-3; Tc = 190.58°C; m = –0.723; T = -161.5 °C;
  ⇨ β_{CH_4} = 0.00342 [1/K]; [37]

- Latent heat of vaporization of CH4: $\Delta H_v = \Delta H_{v1}\left[\frac{T_c - T}{T_c - T_1}\right]^n$;
  $\Delta H_{v1} = 121.7\ [cal/g]; T_1 = -161.5°C; T_c = -82.6°C;\ n = 0.38; T = -161.5°C;$
  ⇨ $\Delta H_{v_{CH_4}} = 121.7\ [cal/g] = 509.53\ [kJ/Kg]$; [15]

	LNG (@ -111.65oK)	Kerosene (@ 298oK)
Heating value [MJ/Kg]	50.03	43.031
Density: ρ [kg/m3]	420	810

Appendix B
Material Properties for the tank design

	LNG (@ -111.65 oK)	Air (@ 298 oK)
Density: ρ [kg/m3]	420	1.1707
Specific heat: c_p [J/Kg.K]	3449.9217	1006.96
Thermal conductivity: K [W/m.K]	0.195	0.02614
Dynamic Viscosity: μ [N.s/m2]	1.13 e-4	1.8394 e-5
Kinematic Viscosity: γ [m2/s]	2.69 e-7	15.712 e-6
Coefficient of thermal expansion: β [1/K]	0.0034	$1/T_{air}$

Table 1. Thermal properties of LNG and air.

- Thermal diffusivity: $\alpha = \frac{K}{\rho \times c_p}$; (m2/s)
- Kinematic Viscosity: $\gamma = \frac{\mu}{\rho}$; (m2/s)

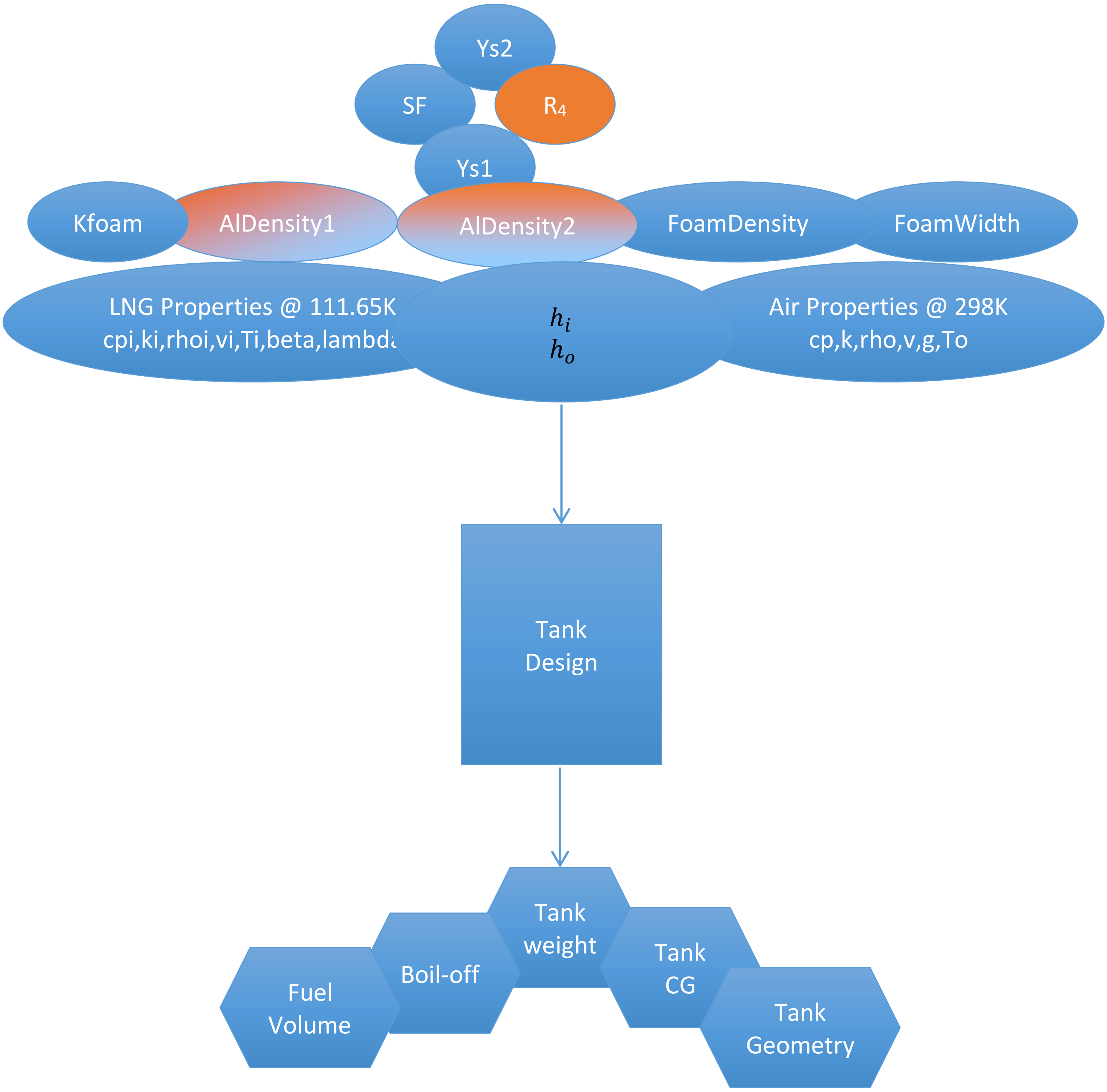
Properties of tank materials:

	Al 2219-T81 (@ -161.5 oC)	Al 2024-T4 (@ 24 oC)	Foam	Al 2090-T81 (@ -161.5 oC)	CFRP
Yield Strength: σ_y (MPa)	386.57	324	–	559	–
Density: ρ (Kg/m3)	2840	2770	32	2590	1800
Conduction coefficient	–	–	0.05	–	–

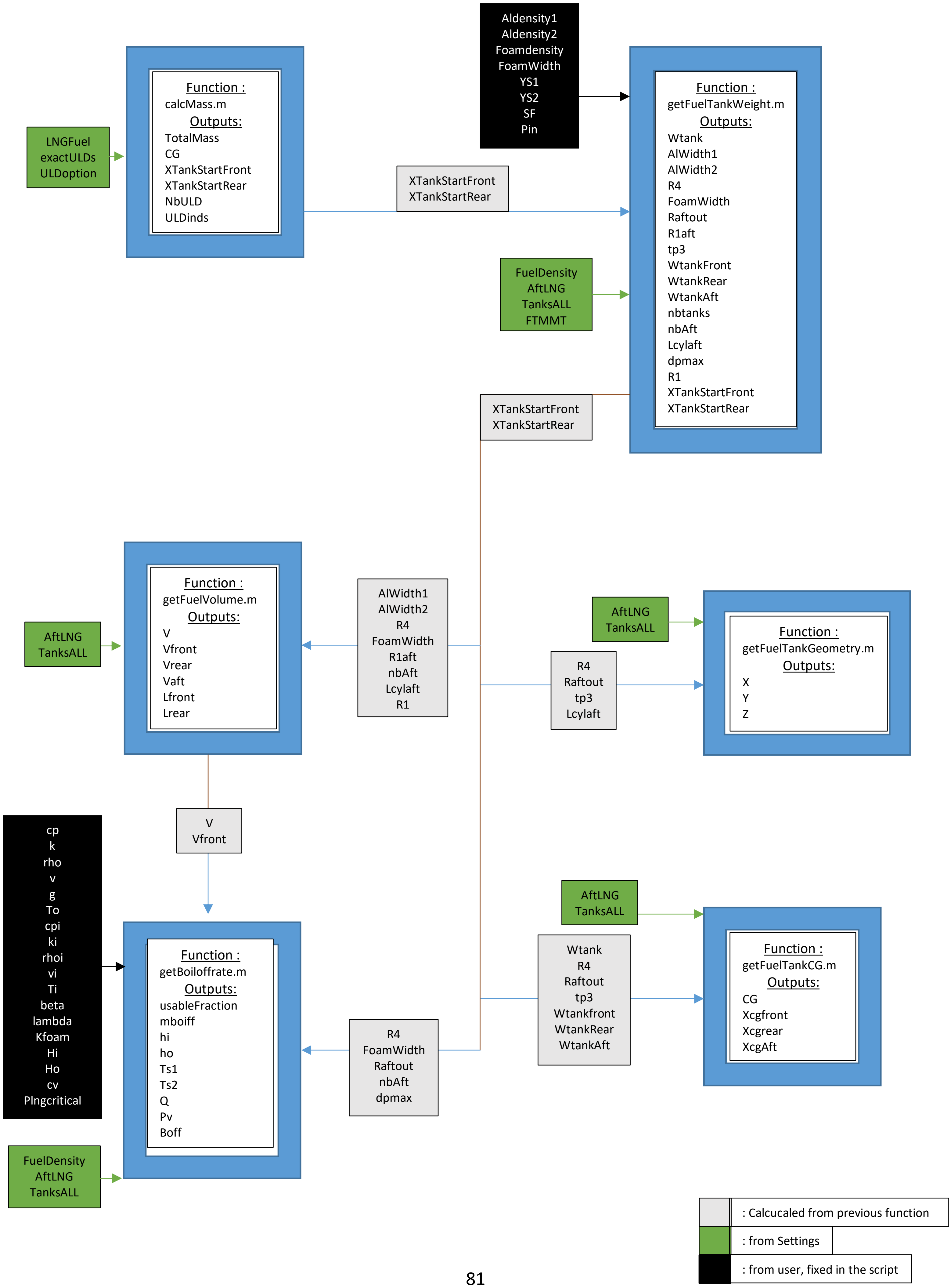
Table 2. Tank materials' properties.

Appendix C

Required inputs for the LNG Tank design



Appendix D
Fuselage Tank design , methods’ dependencies, inputs and outputs



LNGFuel
exactULDs
ULDoption
Function :
calcMass.m
Outputs:
TotalMass
CG
XTankStartFront
XTankStartRear
NbULD
ULDinds
Aldensity1
Aldensity2
Foamdensity
FoamWidth
YS1
YS2
SF
Pin
XTankStartFront
XTankStartRear
Function :
getFuelTankWeight.m
Outputs:
Wtank
AlWidth1
AlWidth2
R4
FoamWidth
Raftout
R1aft
tp3
WtankFront
WtankRear
WtankAft
nbtanks
nbAft
Lcylaft
dpmax
R1
XTankStartFront
XTankStartRear
FuelDensity
AftLNG
TanksALL
FTMMT
XTankStartFront
XTankStartRear
AftLNG
TanksALL
Function :
getFuelVolume.m
Outputs:
V
Vfront
Vrear
Vaft
Lfront
Lrear
AlWidth1
AlWidth2
R4
FoamWidth
R1aft
nbAft
Lcylaft
R1
AftLNG
TanksALL
R4
Raftout
tp3
Lcylaft
Function :
getFuelTankGeometry.m
Outputs:
X
Y
Z
V
Vfront
cp
k
rho
v
g
To
cpi
ki
rhoi
vi
Ti
beta
lambda
Kfoam
Hi
Ho
cv
Plngcritical
Function :
getBoiloffrate.m
Outputs:
usableFraction
mboiff
hi
ho
Ts1
Ts2
Q
Pv
Boff
R4
FoamWidth
Raftout
nbAft
dpmax
AftLNG
TanksALL
Wtank
R4
Raftout
tp3
Wtankfront
WtankRear
WtankAft
Function :
getFuelTankCG.m
Outputs:
CG
Xcgfront
Xcgrear
XcgAft
FuelDensity
AftLNG
TanksALL
: Calcucaled from previous function
: from Settings
: from user, fixed in the script

Symbol	Unit	Definition
LNGFuel	Boolean	Select LNG as fuel
exactULDs	Boolean	Select the exact number of ULDs
ULDoption	Integer from 1 to 4	Select the ULD arrangement option
AftLNG	Boolean	Adds a cryogenic tank in the AFT
FuelDensity	420 [kg/m^3]	Set Fuel the density
FTMMT	0.002 [m]	Minimum manufacturing for cryogenic tank's material.
TanksALL	Boolean	Generate a continuous cryogenic tanks between ULDs
TotalMass	[Kg]	Required luggage Mass
CG	-	3D coordinates of the center of gravity of the ULDs
XTankStartFront	-	
XTankStartRear	-	
NbULD	Integer	Number of ULDs required to fit the luggages.
ULDinds	Integer	Index of ULDs based of ULDoption
Wtank	[Kg]	Total Weight of cryogenic tanks
AlWidth1	[m]	Thickness of the internal Aluminum layer of the cryogenic tank
AlWidth2	[m]	Thickness of the external Aluminum layer of the cryogenic tank
R4	[m]	External radius of the cryogenic tanks
FoamWidth	[m]	Thickness of insulation foam
Raftout	[m]	Radius of the AFT cryogenic tanks
R1aft	[m]	Internal radius of the AFT cryogenic tanks
tp3	-	3D coordinates
WtankFront	[Kg]	Weight of the frontal tanks
WtankRear	[Kg]	Weight of the rear tanks
WtankAft	[Kg]	Weight of the Aft tank
Nbtanks	Integer	Number of tanks as front-rear-aft (1 to 3)
nbAft	Integer	Number of tanks in the Aft (1 to 2)
LcylAft	[m]	Length of the cylindrical part of the Aft tank
dpmax	[MPa]	Max pressure that the internal Aluminum alloy can withstand
R1	[m]	Internal radius of the cryogenic tank
V	[m^3]	Total Volume of the cryogenic tanks
Vfront	[m^3]	Volume of the frontal tanks
Vrear	[m^3]	Volume of the rear tanks
Vaft	[m^3]	Volume of the aft tank
Lfront	[m]	Length of the cylindrical part of frontal tanks
Lrear	[m]	Length of the cylindrical part of rear tanks
usableFraction	Decimal	0 to 1: fraction the cryogenic tank that can be filled with LNG
mboiff	[Kg/s]	Boil-off rate of the LNG

hi	124.8[W/(m^2 K)]	Convection coefficient of LNG
ho	2.8 [W/(m^2 K)]	Convection coefficient of air
Ts1	[K]	Temperature of the internal Al surfaces
Ts2	[K]	Temperature of the external Al surface
Boff	[Kg]	Total boil-off mass for the flight
X,Y,Z	3D coordinate	3D coordinates of the fuselage tanks' geometry
CG	3D coordinates	3D coordinates of the resulting fuel tank center of gravity
Xcgfront	3D coordinates	3D coordinates of the frontal tanks
Xcgrear	3Dcoordinates	3D coordinates of the rear tanks
AcgAft	3Dcoordinates	3D coordinates of the aft tank
Aldensity1	2590 [kg/m^3]	Density of the tank's internal layer
Aldensity2	2770 [kg/m^3]	Density of the tank's external layer
Foamdensity	32 [kg/m^3]	Density of the tanks's insulation material
YS1	559 [MPa]	Yield strength of the tank's internal layer
YS2	324 [MPa]	Yield strength of the tank's external layer
SF	1.5	Safety factor for the tank stress calculation
Pin	0.6278 [MPa]	Pressure inside of the tank
cp	1006.96 [J/Kg.K]	Heat capacity of air
k	0.02614 [W/m.K]	Thermal conductivity of air
rho	1.1707 [kg/m^3]	Density of air
v	15.712e-6 [m^2/s]	Thermal conductivity of air
g	9.81 m/s^2	Gravity constant
To	298 [K]	Temperature outside the tank
cpi	3449.9217 [J/Kg.K]	Heat capacity of liquid CH_4
ki	0.195 [W/m.K]	Thermal conductivity of LNG
rhoi	420 [kg/m^3]	Density of LNG
vi	2.69e-7 [m^2/s]	Kinetic velocity of LNG
Ti	111.65 [K]	Temperature of the LNG inside the tank
beta	0.0034 [1/K]	Thermal expansion coefficient of LNG
lambda	509.53 [KJ/Kg]	Latent heat of vaporization of LNG
Kfoam	0.015 [W/m.K]	Conduction coefficient of the insulation material
cv	2086.8 [J\Kg.k]	Specific heat capacity of the two phase CH_4at constant Volume
Plngcritical	4.64 [MPa]	Pressure of Methane at critical point

Appendix E

How to replace the cryogenic tank materials.

The cryogenic tank's materials can easily be changed by modifying few variables. For example to change the insulation material from Polyurethane to Cryogel-Z, the conduction coefficient of Cryogel-Z and its density needs to be inputted.

The conduction coefficient variable is called "Kfoam" and the density variable is called "Foamdenisty" and are available in the "getBoiloffrate.m" method. The conduction coefficient units is [W/m.K], while the insulation density in [Kg/m^3]

To change the insulation materials, "Kfoam" value should be modified from 0.015 (conduction coefficient of PU) to 0.01125 (Cryogel-Z) ,and the "Foamdenisty" from 32 to 130. Note: the thickness of the insulation is fixed to 0.1[m]. So after changing to the Cryogel-Z , if the thickness needs to reduced, the new value can be inputted into "FoamWidth" variable in "getFuelTankWeight.m" method.

The same can be done for the internal and external tank's layers. For the internal layer, the new material 's density and yield strength needs to be inputted in "getFuelTankWeight.m" method. The two variables are called "Aldensity1" and "YS1". In the same way the external materials can be replaced by changing the "Aldensity2" and "YS2".

Also in case the new materials have different minimum manufacturing thickness then 2 [mm], this should be inputted in the "FTMMT" variable in the "settings.xml" file.

Results example for using Cryogel-Z for the insulation for the same design mission:

	Polyurethane	Cryogel-Z	Difference (%)
Density (Kg/m^3)	32	130	306.25
Conduction coefficient (W/m.K)	0.015	0.01125	-25
Insulation thickness (mm)	10	6	-40
Available Fuel Volume (m^3)	23.96	27.67	15.5
Max Fuel range (Km)	3160	3950	25
Max Passenger range (Km)	3170	3251	2.6
Tank's weight (Kg)	1384	1305	-5.7
Boil-off rate (Kg/hr)	18.02	22.91	27.1
Boil-off flight (Kg)	41.63	52.93	27.1
Pressure due to 72h of no boil-off (MPa)	0.974	1.103	13.2

Appendix F
Fuselage tank added methods.

I. getFuelTankGeometry.m

```
function [X,Y,Z] = getFuelTankGeometry(obj)
%GETFUELTANKGEOMETRY Returns the fuel tank geometry

if obj.FuelTank
    [~,~,~,R4,~,Raftout,~,tp3,~,~,~,~,~,Lcylaft,~,~,XTankStartFront,XTankStartRear]
= obj.getFuelTankWeight;

    %----------generate 3D cartisian coordinates of the exterial of the fuselage
tank
    %Since the tank is long cylinder with 2 half cup sphere at both ends, we
    %can use the cylinder and sphere functions of Matlab to generates the
    %coordinates.

    [X,Y,Z] = cylinder;
    [Xx,Yy,Zz] = sphere;

    Xx1 = R4*Xx;  % * Rexternal of the tank to get the dimensions correct
    Yy1 = R4*Yy;
    Zz1=R4*Zz;
    %----half sphere cups on both sides
    Xxleft = Xx1(1:11,:);
    Xxright = Xx1(11:end,:);
    Yyleft = Yy1(1:11,:);
    Yyright = Yy1(11:end,:);
    Zzleft = Zz1(1:11,:);
    Zzright = Zz1(11:end,:);
    %-----------------------

    %----------------------Rear LNG  TANK----------------
    if obj.Controller.getSetting('AftLNG')
        sphereAft = false;
        if sphereAft
            [Xb,Yb,Zb] = obj.rotate(Xx*Raftout,Yy*Raftout,Zz*Raftout,[90 0 0]);
            [Xb,Yb,Zb] = obj.rotate(Xb,Yb,Zb,[0 0 90]);
            [Xb,Yb,Zb] = obj.translate(Xb,Yb,Zb,obj.Position);
            [Xb,Yb,Zb] = obj.translate(Xb,Yb,Zb, tp3);
            %---------------------------Added for cylinder +2cups as Aft tank
        else
            Lcylaft =Lcylaft/2 ;%  Divide by 2 so to draw one side, and the other
side will be mirrored in the plottool
            Xb = Raftout*X;
            Yb=Raftout*Y;
            Zb=Lcylaft*Z;
            Xxb = Raftout*Xx(1:11,:); %takes half the sphere(left side)
            Yyb=Raftout*Yy(1:11,:);%takes half the sphere(left side)
            Zzb=Raftout*Zz(1:11,:);%takes half the sphere(left side)

            [Xb,Yb,Zb] = obj.rotate([Xxb;Xb],[Yyb;Yb],[Zzb-Lcylaft;Zb],[90 0 0]);
%draws one side only,then it is mirrored for ploting
            [Xb,Yb,Zb] = obj.translate(Xb,Yb,Zb,obj.Position);
            [Xb,Yb,Zb] = obj.translate(Xb,Yb,Zb, tp3);
        end
    end

    %-----------------------------------------------------

    Zcg = (obj.FloorZPosition + obj.CargoBay.Floors{2}(end,3))/2 ;
    if strcmp (obj.CargoBay.Type,'Bulk')
        tp=[XTankStartFront(1)+R4,R4,Zcg];
```

```
        tp2=[XTankStartRear(1)+R4,R4,Zcg];
    elseif strcmp (obj.CargoBay.Type,'ULD')
        tp = [XTankStartFront(1) + R4 ,R4,Zcg];
        tp2=[XTankStartRear(1)+R4,R4,Zcg];
    end

    if obj.Controller.getSetting('TanksALL')
        Lcyl =  XTankStartRear(2) - XTankStartFront(1) - 2*R4;
        X = R4*X;
        Y=R4*Y;
        Z=Lcyl*Z;

        [X,Y,Z] = obj.rotate([Xx1;X;Xx1],[Yy1;Y;Yy1],[Zz1;Z;(Lcyl +Zz1)],[90 0 0]);
        [X,Y,Z] = obj.rotate(X,Y,Z,[0 0 90]);
        [X,Y,Z] = obj.translate(X,Y,Z,obj.Position);
        [X,Y,Z] = obj.translate(X,Y,Z, tp);
    else
        Lcyl1 = abs(diff(XTankStartFront)) - 2*R4;
        Lcyl2 = abs(diff(XTankStartRear)) - 2*R4;
        X1 = R4*X;
        Y1=R4*Y;
        Z1=Lcyl1*Z;
        Z2=Lcyl2*Z;

        %------------drAW  2  half cup sphere instead of 2 whole spheres
        [X,Y,Z] =
obj.rotate([Xxleft;X1;Xxright],[Yyleft;Y1;Yyright],[Zzleft;Z1;(Lcyl1 +Zzright)],[90
0 0]);
        [X2,Y2,Z2] =
obj.rotate([Xxleft;X1;Xxright],[Yyleft;Y1;Yyright],[Zzleft;Z2;(Lcyl2 +Zzright)],[90
0 0]);
        %------------------------
        [X,Y,Z] = obj.rotate(X,Y,Z,[0 0 90]);
        [X2,Y2,Z2] =obj.rotate(X2,Y2,Z2,[0 0 90]);
        [X,Y,Z] = obj.translate(X,Y,Z,obj.Position);
        [X2,Y2,Z2] = obj.translate(X2,Y2,Z2,obj.Position);
        [X,Y,Z] = obj.translate(X,Y,Z, tp);
        [X2,Y2,Z2] = obj.translate(X2,Y2,Z2, tp2);

        %----with LNG in the aft
        if obj.Controller.getSetting('AftLNG')
            X=[X;X2;Xb];
            Y=[Y;Y2;Yb];
            Z=[Z;Z2;Zb];
        else
            [X,Y,Z] = obj.rotate([X;X2],[Y;Y2],[Z;Z2],[0 0 0]);
        end

    end

end
```

II. getFuelTankCG.m

```
function [CG,Xcgfront,Xcgrear,XcgAft] = getFuelTankCG(obj)
%GETFUELTANKCG Calculates the CG of the fuel tank

if obj.FuelTank


[Wtank,~,~,R4,~,Raftout,~,tp3,WtankFront,WtankRear,WtankAft,~,~,~,~,~,XTankStartFro
nt,XTankStartRear] = obj.getFuelTankWeight;

    Xstart = min(XTankStartFront);
    Xend = max(XTankStartFront);
    Xbstart = min(XTankStartRear);
    Xbend = max(XTankStartRear);


    Xcgfront = (Xstart + Xend)/2;
    Xcgrear = (Xbstart + Xbend)/2;
    Ycg= 0 ;
    Zcg=(obj.FloorZPosition + obj.CargoBay.Floors{2}(end,3)) /2 ;

    CG = [ ((Xcgfront * WtankFront) + (Xcgrear *WtankRear) )
/(WtankFront+WtankRear),Ycg,Zcg];  % tank front + back in all cargoBay using Weight

    if obj.Controller.getSetting('TanksALL')
        %------------------------Tanks in between the ULDs---------------
        Xcg = (Xbend-Xstart)/2;
        CG(1) = Xcg;
    end
    %-------------------LNG rear tank in the AFT
    if obj.Controller.getSetting('AftLNG')
        CG(1) = (CG(1) * (WtankFront+WtankRear) + (tp3(1) *WtankAft) ) /Wtank
        CG(3) = ( (CG(3) * (WtankFront+WtankRear)) + (tp3(3) *WtankAft) ) /Wtank
        XcgAft = tp3(1);
    else
        XcgAft = 0;
    end
else
    CG = nan(1,3);
    Xcgfront = 0;
    Xcgrear = 0;
    XcgAft = 0;
end

end
```

III. getFuelVolume.m

```
function [V,Vfront,Vrear,Vaft,Lfront,Lrear] = getFuelVolume(obj)
%GETFUELVOLUME Returns 0, if no fuselage tank

if obj.FuelTank


[~,AlWidth1,AlWidth2,R4,FoamWidth,~,R1aft,~,~,~,~,~,nbAft,LcylAft,~,R1,XTankStartFr
ont,XTankStartRear] = obj.getFuelTankWeight;

    if obj.Controller.getSetting('TanksALL')
        %------------------------Tanks in between the ULDs---------------
        Lcyl=(XTankStartRear(2) - XTankStartFront(1))- 2*R4;    %Xbend-Xstart -
2*R4;
        V = 2 * (((4/3)*pi*R1^3)+(pi*Lcyl*R1^2));
    else
        Lfront = diff(XTankStartFront);
        Lrear = diff(XTankStartRear);
        LcylFront = diff(XTankStartFront)- 2*R4  ;  %Ltotal1 - 2*R4;
        LcylRear = diff(XTankStartRear)- 2*R4 ; %Ltotal2 - 2*R4;

        Vfront = ((4/3)*pi*R1^3)+(pi*LcylFront*R1^2);
        Vrear = ((4/3)*pi*R1^3)+(pi*LcylRear*R1^2);
        V=2*(Vfront+Vrear) ; %2*(V1+V2);

    end
    %-------------------LNG rear tank in the AFT
    if obj.Controller.getSetting('AftLNG')
        if LcylAft==0
            Vaft = nbAft*((4/3)*pi*R1aft^3);
        else
            Vaft = ((4/3)*pi*R1aft^3)+ (pi*LcylAft*R1aft^2);
        end
        V = V +Vaft;
    else
        Vaft=0;
    end
    %--------------------------------
else
    V = 0;
end
end
```

IV. getBoiloffrate.m

```
%--------------------
%Calculate the boil-off rate of a tank in Kg/hr
%------------------
function [usableFraction,mboiff,hi,ho,Tsin,Tsout,Q,Pvmax,Boff] = getBoiloffrate
(obj)

if obj.FuelTank
    tic
    display = false;

[~,~,~,R4,FoamWidth,Raftout,~,~,~,~,~,nbtanks,nbAft,LcylAft,dpmax,~,XTankStartFront
,XTankStartRear] = obj.getFuelTankWeight;
    fuelDensity = obj.Controller.getSetting('FuelDensity');

    if obj.Controller.getSetting('TanksALL')
        L = (XTankStartRear(2) - XTankStartFront(1)) - 2*R4; % Length of
cylindrical part
    else
        L1 = diff(XTankStartFront) - 2*R4 ; % Length of cylindrical part of front
tank
        L2 = diff(XTankStartRear) - 2*R4; % Length of cylindrical part of rear tank
        L = [L1 L2];
    end

    To = 298; % [k] Outside temperature
    %LNG Properties For  -161.5 oC inner conditions
    Ti=111.65; %[k] LNG temperature = -161.5 oC
    lambda = 509.53; % [KJ/Kg]latent heat of vaporizaton of LNG

    Kfoam = 0.015; %0.05 [[W/m.k] conduction coefficient of foam; PU:0.015
Cryogel-Z : 0.01125
    t = FoamWidth; %0.1; %[m] insulation thickness

    ro = R4; %  [m]tank outer radius
    ri =ro-t;% [m]tank inner radius
    % Convection coefficients found from [hi,ho,Ts1,Ts2] = getBoiloffrateWorking.m
one time then
    % fixed the values below
    hi=124.8;     %180.5;     %[W/(m^2 K)] value fixed to save time(takes few minutes
to find h) for the convergence loop
    ho=2.8;  %3.8;  %[W/(m^2 K)]value fixed to save time(takes few minutes to find
h) for the convergence loop
    Tsin = 111.8;   %112.15; % Temperature of inner surface Layer
    Tsout = 289.25; %275.27;% Temperature of outer surface Layer

    for i = 1 :length(L)
        %For the cylindrical part
        Rconvout(i) = 1/(2*pi*ro*L(i)*ho);
        Rconvin(i) = 1/(2*pi*ri*L(i)*hi);
        Rcond(i) = log(ro/ri)/(2*pi*L(i)*Kfoam);

        %for the 2 cup (half sphere) of the tank's end
        Rconvoutsphere(i) = 1/(ho*pi*ro^2);  %
        Rconvinsphere(i)  = 1/(hi*pi*ri^2); %
        Rcondsphere(i) = (1/ri - 1/ro)/(4*pi*Kfoam); %

        % --- Uncomment for viewing the heat input to the cylindrical part, and
        % the heat input to the 2 half cup sphere at each side

        %Qcyl(i) = (To - Ti)/(Rconvout(i) + Rconvin(i) +Rcond(i)) % [W= J/s]
        % Qsphere(i) = (To - Ti)/( Rconvoutsphere(i) + Rconvinsphere(i)
+Rcondsphere(i)) % [W= J/s]
        %----------------------------------------------------------------------
---------
```

```
        Q(i) = (To - Ti)/(Rconvout(i) + Rconvin(i) +Rcond(i)) + (To - Ti)/(
Rconvoutsphere(i) + Rconvinsphere(i) +Rcondsphere(i)) ; % [W= J/s]
        %----Considering Conduction only ----Delete after
        %Q(i) = (To - Ti)/ Rcond(i) + (To - Ti)/Rcondsphere(i) % Heat input only by
conduction [W= J/s] // Testing for simplying the Heat input equation
        %----
        mboiff(i)= Q(i)/ (1000*lambda); %[Kg/s] boill-off rate of LNG
        mboiff(i)= mboiff(i)*3600; %[Kg/hr]
    end

    Qtot = 2* sum(Q);
    mboiff = 2* sum(mboiff); % [Kg/hr] boil off from the all the tank length,
multiplied by 2 for the mirrored tanks

    Vc = obj.Controller.Aircraft.Requirements.CruiseSpeed * 3600/1000 ; %cruise
speed (m/s) to Km/hr
    Range = obj.Controller.Aircraft.Requirements.Range;
    tflight= Range / Vc;  % [hr] flight time  assuming the speed is Vc for the
whole flight.
    Boff = (tflight + 0.5) * mboiff; % [Kg] of LNG boiled during the flight, added
0.5hours to account for takeoff and landing.
    Voff = Boff / fuelDensity; %Volume of LNG that is boiled-off during the flight
    [Vtotal,Vfront,Vrear,Vaft] = obj.getFuelVolume; % Volume capacity of the
fuselage tanks
    Vtank = [Vfront Vrear Vaft];

    %-------------------LNG rear tank in the AFT
    if obj.Controller.getSetting('AftLNG')
        roAft = Raftout; %0.55;%Rout; % 0.57;%[m]outer radius
        riAft =roAft-t;% sqrt(V/(l*pi));

        %Cylindrical part
        RconvoutAft = 1/(2*pi*roAft*LcylAft*ho);
        RconvinAft = 1/(2*pi*riAft*LcylAft*hi);
        RcondAft = log(roAft/riAft)/(2*pi*LcylAft*Kfoam);

        %Spherical part
        RconvoutAftsphere = 1/(ho*pi*roAft^2);
        RconvinAftsphere  = 1/(hi*pi*riAft^2); %
        RcondAftsphere = (1/riAft - 1/roAft)/(4*pi*Kfoam); %

        %------------------------------------------------------------------------
---------
        QAft =  (To - Ti)/( RconvoutAft + RconvinAft +RcondAft) +  (To - Ti)/(
RconvoutAftsphere + RconvinAftsphere +RcondAftsphere) ;  % [W= J/s]
        %----Considering Conduction only ----Delete after
        %QAft = (To - Ti)/ RcondAft + (To - Ti)/RcondAftsphere % Heat input only by
conduction [W= J/s] // Testing for simplying the Heat input equation
        %----

        QAft = nbAft*QAft;%take care if 2 symetrical aft tanks exists
        mboiffAft= QAft/ (1000*lambda); %[Kg/s] boill-off rate of LNG
        mboiffAft= mboiffAft*3600; %[Kg/hr]

        BoffAft = (tflight + 0.5) * mboiffAft ; % [Kg] of LNG boiled during the
flight
        VoffAft = BoffAft / fuelDensity; %Volume of LNG that is boiled-off during
the flight
        mboiff = mboiff+ mboiffAft;
        Boff= Boff +BoffAft;
        Voff = Voff + VoffAft;
        Qtot =Qtot+  QAft  ;
        Q=[Q QAft];

    end
    usableFraction = 1 - (Voff/Vtotal) ;% usable fuel volume, this is to account
for the boil-off
```

```
    %----- loop for checking all tanks : front,rear and aft if present
    %condition for 72hours of no boil-off
    for q = 1 : nbtanks
        dQ(q)=72*3600*Q(q) ; %heat input due to 72 hours of no boil-off
        mlng(q)=fuelDensity*Vtank(q)*usableFraction ; %mass of LNG within the tank
        cv=2086.8 ;%[J/Kg.k] Specific heat capacity of the two phase CH4 at
constant Volume
        dt(q)=dQ(q)/(mlng(q)*cv); % increase in temperature due to 72h of no-off
rate
        T2(q)=111.65+dt(q);
        logPv(q)=22.573 - 656.24/T2(q) -7.3942*log10(T2(q)) +11.896E-3*T2(q);
        Pv(q)=10^logPv(q); %[mm of Hg]
        Pv(q) = Pv(q)*0.0001333223684; %[MPa] Pressure in the tank after 72hours of
no boil-off
    end
    Plngcritical=4.64 ; %[MPa] critical pressure for methane
    Pvmax = max(Pv);
    if (Pvmax<dpmax)& (dpmax<Plngcritical)
        disp ('Tank pressure is valid');
    else
        error('Increase insulation thickness"FoamWidth"');
    end
    %-----------------------------------------------
    toc
end
end
```

V. getFuelTankWeight.m

```
function
[Wtank,AlWidth1,AlWidth2,R4,FoamWidth,Raftout,R1aft,tp3,WtankFront,WtankRear,WtankA
ft,nbtanks,nbAft,Lcylaft,dpmax,R1,XTankStartFront,XTankStartRear] =
getFuelTankWeight(obj)
%GETFUELVOLUME Returns 0, fuselage tank should be implemented here

if obj.FuelTank
    i=0;
    AlDensity1= 2590; %density [Kg/m3] %2840; % using Al2090-T81 :2590 instead of
Al2219 : 2840
    AlDensity2 = 2770; % Al 2024 : 2770; for CFRP:1800
    FoamDensity= 32; % insulation foam density [kg/m^3] PU=32, Cryogel-Z =130

    %Specify width of foam insulation
    FoamWidth=  0.1;   %default : 0.1 %0.15 %0.2; %0.1

    R4 = max((obj.CargoBay.ULDData.Height0/2 -0.02),((abs(obj.FloorZPosition-
obj.Floors.Bottom{1}(1,3))-0.1)/2 ))  ; % outer radius of tank

    %-----------calculate material thickness based on the yield strength of
    %the material

    YS1 = 559 ; % [MPa];559 (Al2090-T81); 386.57 (Al2219-T81); Inner layer Yield
Strength
    YS2 = 324 ; % [MPa]; 324 (Al2024-T4) % Outer layer Yield Strength
    SF = 1.5 ; % Safety Factor
    %---calsulate cruise pressure
    P= Atmosphere(obj.Controller.Aircraft.Requirements.Altitude).Pressure; %[Pa]
    Pout = P*10^-6 ;      %to [MPa]
    Pin = 0.6278 ; % [MPA]: 1bar ; Pressure inside the tank, after 72hours of no
boil off
    errorrr =1;
    [~,~,XTankStartFront,XTankStartRear] = obj.CargoBay.calcMass;
    LcylFront= (XTankStartFront(2) - XTankStartFront(1))- 2*R4;
    LcylRear= (XTankStartRear(2) - XTankStartRear(1))- 2*R4;
    fuelDensity = obj.Controller.getSetting('FuelDensity');
    FTMMT = obj.Controller.getSetting('FTMMT'); %Fuselage Tank (Inner and outer
layers) Minimum Manifacturing Thickness

    while(errorrr>0.0001)
        i=i+1;
        if i==1
            AlWidth2 = FTMMT    ;
        end

        R3=R4-AlWidth2;
        R2=R3-FoamWidth;
        AlWidth1 = (abs(Pin-Pout) * R2)/(YS1/SF) ;%from hoop stress
:sigma=Delta(P)*r/t
        R1=R2-AlWidth1;     %[m] inner Tank radius

        %--------------------------------thickness based on front cylindrical
        %part-------------
        AlVFront1cyl=(LcylFront*pi)*(R2^2  - R1^2 );
        AlVFront2cyl=(LcylFront*pi)*(R4^2  - R3^2 );
        AlMFrontcyl= AlVFront1cyl*AlDensity1 + AlVFront2cyl*AlDensity2;
        FoamVFrontcyl= (LcylFront*pi)*(R3^2-R2^2);
        FoamMFrontcyl= FoamVFrontcyl*FoamDensity;
        WtankFrontcyl = (FoamMFrontcyl + AlMFrontcyl);
        V1cyl = (pi*LcylFront*R1^2);
        Wfuel1cyl =fuelDensity*V1cyl;

        %------------------- reaarange the AlWidth22 equation-------
```

```
        P22=((WtankFrontcyl+Wfuel1cyl)*9.81)  / (2*pi*R4*LcylFront ) ;   %[Pa]
pressure due to weight of the tank +fuel on outer aluminum layer
        t22=(P22*R4) / ((YS2/SF)*10^6); % [m]
        errorrr=abs(AlWidth2-t22);
        AlWidth2 = t22 ;
    end
    if AlWidth2<FTMMT
        AlWidth2 = FTMMT ;
        R3=R4-AlWidth2;
        R2=R3-FoamWidth;
    end
    if AlWidth1<FTMMT
        AlWidth1 = FTMMT ;
    end
    R1=R2-AlWidth1;

    %-------------------------------------------

    if obj.Controller.getSetting('TanksALL') % tank runs from the front till rear
        Lcyl= (XTankStartRear(2) - XTankStartFront(1))- 2*R4;
        AlV1=(Lcyl*pi)*(R2^2  - R1^2 ) + ((4/3)*pi)*(R2^3  - R1^3 );
        AlV2=(Lcyl*pi)*(R4^2  - R3^2 ) + ((4/3)*pi)*(R4^3  - R3^3 );
        AlM1= AlV1.*AlDensity1;
        AlM2= AlV2.*AlDensity2;
        AlM = AlM1 + AlM2;
        FoamV= (Lcyl*pi)*(R3^2-R2^2) + ((4/3)*pi)*(R3^3-R2^3);
        FoamM= FoamV*FoamDensity;
        Wtank = 2*(FoamM + AlM);
        nbtanks = 1;
    else
        AlVFront1=(LcylFront*pi)*(R2^2  - R1^2 ) + ((4/3)*pi)*(R2^3  - R1^3 );
        AlVFront2=(LcylFront*pi)*(R4^2  - R3^2 ) + ((4/3)*pi)*(R4^3  - R3^3 );
        AlVRear1=(LcylRear*pi)*(R2^2  - R1^2 ) + ((4/3)*pi)*(R2^3  - R1^3 );
        AlVRear2=(LcylRear*pi)*(R4^2  - R3^2 ) + ((4/3)*pi)*(R4^3  - R3^3 );

        AlMFront= AlVFront1*AlDensity1 + AlVFront2*AlDensity2;
        AlMRear= AlVRear1*AlDensity1 + AlVRear2*AlDensity2;

        FoamVFront= (LcylFront*pi)*(R3^2-R2^2) + ((4/3)*pi)*(R3^3-R2^3);
        FoamMFront= FoamVFront*FoamDensity;
        FoamVRear= (LcylRear*pi)*(R3^2-R2^2) + ((4/3)*pi)*(R3^3-R2^3);
        FoamMRear= FoamVRear*FoamDensity;

        WtankFront = 2*(FoamMFront + AlMFront);
        WtankRear = 2* (FoamMRear + AlMRear);
        Wtank = WtankFront + WtankRear;
        nbtanks =2;
    end

    %-------------------LNG Aft tank in the AFT

    if obj.Controller.getSetting('AftLNG')
        [Xaft,Yaft,Zaft]=obj.Surface.Aft.getGeometry;
        Ycgb = 0;
        Zcgb=(max(Zaft(:,3))+ min(Zaft(:,3)))/2;
        RZb=(max(Zaft(:,3))- min(Zaft(:,3)))/2 -0.1; % - 0.1[m] from radius to
allow for pipes+++
        RYb=max(Yaft(:,3))-0.1;  % - 0.1[m] from radius to allow for pipes+++
        %----------------------
        Zv=obj.Controller.Aircraft.Parts.VerticalStabiliser.Position(1,3);
        Xv=obj.Controller.Aircraft.Parts.HorizontalStabiliser.Position(1,1);
        RXb=(Xv-obj.Floors.Top(end,1))/2;
        Xcgb=(Xv+obj.Floors.Top(end,1))/2;

        %------------------
        sphereaft = 0 ; %0:for cylinder+ 2 half cups. 1: for sphere

        if sphereaft == 1
```

```
            Raftout = min([RXb,RYb/2,RZb]);
        elseif sphereaft == 0
            Raftout = min([RXb,RYb,RZb]);
        end

        R3aft=Raftout-AlWidth2 ;
        R2aft=R3aft-FoamWidth;
        R1aft=R2aft-AlWidth1 ;

        if sphereaft == 1
            Lcylaft = 0;
            AlV1aft= ((4/3)*pi)*(R2aft^3  - R1aft^3 );
            AlV2aft= ((4/3)*pi)*(Raftout^3  - R3aft^3 );
            AlM1aft= AlV1aft.*AlDensity1;
            AlM2aft= AlV2aft.*AlDensity2;
            FoamVaft=  ((4/3)*pi)*(R3aft^3-R2aft^3);
            Ycgb= 0;
            %------------------Trying cylinder with 2 cups instead of sphere in
            %the  rear
        else

            Lcylaft=2*(RYb-Raftout)-0.2  ;
            AlV1aft=(Lcylaft*pi)*(R2aft^2  - R1aft^2 ) + ((4/3)*pi)*(R2aft^3  -
R1aft^3 );
            AlV2aft=(Lcylaft*pi)*(Raftout^2  - R3aft^2 ) + ((4/3)*pi)*(Raftout^3  -
R3aft^3 );
            AlM1aft= AlV1aft.*AlDensity1;
            AlM2aft= AlV2aft.*AlDensity2;
            FoamVaft= (Lcylaft*pi)*(R3aft^2-R2aft^2) + ((4/3)*pi)*(R3aft^3-
R2aft^3);
            Ycgb=0;
            %--------------------------------
        end

        AlMaft = AlM1aft + AlM2aft;
        FoamMaft= FoamVaft*FoamDensity;

        if (Ycgb== 0)
            nbAft=1; %1 for one sphere tank in Aft
        else
            nbAft=2; %2 symetrical shoere tank in the aft
        end

        WtankAft = nbAft*(FoamMaft + AlMaft);
        Wtank = Wtank+ WtankAft ;
        nbtanks = nbtanks +1;
        tp3=[Xcgb,Ycgb,Zcgb]; %move to this point
        %-----------------------------
    else
        Raftout = 0;
        R1aft = 0;
        tp3 = 0;
        WtankAft = 0;
        nbAft=0
        Lcylaft=0;
    end
    dpmax=AlWidth1*(YS1/1.5)/R1; %[MPa] :max pressure that the al2090 thickness can
whistand
end
end
```

VI. getConvectionCoefficients.m

```
%--------------------
%Calculate the convection coefficients for air outside the tank and LNG
%inside the tank
%------------------
function [hi,ho,Tsin,Tsout] = getConvectionCoefficients (obj)

if obj.FuelTank
    % tic
    %[~,~,~,R4,FoamWidth] = obj.getFuelTankWeight;

[~,~,~,R4,FoamWidth,Raftout,~,~,~,~,~,nbtanks,nbAft,LcylAft,dpmax,~,XTankStartFront
,XTankStartRear] = obj.getFuelTankWeight;
    L1 = diff(XTankStartFront) - 2*R4 ;
    display = true;

    %Air Propertries For 298 K outter conditions
    cpair= 1006.96; %[J/Kg.K]
    kair = 0.02614; % [W/m.K]
    rhoair = 1.1707; %[kg/m^3]
    vair = 15.712e-6; % [m^2/s]
    g = 9.81;
    To = 298; % [k]
    betaair = 1/To; % expansion coeffecient of air
    alphaair = kair/(rhoair*cpair);

    %LNG Properties For  -161.5 oC inner conditions
    cpLNG =3449.9217 ;% [J/Kg.K] "Physical Properties" p221 +
http://www.endmemo.com/convert/specific%20heat%20capacity.php
    kLNG = 0.195; %[W/m.k] thermal conductivity
    rhoLNG = 420; %[kg/m^3]
    vLNG = 2.69e-7;% [m^2/s],caluclated = viscosity/density,  from
http://www.peacesoftware.de/einigewerte/calc_methan.php5
    Ti=111.65; %[k]
    betaLNG = 0.0034; %http://booksite.elsevier.com/9780750683661/Appendix_C.pdf
    alphaLNG = kLNG/(rhoLNG*cpLNG);
    lambda = 509.53; % [KJ/Kg]latent heat of vaporizaton of LNG

    %Insulation
    Kfoam =0.015; %0.05 [[W/m.k] conduction coefficient of foam
    t = FoamWidth; %0.1; %[m] insulation thickness

    %Tank
    ro = R4 ; %[m]outer tank radius
    ri = ro-t ; % [m] inner tank radius
    Do = 2*ro;  %[m]outer tank diameter
    Di = 2*ri;  %[m]innet tank diameter

    %Prandlt Number for the outter flux
    Pro = (rhoair*cpair*vair)/kair;
    %Prandlt Number for the inner flux
    Pri = (rhoLNG*cpLNG*vLNG)/kLNG;

    err = [];
    err2 = [];
    error=[];
    error2=[];
    Tsoutsolution=[];
    Tsinsolution = [];

    Tsin= [];
    hin=[];
    Tsout= [];
    hout=[];

    Tsin=Ti;
```

```
    Rai=((Tsin-Ti)*(g*betaLNG*(Di^3))) / (vLNG*alphaLNG);
    Nui=( 0.6 + (0.387*Rai^(1/6))/ ((1+((0.559/Pri)^(9/16)))^(8/27)) )^2;
    hLNG =(kLNG/Di)*Nui;

    for Tsout =   260:0.15:298

        Rao=((To-Tsout)*(g*betaair*(Do^3))) / (vair*alphaair);
        Nuo=( 0.6 + (0.387*Rao^(1/6))/ ((1+((0.559/Pro)^(9/16)))^(8/27)) )^2;
        ho =(kair/Do)*Nuo;

        qcond =((Tsout - Tsin)*2*pi*L1*Kfoam)/(log(ro/ri));
        qconvout=(To - Tsout)*(2*pi*ro*L1*ho);

        err =  abs(qconvout - qcond) /((qconvout + qcond)/2); %(qcond+qconvin)
        if err<0.05
            error=[error err];
            Tsoutsolution=[Tsoutsolution Tsout];
            hout =[hout ho];

        end
    end
    ind = find (error == min(error));
    ho = hout(ind);
    Tsout = Tsoutsolution(ind);
    qconvout=(To - Tsout)*(2*pi*ro*L1*ho);
    for Tsin =   111.65:0.15:150

        Rai=((Tsin-Ti)*(g*betaLNG*(Di^3))) / (vLNG*alphaLNG);
        Nui=( 0.6 + (0.387*Rai^(1/6))/ ((1+((0.559/Pri)^(9/16)))^(8/27)) )^2;
        hi =(kLNG/Di)*Nui;

        qcond =((Tsout - Tsin)*2*pi*L1*Kfoam)/(log(ro/ri));
        qconvin=(Tsin - Ti)*(2*pi*ri*L1*hi);
        err2 = abs(qcond - qconvin) /((qconvin + qcond)/2)
        if err2<0.45
            error2=[error2 err2]
            Tsinsolution=[Tsinsolution Tsin];
            hin =[hin hi];
        end
    end
    ind2 = find (error2 == min(error2));
    hi = hin(ind2);
    Tsin = Tsinsolution(ind2);

    if display
        disp(error);
        disp(error2);

        disp(Tsin);
        disp(Tsout);
        disp(hi);
        disp(ho);
        disp('__________________________');

    end

    %   toc

end
```

Appendix G
Other modifications needed for LNG aircraft.

Further modifications to the existing modules in Initiator are needed in order to be able to generate and study an LNG aircraft. This section describes briefly those adjustments.

i. Modification to estimateWing.m in @GeometryEstimation in Sizing Modules.

In this script, the wing's tank was always set to true, so it was always generating wing's tanks and in the LNG case, it resulted in fuel tank in the wing and in the fuselage.
So to make sure that no tanks are created in the wing when LNG is selected, the following line were added:

```
if (obj.Controller.getSetting(LNGfuel))
        MainWings{w}.FuelTank = false;
else
        MainWings{w}.FuelTank = true;
        MainWings{w}.FuelTankSpanPosition = obj.Controller.getSetting('FuelTankSpanPosition');
end
```

ii. Modification to getLongitudinalLoads.m in @FuselageWeightEstimation in Analysis Modules.

The fuel weight is modelled as linear distribution of weight point along the tank's length. This weight distribution is only available for the wing tank, so it should be added in case of the fuselage tank.
The following lines accounts for the weight of the fuel and tanks as a point distribution of individual tanks, similar to the ULDs.

```
case 'Fuselage'
[~,~,~,~,~,~,~,~,WtankFront,WtankRear,WtankAft,nbtanks]= ConnectedPart.getFuelTankWeight;

[~,Xcgfront,Xcgrear,XcgAft] = ConnectedPart.getFuelTankCG;
MassLNGtank = [ WtankFront;WtankRear;WtankAft];
XCGLNGtank = [Xcgfront;Xcgrear;XcgAft];

for j=1:nbtanks
MassDistributionData.(['Fuel' FuelTankNames{i} num2str(j)]).Mass = MassLNGtank(j)
MassDistributionData.(['Fuel' FuelTankNames{i} num2str(j)]).XCG = XCGLNGtank(j);
MassDistributionData.(['Fuel' FuelTankNames{i} num2str(j)]).Position = XCGLNGtank(j) ;
MassDistributionData.(['Fuel' FuelTankNames{i} num2str(j)]).Type = 'Point';
end
```

iii. Mod to getFuel.m in @ Class2WeightEstimation in Analysis Modules.

In this script, a method was added to account for the boil-off rate.
In case the 'LNGfuel' is set to true, then the 'usuableFraction' will be taken from the "getBoiloffrate.m". If not, the 'usuableFraction' is taken from the settings. The following lines where added:

```
if obj.Controller.getSetting('LNGfuel')
        usableFraction = Fuselages{1}.getBoiloffrate
else
        usableFraction = obj.Controller.getSetting('UsableFuelVolume');
end
```

iv. Mod to getFuelWeight.m in @ Class2WeightEstimation in Analysis Modules

Here the weight of the cryogenic tank is added to the fuel system's weight, so it is accounted for in the operating empty weight of the aircraft.
The weight of the cryogenic fuel system is assumed to weight 70% more than the kerosene fuel system, based on DSE05 [21].

```
if obj.Controller.getSetting('LNGfuel')
        FuelTankWeight = obj.Aircraft.findPart('Fuselage').getFuelTankWeight;
        FuelSystem.Mass = 1.7*FS + FuelTankWeight;
else
        FuelSystem.Mass = FS;
end
```

v. Mod to WeightEstimation.m in @ Class25WeightEstimation in Analysis Modules.

These modifications are necessary to make sure that the fuel mass is set for the correct part, and to make sure that for the fuselage's tank the boil-off rate of the LNG is accounted for by calculating the required usable fraction of the available volume.

The program was always adding the mission's fuel mass to the Main Wing. So the script below, writes the fuel mass to the fuselage in case of Fuselage tank, and if not then the fuel mass is written to the Main Wing like before.

```
if strcmp(TheParts{i}.Name,'Fuselage')
        usableFraction = TheParts{i}.getBoiloffrate
        obj.Results.MTOMMissionFuel.Fuselage.Mass = MissionAnalysisResults.Class25.FuelMass;
else
        usableFraction = obj.Controller.getSetting('UsableFuelVolume');
        obj.Results.MTOMMissionFuel.MainWing.Mass = MissionAnalysisResults.Class25.FuelMass;
end
```

vi. Mod to @MissionAnalysis in Analysis modules

Several small modifications are necessary, but mainly the emissions from the combustion of Methane needs to be added. The main script that is responsible for the emissions is "emissions.m". For LNG the amount of CO2, H2O and NOx emitted in kg per kg of fuel burned needs to be added; below are the added lines.

```
if FD
        %For LNG, kg/kg fuel
        CO2_kg = 2.750;
        H2O_kg = 2.263;
        NOx_kg = 0.005;
else
```

The code checks if the Fuel is LNG by examination the "LNGfuel" in the settings file. FD is the Boolean variable representing the "LNGfuel". To be able to distinguish the fuel type, the FD parameter needs to be added to all the scripts below:

- cruise.m
- climb.m
- descent.m
- emissions.m
- hold.m
- landing.m
- MissionAnalysis.m
- takeoff.m

In this manner:

```
FD = obj.Controller.getSetting('LNGfuel');
[dCO2eqCO2_dt,dCO2eqH2O_dt,dCO2eqNOx_dt] = obj.emissions(FD,dWfb_dt/g,S.h(i));
```

vii. convergeWeights.m in @DesignConvergence in WorkflowModules

In this script, the convergence criterions that need to be satisfied so that an aircraft module can converge, are specified.

Since the LNG's volume needed might not fit within the typical length of A320's fuselage, one solution to that is to extend the fuselage.

Initiator modifies the aircraft's geometry in two conditions, one if the required cargo does not fit, then the fuselage is extended until the cargo can fit. The second geometrical change is for the wings, if the fuel does not fit, the wings are extended.
So in a similar way, the program is modified to extend the fuselage if the required mission's LNG fuel does not fit.
This can be enabled by setting "DesignConvergenceFuselageTankFitting" to true in the settings. The added code is found below:

```
while (classItoIIVWeightConvergence > classItoIIVtolerance || ...
            fuelScalingFactor > 1 || cargoScalingFactor > 1 || LNGTankScalingFactor > 1 )
```

So "LNGTankScalingFactor" was added as a criteria to the convergence loop, now this must be satisfied so that the configuration can converged.

```
if obj.Controller.getSetting('DesignConvergenceFuselageTankFitting')
            LNGTankScalingFactor = obj.Controller.getModuleHandle(weightModule).FuelScalingFactor
            if LNGTankScalingFactor > 1
                        if ~exist('geometryEstimationInput','var') ||...
            ~isfield(geometryEstimationInput,'FuselageLengthScalingFactor')
  geometryEstimationInput.FuselageLengthScalingFactor = 1 + fuselageLengthIncrementFuelTank;
                        else
                        geometryEstimationInput.FuselageLengthScalingFactor = ...
  geometryEstimationInput.FuselageLengthScalingFactor + fuselageLengthIncrementFuelTank;
                        end
            obj.showMessage(['Fuselage length increased with ' ...
            num2str((geometryEstimationInput.FuselageLengthScalingFactor-1)*100) '% to allow for     required Fuselage tank']);
            end
else
      LNGTankScalingFactor = 0;
end
```

It should be noted, that for the LNG configuration the 'DesignConvergenceFuelFitting' setting should be set to 'false' in settings file, so that if the fuel does not fit, only the fuselage will be extended and not the wing span.

viii. plotGeometry in @PlotTool in WorkflowModules

This script is responsible for drawing the whole aircrafts and its parts. Since a cryogenic tank was added to the fuselage; it needs to be added to the plotting module.

```
%     plot fueltank
if (ischar(partNames) && (strcmpi(partNames,'Fueltank') || strcmpi(partNames,'all'))) ...
|| (iscell(partNames) && ismember(lower('Fueltank'),partNames))
  if CurrentPart.FuelTank
    X,Y,Z] = CurrentPart.getFuelTankGeometry;
    surface(X+xDispl,Y,Z+zDispl,'FaceColor',fuelTankColour,'EdgeColor',fuelTankColour*0.6);
```

```
    surface(X+xDispl,Y,Z+zDispl,'FaceColor',fuelTankColour,'EdgeColor',fuelTankColour*0.6);
  end
end
```

These lines are also added to “plotGeometry.m” in @ReportWriter in WorkflowModules.

ix. run.m in @ ReportWriter in WorkflowModules

To include the cryogenic tank in the pdf report that is generated by Initiator, a line needs to be added to fuselage plotting. The 262th line from the file needs to be replace by:

```
obj.plotGeometry({FuselagePart.Name,'Fueltank'},false,0);
```

x. settings.xml

In this file, all the settings that were added to Initiator are defined. For the LNG, several new variables need to be defined in this xml file. All the added variables are listed in the table below:

Name	Default Value	Description
LNGfuel	false	Use LNG fuel in cryogenic tanks within the fuselage
AftLNG	false	Generates an additional tank in the aft of the fuselage
TanksALL	false	Generates a whole cryogenic tank that runs across the fuselage between the ULDs, including through the wing box.
exactULDs	false	Generates the exact number of ULDs that fits the required luggage mass.
ULDoption	4	Choose between 4 ULD positions within the cargo bay.
DesignConvergenceFuselageTankFitting	false	Extend the fuselage if the mission’s fuel does not fit
FuselageLengthIncreaseForFuelTank	0.05	Extend the fuselage by the value for each iteration when “DesignConvergenceFuselageTankFitting” is set to true.

xi. operatingCost.m @ CostEstimation in AnalysisModules

The module assumes the fuel to be JET-A FUEL, with the density to be 6.84 [lb/gal(US)], and a fuel price of 4 [$/gal(US)];
So to take account for the LNG, different density and price are added to the module.
To do so, the program detects if the fuel is LNG or the typical fuel, and output the correspondent values.
First the density and LNG price are found and transformed to required units.
LNG has a density of 420 [Kg/m3], this is equal to 3.505 [lbs/gal (US)].
From [21,p9] the forecast price of LNG in 2025 will be double that of the Jet fuel in terms of energy density : [MJ/$].
So taking the 4 [$/gal(US)] and transforming to MJ/$.
With 1 gal = 0.00378541m3;

- ⇨ JET FUEL : 0.00378541 * $\rho_{JetFuel}$ * heating value$_{JetFuel}$ = 0.00378541 * 0.82 * 43.031 = 133.5998 [MJ].
- ⇨ 4 [$/133.5998 [MJ]].

- ⇨ Jet Fuel : **33.3924 [MJ/$]**
- ⇨ LNG : 2 * 33.3924 = **66.7849 [MJ/$]** Assuming LNG energy density is twice the kerosene.
  Transforming this one to [$/gal]:
  $$\frac{66.7849}{\rho_{LNG} \times heatingvalue_{LNG}} = \frac{66.7849}{420 \times 50.03} = 0.00317 \left[\frac{m^3}{\$}\right] = 0.8396 \left[\frac{gal}{\$}\right];$$
- ⇨ **LNG price = 1.191 [$/gal] ;**

The following lines are added to the “operatingCost” function:

```
if obj.Controller.getSetting('LNGfuel')
 FuelPrice = 1.191; % [$/gal] based on double MJ/$ for the LNG
 FuelDensity = 3.505 ; %Fuel density in [lbs/US gal]
else
 FuelDensity = Operator.FuelDensity;     %Fuel density in [lbs/US gal]
 FuelPrice = Operator.FuelPrice;         %Price of fuel [US$/US gal]
end
```

Appendix H
A320-LNG-AFT input xml file


```
<?xml version="1.0" encoding="utf-8"?>
<initiator xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="initiator.xsd">
  <aircraft>
    <name>A320-200-GEOM-mod-LNG</name>
    <description>Airbus A320-200 aircraft geometry and requirements from Elodie
Roux (2007)</description>
    <missions default="Design">
      <mission name="Design">
        <requirement>
          <name>Pax</name>
          <value>150</value>
        </requirement>
        <requirement>
          <name>Range</name>
          <value>1500</value>
        </requirement>
        <requirement>
          <name>CruiseMach</name>
          <value>0.78</value>
        </requirement>
        <requirement>
          <name>Altitude</name>
          <value>11278</value>
        </requirement>
        <requirement>
          <name>TakeOffDistance</name>
          <value>2180</value>
        </requirement>
        <requirement>
          <name>LandingDistance</name>
          <value>1440</value>
        </requirement>
        <requirement>
          <name>NumberOfFlights</name>
          <value>100000</value>
        </requirement>
        <requirement>
          <name>AirworthinessRegulations</name>
          <value>FAR-25</value>
        </requirement>
       <requirement>
          <name>LoiterTime</name>
          <value>30</value>
        </requirement>
        <requirement>
          <name>DivRange</name>
          <value>500</value>
        </requirement>
        </mission>
        </missions>
    <performance>
      <parameter>
        <name>LDmax</name>
        <value>18</value>
      </parameter>
      <parameter>
        <name>SFC</name>
        <value>0.516</value>
      </parameter>
      <parameter>
        <name>Mode</name>
```

```xml
        <value>Fuel</value>
      </parameter>
      <parameter>
        <name>FFStartUp</name>
        <value>0.990</value>
      </parameter>
      <parameter>
        <name>FFTaxi</name>
        <value>0.990</value>
      </parameter>
      <parameter>
        <name>CLmaxLanding</name>
        <value>3</value>
      </parameter>
      <parameter>
        <name>CLmaxTakeOff</name>
        <value>2.56</value>
      </parameter>
      <parameter>
        <name>CLmaxClean</name>
        <value>1.3</value>
      </parameter>
    </performance>
    <configuration>
      <parameter>
        <name>WingAspectRatio</name>
        <value>9.39</value>
      </parameter>
      <parameter>
        <name>WingLocation</name>
        <value>Low</value>
      </parameter>
      <parameter>
        <name>TailType</name>
        <value>Standard</value>
      </parameter>
    </configuration>
    <parts mainPart="Fuselage">
        <landingGear name="Main Gear 1" type="MainGear">
       <location>Main Wing</location>
        <nRows>1</nRows>
        <nWheelsPerRow>2</nWheelsPerRow>
        <orientation>
          <phi>0</phi>
          <psi>0</psi>
          <theta>0</theta>
        </orientation>
        <position>
          <x>17.71</x>
          <y>3.795</y>
          <z>-3.5574</z>
        </position>
        <tyreDiameter>1.27</tyreDiameter>
        <tyreThickness>0.455</tyreThickness>
      </landingGear>
      <landingGear name="Main Gear 2" type="MainGear">
        <location>Main Wing</location>
        <nRows>1</nRows>
        <nWheelsPerRow>2</nWheelsPerRow>
        <orientation>
          <phi>0</phi>
          <psi>0</psi>
          <theta>0</theta>
        </orientation>
        <position>
          <x>17.71</x>
          <y>-3.795</y>
          <z>-3.5574</z>
```

```
    </position>
    <tyreDiameter>1.27</tyreDiameter>
    <tyreThickness>0.455</tyreThickness>
  </landingGear>
  <landingGear name="Nose Gear" type="NoseGear">
  <location>Fuselage</location>
    <nRows>1</nRows>
    <nWheelsPerRow>2</nWheelsPerRow>
    <orientation>
      <phi>0</phi>
      <psi>0</psi>
      <theta>0</theta>
    </orientation>
    <position>
      <x>5.07</x>
      <y>0</y>
      <z>-3.5574</z>
    </position>
    <tyreDiameter>0.82781</tyreDiameter>
    <tyreThickness>0.25436</tyreThickness>
  </landingGear>
  <fuselage name="Fuselage" type="Conventional">
    <length>37.57</length>
    <diameter>4.14</diameter>
    <position>
      <x>0</x>
      <y>0</y>
      <z>0</z>
    </position>
    <orientation>
      <phi>0</phi>
      <theta>0</theta>
      <psi>0</psi>
    </orientation>
    <fuelTank>true</fuelTank>
  </fuselage>
  <wing name="Main Wing" type="MainWing">
    <span>33.91</span>
    <rootChord>7.08</rootChord>
    <sections>SC20614,SC20612,SC20610</sections>
    <sectionPositions mapType="vector">0;0.38;1</sectionPositions>
    <tapers mapType="vector">0.53;0.44</tapers>
    <sweeps mapType="vector">23;26</sweeps>
    <twists mapType="vector">0;-2;-3</twists>
    <dihedrals mapType="vector">5.1;5.1</dihedrals>
    <tcRatios mapType="vector">0.16;0.12;0.10</tcRatios>
    <sparPositions mapType="vector">0.15;0.60</sparPositions>
    <fuelTank>false</fuelTank>
    <symmetric>true</symmetric>
    <mirror>false</mirror>
    <winglets>false</winglets>
    <position>
      <x>11.19</x>
      <y>0</y>
      <z>-1.08</z>
    </position>
    <orientation>
      <phi>0</phi>
      <theta>3</theta>
      <psi>0</psi>
    </orientation>
  </wing>
  <wing name="Horizontal Stabiliser" type="HorizontalTail">
    <span>12.45</span>
    <rootChord>4.17</rootChord>
    <sections>N0010,N0010</sections>
    <sectionPositions mapType="vector">0;1</sectionPositions>
    <tapers mapType="vector">0.256</tapers>
```

```
    <sweeps mapType="vector">29</sweeps>
    <twists mapType="vector">0;0</twists>
    <dihedrals mapType="vector">8</dihedrals>
    <tcRatios mapType="vector">0.10;0.10</tcRatios>
    <sparPositions mapType="vector">0.2;0.7</sparPositions>
    <symmetric>true</symmetric>
    <mirror>false</mirror>
    <winglets>false</winglets>
    <position>
      <x>31.8</x>
      <y>0</y>
      <z>0.84</z>
    </position>
    <orientation>
      <phi>0</phi>
      <theta>0</theta>
      <psi>0</psi>
    </orientation>
  </wing>
  <wing name="Vertical Stabiliser" type="VerticalTail">
    <span>6.26</span>
    <rootChord>5.83</rootChord>
    <sections>N0010,N0010</sections>
    <sectionPositions mapType="vector">0;1</sectionPositions>
    <tapers mapType="vector">0.303</tapers>
    <sweeps mapType="vector">34</sweeps>
    <twists mapType="vector">0;0</twists>
    <dihedrals mapType="vector">0</dihedrals>
    <tcRatios mapType="vector">0.10;0.10</tcRatios>
    <sparPositions mapType="vector">0.2;0.7</sparPositions>
    <symmetric>false</symmetric>
    <mirror>false</mirror>
    <winglets>false</winglets>
    <position>
      <x>29.8</x>
      <y>0</y>
      <z>1.66</z>
    </position>
    <orientation>
      <phi>90</phi>
      <theta>0</theta>
      <psi>0</psi>
    </orientation>
  </wing>
  <engine name="CFM56-5A3-1" type="TurboFan">
    <location>Main Wing</location>
    <bypassRatio>6</bypassRatio>
    <length>2.423</length>
    <diameter>1.829</diameter>
    <thrust>117877</thrust>
    <position>
      <x>11.19</x>
      <y>5.755</y>
      <z>-1.82</z>
    </position>
    <orientation>
      <phi>90</phi>
      <theta>0</theta>
      <psi>0</psi>
    </orientation>
  </engine>
  <engine name="CFM56-5A3-2" type="TurboFan">
    <location>Main Wing</location>
    <bypassRatio>6</bypassRatio>
    <length>2.423</length>
    <diameter>1.829</diameter>
    <thrust>117877</thrust>
    <position>
```

```
          <x>11.19</x>
          <y>-5.755</y>
          <z>-1.82</z>
        </position>
        <orientation>
          <phi>90</phi>
          <theta>0</theta>
          <psi>0</psi>
        </orientation>
      </engine>
    </parts>
  </aircraft>
  <runList>DesignConvergence,ReportWriter,PlotTool</runList>

   <settings source="settings.xml">
        <setting>
        <name>PaxMass</name>    <!-- Mass per Passenger     -->
        <value>80</value>       <!-- [kg]   -->
    </setting>
       <setting>
        <name>LuggageMass</name>    <!-- Luggage Mass per Passenger -->
        <value>25</value>           <!-- [kg] -->
    </setting>
       <setting>
        <name>TanksALL</name>       <!-- Tanks in between the ULDs, including the
wing box space    -->
        <value>false</value>        <!-- set to true for all generating Fuselage
tank in all the lower cargo space                      -->
    </setting>
       <setting>
        <name>LNGfuel</name>        <!-- Full LNG fuel, tank in fuselage, no tank
in wing   -->
        <value>true</value>     <!-- set to true for all LNG
-->
    </setting>
    <setting>
        <name>AftLNG</name>     <!-- ADD sphere LNG TANK in Aftbody     -->
        <value>true</value>     <!-- set to true to add Rear LNG tank
-->
    </setting>
    <setting>
        <name>FuelDensity</name> <!-- [kg/m^3] -->
        <value>420</value> <!--450 LNG, Default Kerozene 810 -->
    </setting>
    <setting>
        <name>FuelHg</name>     <!-- H/g; H = Calorific value of fuel   -->
        <value>5003</value>     <!-- 5100 LNG, Default Kerozene 4350 -->
    </setting>
    <setting>
      <name>PaxPerArea</name>
      <value>1.50</value>
      <!-- Three class:1.09 Two class: 1.29 All Economy: 1.50 pax/m2 ,try 1.79 for
179 pass economy to fit  -->
    </setting>
    <setting>
        <name>MinimumCargoPackingEfficiency</name> <!-- Minimum packing efficiency
required for a cargobay with ULD's; otherwise bulk will be used -->
        <value>0.6</value> <!--Default 0.7 -->
        </setting>
    <setting>
        <name>DefaultRelativeFloorZPosition</name>
        <value>-0.04</value> <!-- Default -0.08 ,Multiplied with the diameter -->
    </setting>
    <setting>
        <name>exactULDs</name>        <!-- generates exact nb of required ULDs(or
Bulk),to fit the exact Payload mass    -->
        <value>true</value>        <!-- set to true                        -->
    </setting>
```

```xml
    <setting>
        <name>ULDoption</name>
        <value>4</value>    <!-- 4:best for CG      1: for LNG in between ULDs, 2:
for ULDs arround the wing, 3 :Front: ULd-tank. Rear:Uld-tank,4:All Ulds in front
and behind it tanks.    -->
    </setting>
  <setting>
        <name>DesignConvergenceFuelFitting</name>
        <value>false</value>
    </setting>
    <setting>
        <name>DesignConvergenceCargoFitting</name>
        <value>false</value>
    </setting>
     <setting>
        <name>DesignConvergenceFuselageTankFitting</name>
        <value>false</value>
    </setting>
    <setting>
        <name>WingLoadingDecreaseForFuel</name>
        <value>0.1</value>
    </setting>
    <setting>
        <name>FuselageLengthIncreaseForCargo</name>
        <value>0.1</value>
    </setting>
     <setting>
        <name>FuselageLengthIncreaseForFuelTank</name>
        <value>0.05</value>
    </setting>
    <setting>
        <name>MaxIterWeight</name>
        <value>15</value>
    </setting>
    <setting>
        <name>MaxIterRange</name>
        <value>10</value>
    </setting>
    <setting>
        <name>DesignConvergenceWeightMethod</name>
        <value>Class25</value>
    </setting>
    <setting>
        <name>WeightTolerance</name>
        <value>0.005</value>
    </setting>
     <setting>
        <name>RangeTolerance</name>
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    </input>
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</initiator>
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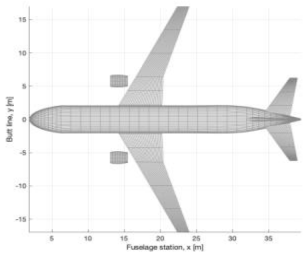
Appendix I
A320-kerosene results

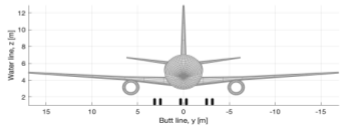
A320-200-GEOM-mod-F-Report

Initiator version

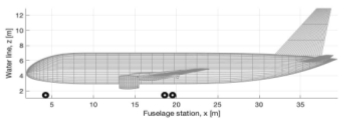
September 13, 2019



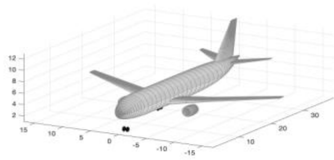
(a) Top view



(b) Front view



(c) Side view



(d) 3D view

Figure 1: Aircraft geometry (all dimensions in meters)

1 General Characteristics

Aircraft “A320-200-GEOM-mod-F-Report” generated by the Initiator version . The aircraft is a conventional aircraft with a wing aspect ratio of 9.39. The aircraft is designed to transport 150 passengers with a total payload mass of 15750kg over 1500km.

2 Specification

Table 1: Design

Pax	150	-
Range	1500	km
Cruise Mach	0.78	-
Altitude	11278	m
Take Off Distance	2180	m
Landing Distance	1440	m
Payload Mass	15750	kg

3 Operational Performance

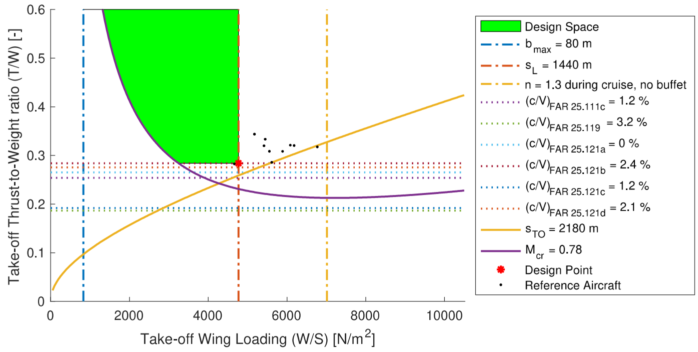


Figure 2: Loading Diagram

Result: Wing loading at MTOM: 4768 N/m^2
Thrust-to-weight ratio: 0.284 -

Table 2: Performance results

L/D_{cruise}	15.1	-
Cruise altitude	11278	m
Harmonic range	1400	km
Ferry range	7350	km
Maximum fuel range	7080	km

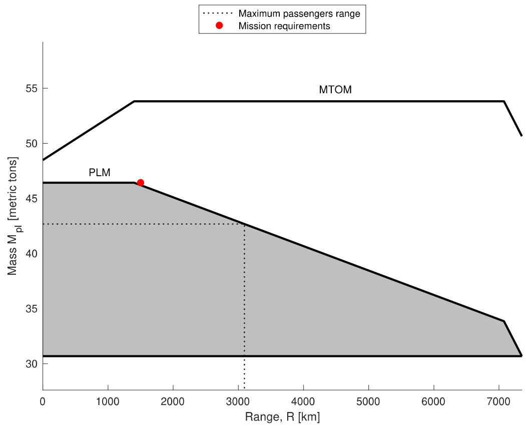


Figure 3: Payload-Range

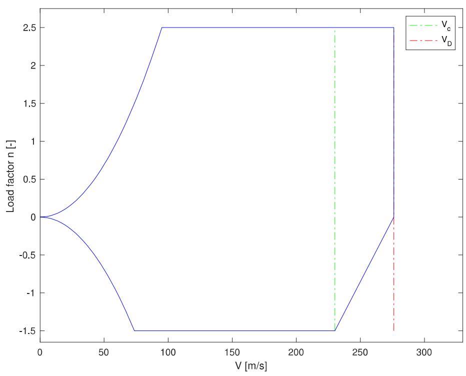


Figure 4: V-n diagram

3

4 Weight estimation

Table 3: Mass summary

Maximum take-off mass	53810	kg
Operational empty mass	30680	kg
Design landing mass	48230	kg
Maximum landing mass	50860	kg
Maximum ramp mass	54910	kg
Maximum fuel mass (ferry)	19970	kg
Harmonic range mission:		
Payload mass	15750	kg
Total fuel mass	7380	kg
Design mission:		
Payload mass	15750	kg
Total fuel mass	7640	kg
Reserve fuel mass	2060	kg

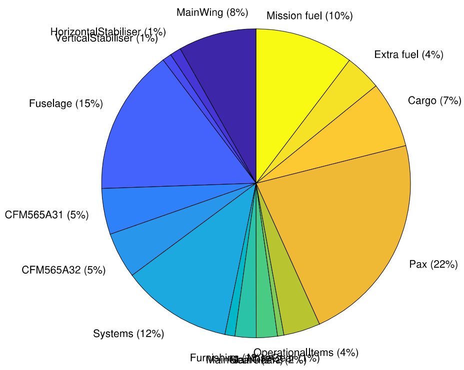


Figure 5: Mass distribution

Table 4: Component masses

CFM565A31	2118	kg
CFM565A32	2118	kg
Furnishing	571	kg
Fuselage	8249	kg
Horizontal Stabiliser	618	kg
Main Gear1	1194	kg
Main Gear2	1194	kg
Main Wing	4421	kg
Nose Gear	353	kg
Vertical Stabiliser	522	kg
SUM1	21358	Kg
APU	1837	kg
Air Conditioning	1025	kg
Anti Ice	108	kg
Avionics	766	kg
Electrical	400	kg
Flight Controls	248	kg
Fuel System	112	kg
Handling Gear	16	kg
Hydraulics	1648	kg
Instruments	106	kg
SUM2	27624	Kg
Cabin Supplies	953	kg
Crew Provisions	390	kg
Residual Fuel	128	kg
Safety Equipment	510	kg
Water Toilet Chemicals	102	kg
SUM	29707	Kg

Table 5: Centre-of-gravity locations

X_{cg} (MTOM)	15.8	m
X_{cg} (OEM)	16.5	m
X_{cg} (ZFM)	15.9	m
X_{np}	18.5	m
SM	61	%

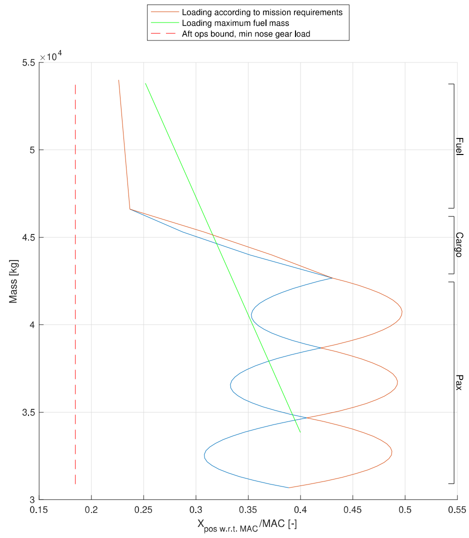


Figure 6: Loading diagram

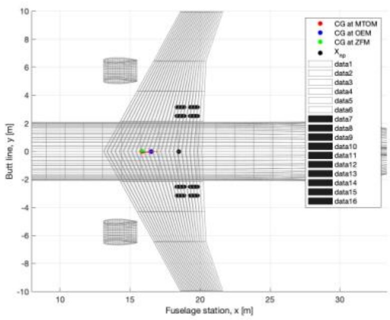


Figure 7: CG location

6

5 Aerodynamics

Table 6: Aerodynamic properties at cruise

$C_{L,\text{cruise}}$	0.45	-
$C_{D,\text{cruise}}$	299	cts
L/D_{cruise}	15.1	-
C_{D_0} (Clean)	217	cts
C_{D_0} (Take-Off)	562	cts
C_{D_0} (Landing)	1062	cts
Oswald factor (e) (Clean)	0.847	-
Oswald factor (e) (Take-Off)	0.897	-
Oswald factor (e) (Landing)	0.947	-
C_{L_α}	5.3	rad^{-1}
C_{m_α}	-3.21	rad^{-1}
$C_{L_{\text{max,clean}}}$	1.89	-
$C_{L_{\text{max,take-off}}}$	2.56	-
$C_{L_{\text{max,landing}}}$	3	-

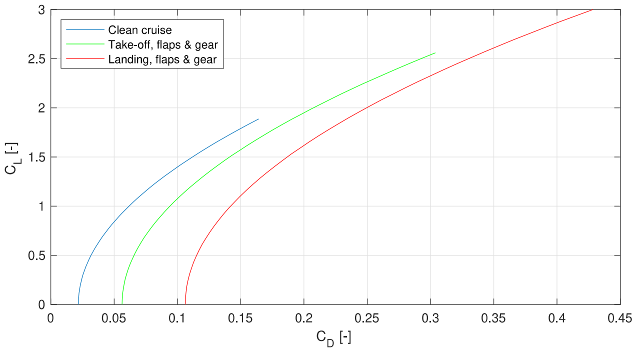


Figure 8: Drag Polars

7

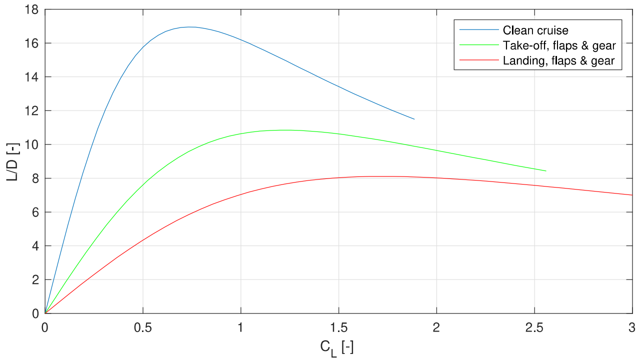


Figure 9: Aerodynamic efficiency of the aircraft

6 Propulsion

Table 7: Propulsion

Number of engines	2	-
SFC_{cruise}	0.6	h^{-1}
Bypass Ratio	6	-
Diameter	1.83	m
Length	2.42	m

7 Aircraft Geometry

Table 8: Main Wing dimensions

Span	33.9	m
Planform area	126.5	m^2
MAC	4.35	m
Root Chord	5.81	m
Root t/c	0.16	-
Tip Chord	1.65	m
Tip t/c	0.1	-
Sections (root to tip)	SC20614, SC20612, SC20610	
Sweep 0.25c	24.9	°
Taper ratio	0.284	-
Twist	1.6	°
Dihedral	5.1	°

Table 9: Horizontal Stabiliser dimensions

Span	12.4	m
Planform area	32.23	m^2
MAC	2.93	m
Root Chord	4.11	m
Root t/c	0.1	-
Tip Chord	1.07	m
Tip t/c	0.1	-
Sections (root to tip)	N0010, N0010	
Sweep 0.25c	29	°
Taper ratio	0.26	-
Twist	0	°
Dihedral	8	°

Table 10: Vertical Stabiliser dimensions

Span	6.26	m
Planform area	23.5	m^2
MAC	4.16	m
Root Chord	5.74	m
Root t/c	0.1	-
Tip Chord	1.77	m
Tip t/c	0.1	-
Sections (root to tip)	N0010, N0010	
Sweep 0.25c	34	°
Taper ratio	0.308	-
Twist	0	°
Dihedral	0	°

Table 11: Fuselage dimensions

Length	37.6	m
Floor Position	-54	% of fuselage height
Diameter	4.14	m
Nose Fineness Ratio	0.18	-
Aft Fineness Ratio	0.55	-
Cabin Height	1.4	m
Nose Length	4.41	m
Aft Cutoff	0.8	-
Aft Ratio	0.05	-

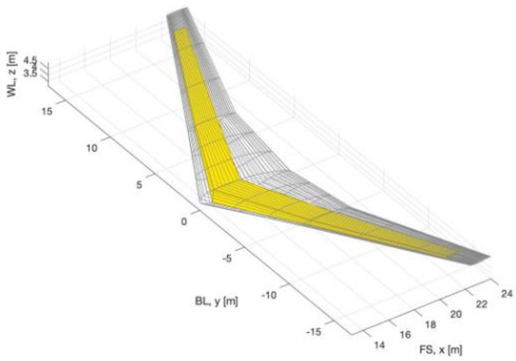


Figure 10: Fuel tank layout

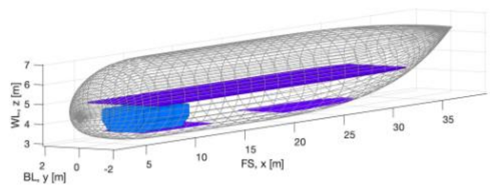


Figure 11: Fuselage geometry; (blue = cargo ULDs, purple = floors,yellow = LNG tanks)

8 Mission analysis estimation

Table 12: Emission results

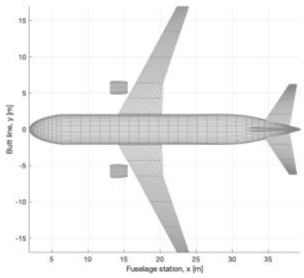
CO_2	14697.8052	Kg
H_2O	1165.9282	Kg
NO_x	2514.3527	Kg
DOC	25.0609	US dollars/nm

Appendix J
A320-LNG-Aft results

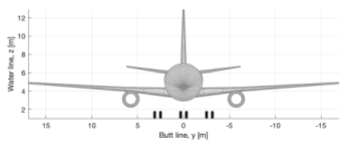
A320-200-GEOM-mod-LNG-F-AFT-Report

Initiator version 2.6

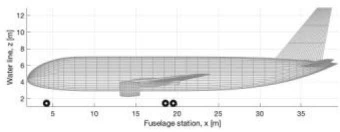
September 13, 2019



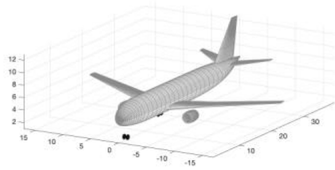
(a) Top view



(b) Front view



(c) Side view



(d) 3D view

Figure 1: Aircraft geometry (all dimensions in meters)

1 General Characteristics

Aircraft "A320-200-GEOM-mod-LNG-F-AFT-Report" generated by the Initiator version 2.6. The aircraft is a conventional aircraft with a wing aspect ratio of 9.39. The aircraft is designed to transport 150 passengers with a total payload mass of 15750kg over 1500km.

1

2 Specification

Table 1: Design

Pax	150	-
Range	1500	km
Cruise Mach	0.78	-
Altitude	11278	m
Take Off Distance	2180	m
Landing Distance	1440	m
Payload Mass	15750	kg

3 Operational Performance

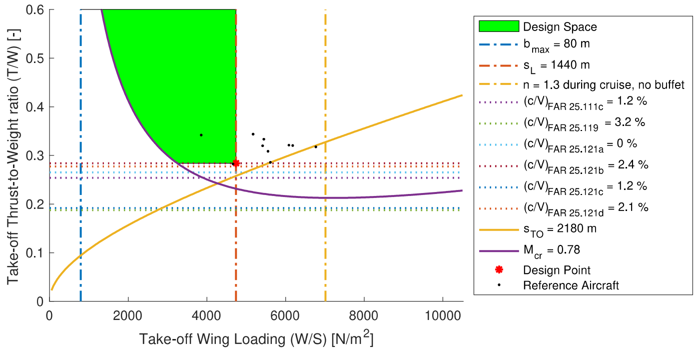


Figure 2: Loading Diagram

Result: Wing loading at MTOM: 4741 N/m^2
Thrust-to-weight ratio: 0.284 -

Table 2: Performance results

L/D_{cruise}	15.1	-
Cruise altitude	11278	m
Harmonic range	1330	km
Ferry range	3830	km
Maximum fuel range	3160	km

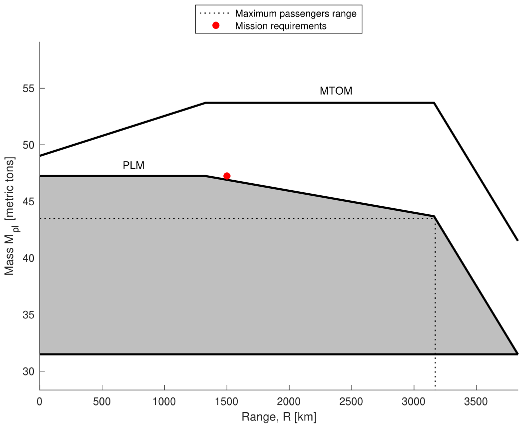


Figure 3: Payload-Range

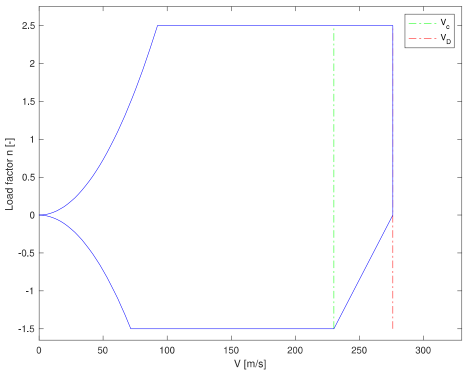


Figure 4: V-n diagram

4 Weight estimation

Table 3: Mass summary

Maximum take-off mass	53710	kg
Operational empty mass	31490	kg
Design landing mass	48640	kg
Maximum landing mass	51130	kg
Maximum ramp mass	54800	kg
Maximum fuel mass (ferry)	10020	kg
Harmonic range mission:		
Payload mass	15750	kg
Total fuel mass	6460	kg
Design mission:		
Payload mass	15750	kg
Total fuel mass	6850	kg
Reserve fuel mass	1780	kg

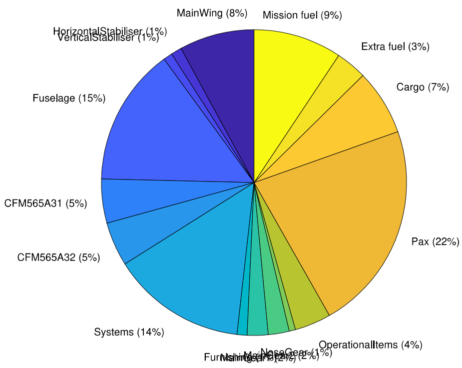


Figure 5: Mass distribution

Table 4: Component masses

CFM565A31	2044	kg
CFM565A32	2044	kg
Furnishing	571	kg
Fuselage	7881	kg
Horizontal Stabiliser	617	kg
Main Gear1	1203	kg
Main Gear2	1203	kg
Main Wing	4296	kg
Nose Gear	355	kg
Vertical Stabiliser	521	kg
SUM1	20735	Kg
APU	1837	kg
Air Conditioning	1025	kg
Anti Ice	107	kg
Avionics	766	kg
Electrical	400	kg
Flight Controls	248	kg
Fuel System	1570	kg
Handling Gear	16	kg
Hydraulics	1648	kg
Instruments	106	kg
SUM2	28458	Kg
Cabin Supplies	953	kg
Crew Provisions	390	kg
Residual Fuel	125	kg
Safety Equipment	510	kg
Water Toilet Chemicals	102	kg
SUM	30538	Kg

Table 5: Centre-of-gravity locations

X_{cg} (MTOM)	16.8	m
X_{cg} (OEM)	16.8	m
X_{cg} (ZFM)	16.1	m
X_{np}	18.5	m
SM	38	%

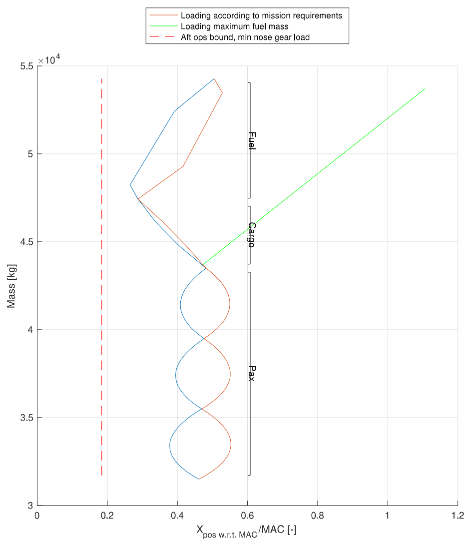


Figure 6: Loading diagram

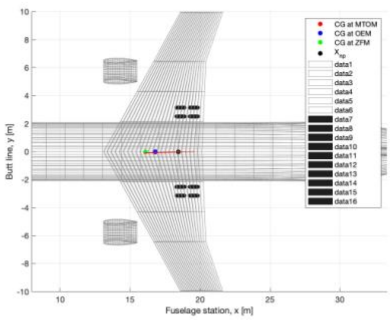


Figure 7: CG location

5 Aerodynamics

Table 6: Aerodynamic properties at cruise

$C_{L,\text{cruise}}$	0.45	-
$C_{D,\text{cruise}}$	298	cts
L/D_{cruise}	15.1	-
C_{D_0} (Clean)	218	cts
C_{D_0} (Take-Off)	563	cts
C_{D_0} (Landing)	1063	cts
Oswald factor (e) (Clean)	0.863	-
Oswald factor (e) (Take-Off)	0.913	-
Oswald factor (e) (Landing)	0.963	-
C_{L_α}	5.3	rad^{-1}
C_{m_α}	-2.03	rad^{-1}
$C_{L_{\text{max,clean}}}$	1.99	-
$C_{L_{\text{max,take-off}}}$	2.56	-
$C_{L_{\text{max,landing}}}$	3	-

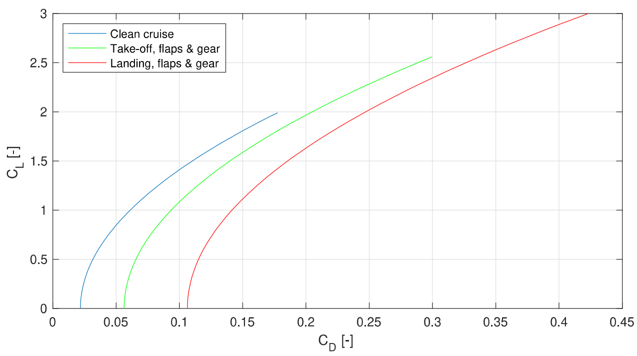


Figure 8: Drag Polars

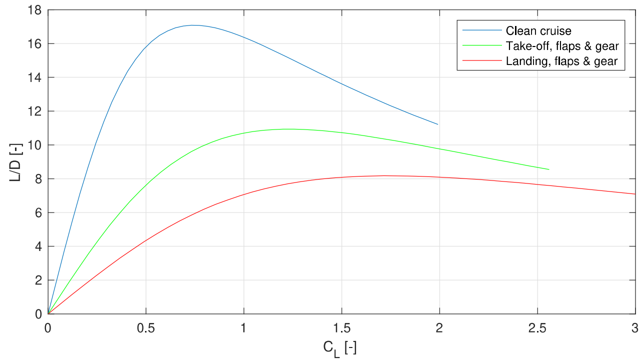


Figure 9: Aerodynamic efficiency of the aircraft

6 Propulsion

Table 7: Propulsion

Number of engines	2	-
SFC_{cruise}	0.516	h^{-1}
Bypass Ratio	6	-
Diameter	1.83	m
Length	2.42	m

7 Aircraft Geometry

Table 8: Main Wing dimensions

Span	33.9	m
Planform area	126.5	m^2
MAC	4.35	m
Root Chord	5.81	m
Root t/c	0.16	-
Tip Chord	1.65	m
Tip t/c	0.1	-
Sections (root to tip)	SC20614, SC20612, SC20610	
Sweep 0.25c	24.9	°
Taper ratio	0.284	-
Twist	1.6	°
Dihedral	5.1	°

Table 9: Horizontal Stabiliser dimensions

Span	12.4	m
Planform area	32.23	m^2
MAC	2.93	m
Root Chord	4.11	m
Root t/c	0.1	-
Tip Chord	1.07	m
Tip t/c	0.1	-
Sections (root to tip)	N0010, N0010	
Sweep 0.25c	29	°
Taper ratio	0.26	-
Twist	0	°
Dihedral	8	°

Table 10: Vertical Stabiliser dimensions

Span	6.26	m
Planform area	23.5	m^2
MAC	4.16	m
Root Chord	5.74	m
Root t/c	0.1	-
Tip Chord	1.77	m
Tip t/c	0.1	-
Sections (root to tip)	N0010, N0010	
Sweep 0.25c	34	°
Taper ratio	0.308	-
Twist	0	°
Dihedral	0	°

Table 11: Fuselage dimensions

Length	37.6	m
Floor Position	-54	% of fuselage height
Diameter	4.14	m
Nose Fineness Ratio	0.18	-
Aft Fineness Ratio	0.55	-
Cabin Height	1.4	m
Nose Length	4.41	m
Aft Cutoff	0.8	-
Aft Ratio	0.05	-

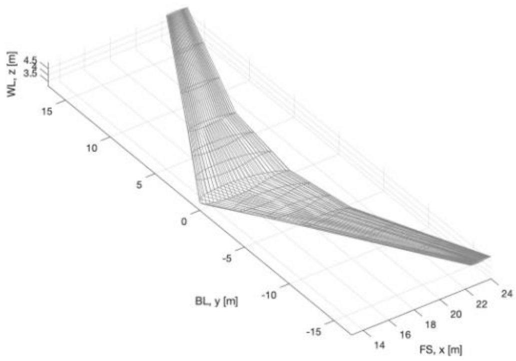


Figure 10: Fuel tank layout

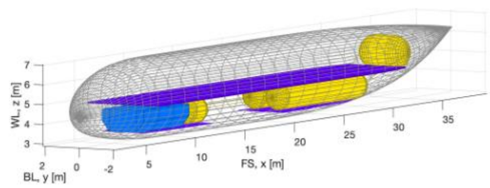


Figure 11: Fuselage geometry; (blue = cargo ULDs, purple = floors,yellow = LNG tanks)

8 Mission analysis estimation

Table 12: Emission results

CO_2	11177.464	Kg
H_2O	1720.4643	Kg
NO_x	783.1978	Kg
DOC	20.8396	US dollars/nm

Table 13: LNG Tank Properties

LNG tank	1384.0648	Kg
Front tank	227.3838	Kg
Rear tank	966.1523	Kg
Aft tank	190.5288	Kg
Total tank volume	23.9578	m3
Front tank volume	3.2364	m3
Rear tank volume	16.9628	m3
Aft tank volume	3.7585	m3
Tank Volume usable Fraction	0.99586	-
Boil-off rate	18.0198	Kg/hr
Mission Boil-off	41.6326	Kg
Ts in	111.8	K
Ts out	289.25	K
P due to 72h	0.97371	MPa
External tank radius	0.67	m
Internal tank radius	0.566	m
Front tank length	2.1932	m
Rear tank length	9.0126	m
External Aft tank radius	0.872	m
Internal Aft tank radius	0.768	m
Aft tank length	2.7484	m
Al-in thickness	0.002	m
Al-out thickness	0.002	m
Insulation thickness	0.1	m

Appendix K
Case study : Wizz Air

As a case study, the low cost airline Wizz Air is taken as example. Wizz Air has 68 Airbus A320-200 in service. Based on the flight data of 463 routes from [37], the table below summarize the ranges of how the aircraft is operated.

	Range (Km)
Minimum Range	401.9
Lower Quartile (25%)	1179.7
Median	1481.6
Upper Quartile (75%)	1929.8
Maximum Range	4626.3
Average Range	1601.5

So a Range of 1500 Km and 2000 is the most common range. Thus the LNG aircraft can operates on more than 75% of its current route.
Taking all the routes with less than 2000 Km, the number of routes is 359 , the average range is 1363 Km with 75% of the flight are less then 1677 Km.
So two configuration ,kerosene and LNG, were generated using the Initiator with a design range of 1363 Km (736nm) , the table below shows the potential cost and emissions reduction:

	A320-Kerosene	A320-LNG	Difference
Number of routes	359	359	0
DOC ($/nm)	25.4	21.12	-4.28
Total Operating Cost ($) = avg range(736nm) *DOC *number of routes	6711290	5580411	-1130879
CO_2 emissions (Kg) * 359 routes.	4870194	3700572	-1169622
NO_x emissions (Kg) * 359 routes = tonne	21576	6713	-14863
H_2O emissions (Kg) * 359 routes	1875201	3045218	1170017
Total emissions (CO_2 equivalent) (Kg) * 359 routes	6040246.8	4485381.9	-1554864.9

So for 359 routes, The company can save 1130879 $ per flight, by operating on LNG instead of Kerosene.
So the potential of savings is large, and it can easily overcome the price for retrofitting the aircraft to work on LNG. Adding to the cost savings is the significant reduction in CO_2 and NO_x emissions.
The A320-LNG reduces the CO_2 emissions by 1169.6 tonne, NO_x by 14.8 tonne, while producing 1170 tonne more H_2O.

In term of CO_2 equivalent, using LNG instead of kerosene will reduce emissions by 1554.8 tonne, for 359 routes per flight.