Quantified Interactive Morphological Matrix
An automated approach to aircraft fuel system synthesis

Carl Svahn
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1 Introduction

1.1 Background

1.1.1 Saab

Saab Aerosystems is a Swedish company with about 1900 employees that for 70 years have been making aircrafts for the Swedish airforce. Saab Aerosystems focus on system responsibility for the Gripen-aircraft, shared system responsibility for advanced unmanned aerial vehicles in international partnerships and sub-system deliveries for other air systems.

The military aircraft market of today is from a Swedish point of view more international than before. The Gripen has been sold to a few other countries and by some; Gripen is believed to be the last complete aircraft delivered only by Saab alone.

The same tendencies can be seen in the civil market where Saab for example manufactures a few parts for the Airbus A380.

1.1.2 Aircraft design rationalization

In today’s optimized and technologically advanced society the demands on aircrafts are similarly at a high level. Commercial aircraft design diversity has more or less leveled out which can be a sign of an already optimized shape. One way of making a civil airliner more efficient without changing its shape is to simply make it bigger, like the Airbus A380. The experimental days when aircraft still had fundamentally different designs and the design was driven by curiousness are over. What directs the civil technology forward today is to minimize the cost per transported passenger thru different ways, availability for example. Availability is the amount of time the aircraft is available when in service. If there is a malfunction during service that immobilizes the aircraft, passengers can not be transported as planned, which is very expensive. In this competitive market product development is as important as ever.

Also in the military industry the demands on a successful modern fighter aircraft are great and the cost of developing a new fighter aircraft capable of out performing other aircrafts on the market is huge and can in most cases not be covered by a single company or the government of a single country. In today’s political circumstances there is an opportunity for cooperation between certain groups of countries that gives the advantage of sharing the financial load of creating a new aircraft. There is of course money to be saved if the design process can be made more efficient.
Rationalization and automization of the design process, if possible, is a way of helping the engineer by simplifying the calculations and to partly calculate the most common measures of merit on which to evaluate the different concepts. The designer is then relieved of lots of hand made calculations and can with a smaller effort discard obviously bad or unsuitable concepts and concentrate on choosing the best solutions from the smorgasbord of remaining concepts more suitable for the design in question.

1.2 **Purpose**

The largest and most important fluid system in an aircraft is the fuel system. Obviously all aircraft projects involve the design of fuel systems to some degree.

The objective of this thesis is to try to rationalize the early fuel system concept generation process, the part where fuel system concepts are put together. The rationalization is an attempt to automize fundamental calculation steps done in almost every new fuel system concept study. The automization replaces the rough estimations otherwise done by an engineer at an early level. The use of an automated morphological matrix with its pick and choose characteristics is assumed to much quicker produce a fairly reliable basis for early concept screening than a series of unique calculations done by hand. If information can be acquired at a quicker rate, concepts with unsuitable properties or other unwanted flaws can easily be found and discarded early in the design process and time and money can be saved, maybe for later in the design process. This increases the probability of choosing the most successful solution.

1.3 **Task**

The task is to perform a rationalization of the morphological matrix in synthesis process. The rationalization will be realized by a partly automatized and quantified morphological matrix. Automization here means that certain predefined properties are automatically calculated for all concepts. Interactive stands for the possibility for the user to choose the concept that is to be summarized and presented by the matrix. This rationalizes the synthesis so that obviously bad concepts do not have to be generated.
1.4 Limitations

- This synthesis tool will be based on a fuel system model. As with all models they are imperfect images of reality. A model attempting to simulate a not yet designed fuel system may be even more inaccurate. Based on a combination of rules of thumb, available components properties and experience the results of this synthesis rationalization tool should be interpreted as guidelines and not established parameters for the fuel system about to be designed.

- The chosen areas in which to investigate the fuel system concepts are consumed electrical power (in a few cases pneumatical pressurization power), weight and reliability measured in MTBF. There are of course additional areas in which to evaluate the concepts but these three have been chosen and are possible to take into account within the limits of a masters thesis work.

- The quantified matrix will be implemented in the spreadsheet program MS Excel.

- This work will be done in the usual time period for a master thesis; 20 weeks.
2 The design process

There have been many attempts to draw up maps or models of the design process according to Nigel Cross[1] who continues: Some of these models simply describe the sequences of activities that typically occur in designing; other models attempt to prescribe a better or more appropriate pattern of activities.

An example of a descriptive design process is the basic design cycle from N.F.M. Roozenburg & J. Eekels[2].

A more prescriptive process is the one described by G. Pahl & W. Beitz [3].
Another process described in literature is the product development process suggested by Karl T. Ulrich & Steven D. Eppinger [4].

2.1 The concept phase

Most models, either descriptive or prescriptive, contain one concept phase. In this phase the first complete concepts for the product is created and one single concept or very few concepts are chosen for embodiment and realization. Because this thesis investigates rationalization of the concept generation it focuses on the concept phase and its synthesis part. For reading about other parts of the design process consider the references.

According to Karl T. Ulrich & Steven D. Eppinger [4] the concept phase may be divided into two principally different parts. These will now be described.
2.1.1 Synthesis

The first part is called concept generation or synthesis and means that concepts are put together or created. Here the number of concepts increase and the process can be called divergent.

2.1.2 Analysis

Analysis or concept selection is where the concepts are evaluated and selected. This procedure could be called convergent because the number of concepts is decreasing or converging. Here non compatible concepts and such concepts that are impossible or for some other reason not suitable are discarded. The concept selection can in turn be divided into two parts: screening and scoring.

2.1.2.1 Screening

The purpose of concept screening is to narrow the number of concepts quickly by rating them and discarding the worst. However according to Micael Derelöv [9] the solution space should not converge to quickly because potentially good solutions may be discarded, nor should it converge to slowly because it is a waste if resources. At the same time the concepts are screened much can be learnt about them which may help in the other part known as scoring.

2.1.2.2 Scoring

Scoring is a way of comparing the concepts with each other. They are ranked and one or a very few are selected as the best or most suitable.

Figure 4 – The concept phase according to Ulrich & Eppinger.
2.1.3 Decision making

In the analysis part of the design process decisions are taken about which concepts to keep and which to discard. According to Micael Derelöv [10] it takes more information to choose the best alternatives than it takes to discard the worst. Methods used for discarding alternatives (see Figure 5) based on less information are suitable in the beginning of the analysis process when the information might be scarce. Methods for choosing the best alternatives (see Figure 6) may be used later in the process when the knowledge about the product and the different concepts are greater and the alternatives are fewer.

![Figure 5 – Discarding the worst concepts](image)

![Figure 6 – Choosing the best concepts](image)

This automated morphological matrix is a tool of concept generation, or synthesis. However it contains analysis to a certain degree in the meaning that it indicates which concepts, which for any reason, are not suitable. This might be called a way of screening where the worst concepts are discarded.
2.1.4 The importance of the concept phase

A known phenomenon in technical development, according to D.G. Ullman [7], is that as the design process goes on, much is learned about the concept and its characteristics. But at the same time limitations are set for principal changes. This means that at an early stage when fundamental decisions are made they are based on less information than decisions with lesser significance made later in the process. This is visualized in the following figure.

G. Pahl & W. Beitz [3] state that “In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from concentration on technical detail”. In other words: the importance of the concept choice lies in the fact that it directs the design of the product in a bigger extent than any following singular detail decision.

According to M.P. Weiss and Y. Gilboa [8], “Conceptual design is considered as the most important step in the design of a new product. There the performance of the product is generated and about 75% of the life cycle cost (LCC) is committed.” Because the concept choice is of such great importance the design space should be thoroughly investigated before a decision is taken. If a thorough investigation in any way may be rationalized time can be saved and knowledge may be acquired at a quicker rate. This may positively affect the process described in Figure 7 by a quicker intake of information.

![Figure 7 – A design “paradox”](image)
2.1.5 Synthesis tools

The previously described first step in concept generation, synthesis, is the process of putting together concepts that later are to be evaluated in the analysis part. There are many ways of performing synthesis. One way is by using the FM tree and the morphological matrix.

2.1.5.1 FM tree

The idea of the FM tree is to divide the product that is to be designed into smaller parts. It’s a way of splitting up the big problem into smaller problems.

In the root of the FM tree there is a function describing the need that is to be fulfilled by the future product. This could for example be “Self propelled transport of one person on ground” for what is later decided to be designed as a bicycle or to “contain fluid” for what is to finally be a glass. This function is called the main function.

The next level of the FM tree is made up of all different kinds of solutions the designer can think of, fulfilling the main function. For the transportation example this could be rollerblades, a bike (leg propelled), a pogo-stick or a wheelchair (arm propelled).

The third level in the FM tree contains the sub functions to these solutions. The bike may have sub functions like admit propulsion, carry person, admit speed control and admit direction control.
The sub functions have solutions of their own, fulfilling their functionality. Solutions for the speed control sub function may be rim brakes, disc brakes or not speed control at all.

The tree grows like this with new levels if needed. Every “odd” level contains functions and every “even” level contain solutions. The name FM tree comes from the layers of functions and means.

2.1.5.2 Morphological matrix

The last sub functions and their solutions in the FM tree are the ones used to build up new concepts. In order for a complete concept to be created every sub function must have a solution. This can be visualized in a matrix where the sub functions make up a column and the solutions are lined as rows after each sub function.

<table>
<thead>
<tr>
<th>Sub functions</th>
<th>Sub solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admit propulsion</td>
<td>Drive shaft</td>
</tr>
<tr>
<td>Carry person</td>
<td>Saddle</td>
</tr>
<tr>
<td>Admit speed control</td>
<td>Rim brakes</td>
</tr>
<tr>
<td>Admit direction</td>
<td>Handle bar</td>
</tr>
</tbody>
</table>

Figure 9 – A morphological matrix for bikes with one marked concept

In the matrix a concept can be visualized by a line drawn from the top and down thru one cell in every row. This way every function in the concept is considered.

This matrix is called a morphological matrix. According to Nigel Cross [1] the word morphology means the study of form or shape. The word morphological in “morphological matrix” comes from the fact that it is here the concepts shape or form is studied.

The morphological matrix is a tool for creating order on the combinatorial explosion of functions and means from the FM tree. An advantage is that it takes every possible concept into account, in other words no valuable concepts are missed. A flaw on the other hand is that because every concept is included the matrix presents a large number of concepts to evaluate in the analysis step.
The morphological matrix above can generate $3 \times 3 \times 3 \times 3 = 81$ unique concepts, or 81 unique bikes. However by looking at the solutions it is obvious that some of them are quite worthless. For example the author of this thesis has decided he does not want to hang lifted by strings pedaling a belt driven bike with no steering and no brakes. This may be obvious in a simple case like this with a well known application, but for more complex systems with not so well known solutions it may not be that easy. This is an example of how valuable knowledge about the design problem is.

However considering another more unusual scenario the seemingly worthless concept might not be so worthless, the evaluation of the concepts is all up to the specification of the needs.
3 Aircraft fuel systems

In this chapter the different fuel system functions and there various solutions are explained. First the function is presented, followed by some possible solutions. In some cases pictures are added for simplification. For areas where the solutions are considerabely different, a table is shown that summarizes the virtues and flaws of the different solutions.

3.1 Engine feed

If the engine of a car breaks down the car just stops where it is and stays there until repaired or moved. If an aircraft engine starts to malfunction on a multiengine aircraft in most cases the plane can safely reach its target. However on a single engine aircraft an engine breakdown inevitably leads to emergency landing or crash. Therefore the fuel system in an aircraft is absolutely vital and the engines must be supplied with fuel at all times regardless of altitude, orientation, velocity or g-force.

A common way to solve this and other problems associated with aircraft fuel systems is to feed the engine from one single tank that is continuously receiving fuel from other tanks in order to keep it as full at possible. This tank is called the collector tank and can be designed in different ways to ensure continuous engine fuel supply in all flight modes. The pump that provides the engine with fuel from the collector tank is called the boost pump. The jet engine often has a high inlet pressure, especially compared to the pressure in the collector tank. This means that the boost pump often is vital.

3.1.1 Negative gravity tank

In order to feed the engine in negative gravity flight when the aircraft is flying upside down, a compartment called a negative gravity tank can be created in the bottom of the collector tank. This compartment is designed so that the boost pump inlet always will be under a fuel surface regardless of the orientation of the aircraft.

![Figure 10 – Schematic drawing of a negative gravity tank.](image-url)
3.1.2 **Negative gravity accumulator**

Another way of assuring continuous engine fuel feed is to put a fuel accumulator between the boost pump and the engine. When the collector tank no longer has any fuel to pump towards the engine the accumulator takes over and feeds the engine. When the boost pump hopefully kicks in again later on, the accumulator starts recharging.

![Figure 11 – Schematic drawing of a negative gravity accumulator.](image)

3.1.3 **HOPPER tank**

A third way of dealing with the problem of how to keep the boost pump inlet constantly under the fuel surface is the HOPPER tank. The principle is to have a smaller container in the tank only connected to the rest of the collector tank via non return valves or NRVs. They allow the fuel to flow into the smaller tank but not out of it. This way the inner tank called the HOPPER tank is always at least as full as the outer regular tank. This is a solution used in Saab 340.

![Figure 12 – The fuel system of the Saab 340 aircraft.](image)
To further make sure the HOPPER tank is constantly filled jet pumps can be mounted in addition to the NRVs. This forces fuel to flow into the tank with lesser regard to the remaining fuel amount or the aircrafts orientation. The Saab 2000 is equipped with such an engine feed system where the jet pumps are driven by the engine feed flow.

3.2 Fuel transfer

For space, slosh, safety and center of gravity or CG reasons the transfer tank is in many cases consisting of several tanks. Because the fuel may be a considerable part of the aircrafts take-off weight it affects the CG greatly. Therefore fuel can, in some aircrafts, be transferred between the transfer tanks in order to adjust the CG. This is the case in many modern fighter aircrafts. However this is not specifically taken into consideration in the calculation model.

Unlike the boost pump which often has a big pressure difference to counteract, the transfer pump might from time to time be superfluous. If the pressure difference, due to pressurization, of the tanks involved in a transfer case has a negative pressure difference (higher pressure in the giving tank and lower pressure in the receiving tank) the transfer may occur by itself. This assuming the negative pressure difference overcomes the pressure losses in the transfer system.
3.2.1 Distributed pumps

A fuel system where each tank has its own pump has a good resistance against cavitation. This is because cavitation in most cases first appears where the pressure is lowest. The principal in a system with distributed pumps is to push the fuel towards the other tanks and pressure losses in the pipes are compensated with higher pressure “after” the distributed pump. A drawback with distributed pumps is increased weight. Another is that the system becomes more complex.

3.2.2 Inline pump

An inline pump is situated outside the tanks and transfers fuel from multiple tanks. A result if this solution is that cavitation more easily occurs compared to a system of distributed pumps. Pressure losses in the transfer system have to be compensated by lowered pressure on the low-pressure side of the transfer pump.

3.2.3 Jet pump

A jet pump system could also be called a semi distributed system. The jet pumps themselves can be distributed anywhere in the aircraft, but in order to function; a high pressure drive flow is needed. This flow could be for example part of the engine feed. The drive flow is often produced in some sort of central pump, hence the expression semi distributed.

3.2.3.1 The jet pump principle

The drive flow, or primary flow, is lead thru a nozzle which increases the dynamic pressure and because of this, the static pressure decreases. The nozzle is surrounded by the secondary medium that is to be transferred to another tank. The lowered static pressure induces a flow in the secondary medium which is ejected along with the primary flow. The result is a mixture of the primary and the secondary medium.

The jet pumps biggest advantage is its simplicity and its biggest drawback is its poor efficiency.

In order to calculate the efficiency, a jet pump on the Gripen aircraft was modeled and analyzed and different flow cases investigated.
The jet pump principle is also applicable on air. An “air jet pump” is called an ejector.

![Figure 14 – Jet pump, schematic drawing and example of actual design.](image)

### 3.2.4 Gravity transfer

Fuel transfer by gravity is very simple and does not require either pump or pressurization of the tank. However transfer in negative or zero G is not possible. This does not only stop the aircraft from flying upside down but must also be taken into account during severe turbulence. Another limitation is that the collector tank has to be situated below the transfer tank in order for the fuel to flow the right way. Among many others the Saab 2000 aircraft can use gravity transfer thanks to the angle of the wings.

![Figure 15 – Gravity transfer on the Saab 2000 aircraft](image)

### 3.2.5 Siphoning

Siphoning means to achieve fuel transfer by pressure difference between tanks so that the fuel by itself flows from one tank to another. No specific fuel pump is required but certain demands are set on the pressurization system.
3.2.6 A summary of fuel transfer systems

Table 1 – Fuel transfer systems

<table>
<thead>
<tr>
<th>+</th>
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<tbody>
<tr>
<td>Cavitation resistance</td>
<td>Heavy</td>
</tr>
<tr>
<td>Redundant engine feed</td>
<td>Complex</td>
</tr>
<tr>
<td>Distributed pumps</td>
<td>Bulky</td>
</tr>
<tr>
<td>Inline pump</td>
<td>Cavitation risk</td>
</tr>
<tr>
<td>Compact</td>
<td>Complex</td>
</tr>
<tr>
<td>Redundant engine feed</td>
<td>Low efficiency</td>
</tr>
<tr>
<td>Compact</td>
<td>Needs primary flow</td>
</tr>
<tr>
<td>Jet pumps</td>
<td>No Zero G transfer</td>
</tr>
<tr>
<td>Simple</td>
<td>Light</td>
</tr>
<tr>
<td>Robust</td>
<td>Light pressurization system</td>
</tr>
<tr>
<td>Simple</td>
<td>Low energy consumption</td>
</tr>
<tr>
<td>Gravity transfer</td>
<td>Puts demands on pressurization</td>
</tr>
<tr>
<td>Simple</td>
<td>No cavitation</td>
</tr>
<tr>
<td>Light</td>
<td>Heavy structure</td>
</tr>
<tr>
<td>No cavitation</td>
<td>Light pressurization system</td>
</tr>
<tr>
<td>Gravity transfer</td>
<td>No Zero G transfer</td>
</tr>
<tr>
<td>Siphoning</td>
<td>Light pressurization system</td>
</tr>
<tr>
<td></td>
<td>Low energy consumption</td>
</tr>
</tbody>
</table>

3.3 Ventilation & Pressurization

3.3.1 Cavitation

A known problem in aircraft fuel systems is cavitation. According to Malin Åhman [14] Cavitation may occur when the pressure at any point in the fuel system decreases below the vaporization pressure for the fuel. Bubbles are then formed just as during boiling. The bubbles contain a certain overpressure which makes them survive the surrounding pressure. A common place for cavitation to occur is where the pressure usually is lowest; in the inlet of pumps. They travel thru the pump over to the high pressure side where they, if their own pressure is exceeded by the surrounding pressure, collapse and can cause damage to the fuel system, noise and reduced pump efficiency.

3.3.1.1 How to avoid cavitation

A way to avoid cavitation is to increase the pressure on the low pressure side of the pump, which in this case means the whole transfer tank has to be pressurized. Which in turn means the tanks has to be reinforced in order to withstand the increased pressure. However there also is an advantage with pressurizing the tank, the risk of spontaneous cavitation within the tank is decreased.
The dimensioning case for most pressurization systems is descent. When the aircraft dives or is losing altitude an increase in air density is experienced, which leads to increased atmospheric pressure. This pressure increase may, if it gets to big implode the tanks. At level flight the pressure difference change is usually smaller and at climb, air can if it is allowed by itself be vented out of the tanks.

The pressurization system can, as a fire precaution, be designed to pressurize the tanks with inert gas. However this increases the complexity of the system. Fire protection by inerting is discussed in chapter 3.5 Fire and explosion protection.

3.3.2 Closed pressurization system

A closed pressurization system is closed in the way that air cannot by itself flow in and out of the tanks. It has to be deliberately pumped by the pressurization system. A drawback with such a system is that a lot of air has to be pumped during ascent or climb. On the other hand, if a fire prevention system is used to control the quality of the air in the tank, a closed or partly closed system is more or less a necessity.

3.3.3 Ejector pressurization system

An ejector system could also be called a semi-closed system. It consists of some sort of pump, compressor or other form of pressure increasing device. The difference compared to a closed system is that the controlled airflow is not the only connection between the ullage and the environment. The pressurization air is injected into the tank as the primary flow in an ejector. This gives a possibility to increase the pressure at the same time as air can flow thru the pressurization system, should the pressure difference over the system become big enough. This has the positive side effect that when the surrounding air pressure is increasing rapidly, the controlled airflow does not have to compensate for the whole pressure difference. If a big pressure difference occurs it helps to increase the flow thru the ejector and can drastically decrease the load on the pressurization system which in turn can be made smaller and lighter. A drawback is that if the tanks are to be pressurized in level flight, the pressurization pump cannot be shut off as in a closed system.

3.3.4 Non pressurized system

A non pressurized system saves weight and complexity by the absence of a pressurization system and the lack of need for pressure reinforced tanks. The drawback is that is has no means to fight cavitation. Also siphoning can not be used as a transfer method because the tanks have no pressure difference to induce a flow of fuel.
3.3.5 A summary of pressurization systems

Table 2 – Pressurization systems

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low steady state outtake</td>
<td>Low maximum outtake</td>
</tr>
<tr>
<td>Closed system</td>
<td>Ejector</td>
</tr>
<tr>
<td>Light</td>
<td>Non pressurized</td>
</tr>
<tr>
<td>Simple</td>
<td>Cavitation risk</td>
</tr>
</tbody>
</table>

3.3.6 Pressure source

3.3.6.1 Bleed air

In order to achieve an increased pressure there has to be a pressure source present, some kind of compressor. As a matter of fact, all jet powered aircraft are equipped with powerful compressors in their engines. A way of pressurizing the tanks is to drain some of the pressurized air in the compressor stage of an engine and, after cooling or other treatment, let it in to the tanks in one way or another. The air drained from the engine is called bleed air. The bleed air often has a sufficient pressure regardless of flight mode but it may have to be decreased from the high levels in the engine to what is needed in the tanks. This means that a not negligible part of the engine power is diverted to tank pressurization or just lost in the pressure reducing stages the bleed air must pass on its way to the tanks.

3.3.6.2 Ram air

Because most aircraft (not helicopters) always has some speed in the air there is always a dynamic pressure on the outside of the aircraft that can be used to pressurize the tanks. The air let in from outside the aircraft is called Ram air. The ram air is not as “expensive” as the bleed air but may on the other hand not always have the required pressure.

3.3.6.3 Separate compressor

It is of course possible to use a separate compressor to produce pressurized air exclusively for tank pressurization, this way the power used for pressurization can be reduced to a minimum. But there is also extra weight added to the aircraft that can be considered as “expensive” in the same way that the other systems consume power.
3.4 Measurement

A problem with assessing the fuel amount in an aircraft is its changing orientation and velocity. The aircraft's freedom of movement in all three dimensions also gives freedom of movement for the load factor vector. In level flight and at constant speed the load factor vector points more or less straight down, towards the bottom of the aircraft. In inverted (up side down) static flight however, it points in the opposite direction. Because the fuel obeys the load factor vector it flows around in the tank and measures has to be taken in order to assess the correct amount of fuel regardless of the aircraft's orientation or acceleration. However, because most aircraft is flying in level flight most of the time, compromises can be done so that the measuring is limited to orientations around level flight, or in other words when the load factor vector is in the vicinity of the gravity vector. This way the fuel can still be measured most of the time and the measuring system can be drastically simplified. In order to still have a clue of how the fuel amount is changing outside the measuring interval, the flow rate of fuel to the engine can be measured and a theoretical remaining fuel amount can be calculated. When the aircraft returns into a state were the fuel amount in the tank can be correctly measured the theoretical amount is corrected and measurement is returned to the in-tank-sensors.

3.4.1 Level sensors

Level sensors are point shaped sensors that can detect if they are submerged in fuel or not.

3.4.2 Capacitive probes

The capacitive probes are rods that can detect the fuel surface along an interval. They can be mounted in any orientation in the tank and hence measure the fuel surface in any limited interval.

3.5 Refueling

3.5.1 Pressurized refueling

Pressurized refueling is the most common way of refueling large aircraft and fighters. The fuel system must be dimensioned to withstand the pressures associated with refueling and over fill, this may increase the structure weight. There is also a system of valves included in refueling that adds to the total weight.
3.5.2 Gravity refueling

Gravity refueling is performed in the same way as with most cars. Fuel is poured into the tanks and there is no pressurization involved, hence the tanks do not have to be reinforced with respect to over fill and the weight added to the fuel system is only that of the refueling valves.

3.5.3 AAR

Air to air refueling or AAR is performed in the air. A tanker aircraft provided with a drogue connects with the aircraft that is to be refueled and fuel is transferred under pressure.

The AAR refueling system weighs the same as a pressurized refueling system plus the weight of the tank probe. The probe may be retractable or rigid. Here only a retractable probe is modeled, based on the assumption that future aircrafts are designed with respect to lower radar emission.

There exist other systems of air to air refueling such as the USAF boom where the aircraft has no probe. Instead the tanker aircraft has a manually controlled rigid boom which is maneuvered to a refueling valve on the back of the aircraft.

3.6 Fire and explosion protection

There are many ways of preventing a fire or stopping an already occurring fire. One way of prevention is to remove one of the two necessary ingredients in an aircraft fuel fire, the lighting spark. According to an article in Aviation Week & space technology in July 1997 the Ignition energy needed to ignite most jet fuels is approximately 0.25 mJ in the right (or wrong) circumstances. However the minimum ignition energy varies with temperature, oxygen concentration, fuel/air mixture and pressure. This makes it almost impossible to give a single value for the minimum ignition energy. Still it is a very small amount of energy that easily could be induced in either the fuel distribution system or in the fuel. For comparison, according to the mentioned article, a spark generated from walking on a rug is 1-10 mJ or 4-40 times that minimum ignition value.

In most modern civilian aircraft, the fuel system is designed to reduce the risk of sparks by making sure potentials that could lead to sparks can not be induced, but complete protection against fires or explosions can not be ensured this way. Another precaution is to mix the fuel with conduction increasing additives in order to not induce potentials that could lead to dangerous sparks, but here as well the problem can not be completely eradicated.

The other ingredient in a fuel fire is the flammable fuel-air-mixture. If this gas somehow could be reduced or made less flammable, the risk of fire or explosion could be reduced. A way of making this mixture less flammable is to make it more inert.
3.6.1 Inerting

The two ingredients in the flammable ullage gas are fuel vapors and oxygen. If the air in the ullage can be replaced with nitrogen enriched air, or NEA, the oxygen amount decreases and the ullage gas becomes more inert. According to Marcus Schelin [13] the ullage is safe from sparks if the air in the tanks has an oxygen percentage less than 9%. NEA can be added to the fuel tanks from stored Nitrogen tanks on board the aircraft or it can be manufactured in what is called an OBIGGS.

3.6.2 OBIGGS

OBIGGS is an abbreviation for On Board Inert Gas Generating System. According to Marcus Schelin [13] An OBIGGS consists among other parts of some form of Air Separating Module (ASM) that separates the oxygen and the nitrogen in the air. The NEA or Nitrogen Enriched Air is pumped into the tanks in order to lower the oxygen level below 9%. An advantage in the OBIGGS is that it can produce almost unlimited amounts of NEA. However the rate at which NEA is produced is limited and may also be dependent on the pressure of the ram air which in turn, among other things, is dependent of the aircrafts velocity and current altitude.

3.6.3 Liquid Nitrogen

Liquid nitrogen is nitrogen stored in bottles on board the aircraft. When pumped into an environment with lower pressure it immediately transforms into gas phase. Liquid nitrogen does not only have the advantage of being inert, it is also very cold and can be used for cooling of for example avionics or the fuel. Because the fuels vaporization pressure is temperature dependent and decreases with lowered temperature, using cool inert gas also has a positive effect on cavitation. The flame point of the fuel is affected likewise. Liquid nitrogen systems do not have a critical flow limitation in the speed at which NEA can be produced but it can run out of nitrogen, which can also be critical.

3.6.4 SAFOM/quenching

There are also more passive methods of fire protection. A way of dampening the effect of an already occurring explosion is to try to level out the energy produced in the rapid combustion. The rapid increase in pressure can be lowered to a level the tank can withstand by filling the tank with a three dimensional lattice work that can remove energy from the combustion zone. The lattice work, or foam, is destroyed during the explosion but the tank can be saved from the immediate violent pressure wave. This solution can also be called quenching.
Advantages with this solution are that it is simple and totally passive. Its simplicity also gives higher reliability. Other advantages are that the foam actually helps to decrease slosh in the fuel tanks and vibrations in the adjacent structure. The foam can also help to reduce structural damage if the aircraft is hit by a ballistic projectile.

A rather paradoxical drawback however is that the foam itself can cause electrical discharges due to potentials built up in the foam structure. These electrical discharges can cause sparks which in turn causes an explosion which in turn is quenched by the SAFOM. This could be a risk especially with the high flow rates present during refueling. Another flaw is that the weight of SAFOM increases proportionally with the tank volume. Therefore SAFOM is not recommended in bigger aircraft. For example if the tanks of a Boeing 747 were to be filled with SAFOM, the extra weight would end up at about 8500 kg, which is very much. Because SAFOM is installed in the tanks there is also a loss of tank volume.

### 3.6.5 A summary of fire and explosion protection systems

Table 3 – Fire and explosion protection systems

<table>
<thead>
<tr>
<th></th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>High maximum NEA flow</td>
<td>Liquid Nitrogen</td>
<td>Limited amount of NEA</td>
</tr>
<tr>
<td>Unlimited amount of NEA</td>
<td>OBIGGS</td>
<td>Complex</td>
</tr>
<tr>
<td>Simple</td>
<td>SAFOM</td>
<td>Low maximum NEA flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uses tank volume</td>
</tr>
</tbody>
</table>
4 Fuel system modeling

4.1 Modeling

This is a model of a fuel system intended for use as a conceptual synthesis tool. As with all models this is an imperfect image of the real world. This tool is a way of modeling early concepts far from realization and production. It is meant to point out extreme properties of certain concepts and not as a tool to compare final products in order to find the best one.

If nothing else is mentioned in the text discussing the fuel system it currently concerns the model of the system and not the actual fuel system.

4.2 Measures of merit

The output of this tool is the complete weight, power consumption and MTBF of the aircraft fuel system. Of course values for these properties are also needed for the concerned parts, building up the system.

The choosing of these three properties is based on the fact that they are the simplest and most used values to base an evaluation on in the industry. Of course there are more properties on which to base an evaluation but they fall outside the limitations of this thesis due to reasons of complexity or extent.

When flight and environmental circumstances are added and concern is taken towards the parts interacting with each other the earlier mentioned results emerge and can be evaluated. Concepts with obviously bad values in either of those areas can be detected and excluded in an early stage in the design process. The concepts can also, to a certain degree, be evaluated against each other. Of course other additional outputs and hence inputs adds increasing precision to the method and the evaluation but they also bring greater complexity. If further investigation in certain concepts is needed and resources are at hand this tool can be extended further. Possible extensions in system properties could be, according to Hampus [5], number of components or component price.

4.2.1 Power

Engine feed, fuel transfer and tank pressurization consumes power. This power consumption must be assessed in order for the different concepts to be considered on this topic. When fuel is transported, the mass flow and the different tank pressures are used as inputs and the required power can this way be approximated. A part from pressurization the calculated power is the electrical power the different technical solutions consume.
4.2.2 MTBF & MTTF

For every function solution MTBF or Mean Time Between Failure has been estimated. MTBF is the time between failures for a system or a unit that can be repaired. Because MTBF is depending not only on the repaired product but also on the quality of the repair it is a statistically based quantity that gets more accurate as more and more repairs are made. The lambda values used for calculating MTBF is always predictions based on earlier experience. Also, Bo Bergman and Bengt Klevsjö [12] supports this by stating that the statistical characteristics of the time between failure may change over time when the unit or system as a whole ages.

MTTF or Mean Time To Failure is the time it takes for a non repairable unit or system to experience a failure. The part is then replaced with a new one. Since MTTF for a product depends only on the product itself it remains the same throughout the life cycle of the system it is a part of. MTTF is defined as a function of $\lambda$, which equals the mean number of failures in one million hours for the part.

In this synthesis rationalization a value is wanted that describes the failure characteristics of different concepts in a straight forward way. MTTF is by definition the correct value received by inverting a given $\lambda$ (See 4.2.2.1). However in the industry MTBF is the most common value associated with calculations concerning reliability. Many of the $\lambda$'s used in this thesis and at Saab are weighted mean values of $\lambda$ which in practicality gives a MTBF. Also, most of the $\lambda$ values in this model are concerning whole repairable systems that consist of separate parts. When such a system fails and a part is replaced, the system is repaired, not replaced. Hence the system has a MTBF that must be based on experience, which hopefully gets more and more accurate as the product is used.

However there is little meaning in a too detailed analysis of the failure characteristics of the product this early in the design process since the details and certain properties of the product is not stated until the detail design stage later in the design process. Also because only new fuel systems are investigated there are only predictions involved and no established
4.2.2.1 Definitions

R equals the reliability in a detail with \( \lambda \) failures/Mh during the time t.

Definition according to Bo Bergman and Bengt Klevsjö [12]

\[
R(\lambda, t) = e^{-\lambda t}
\]

Definition according to [12]

\[
MTTF = \int_{0}^{\infty} R(\lambda, t) dt = \int_{0}^{\infty} e^{-\lambda t} dt = \left[ \frac{e^{-\lambda t}}{-\lambda} \right]_{0}^{\infty} = \frac{e^{-\lambda \cdot 0}}{-\lambda} - \frac{1}{-\lambda}
\]

Equation (2) with the first term neglected because \( e^{-\infty} \to 0 \) becomes

\[
MTTF = \frac{1}{\lambda}
\]

The total MTTF for a composite detail consisting of n parts is the inverted sum of the parts \( \lambda \) values

\[
MTTF_{\text{Composite}} = \frac{1}{\sum_{i=1}^{n} \lambda_i}
\]

4.2.2.2 Conclusion regarding MTTF and MTBF

As discussed above in [4.2.2] the value chosen for indicating the life for the different systems and concepts is MTBF and it is calculated by inverting the value \( \lambda \) given for every parts of the system.

MTBF is calculated by

\[
MTBF = \frac{1}{\lambda}
\]

MTBF for a system or a composite detail consisting of n parts is the inverted sum of the parts \( \lambda \) values.

\[
MTBF_{\text{Composite}} = \frac{1}{\sum_{i=1}^{n} \lambda_i}
\]
4.3 Engine feed

4.3.1 Engine feed variables

These are the variables used for calculations concerning engine feed.

Table 4 – Engine feed system variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ct}$</td>
<td>Collector tank volume</td>
<td>Input</td>
<td>m3</td>
</tr>
<tr>
<td>$V_{ht}$</td>
<td>HOPPER tank volume</td>
<td>Input</td>
<td>m3</td>
</tr>
<tr>
<td>$V_{acc}$</td>
<td>Accumulator volume</td>
<td>Input</td>
<td>m3</td>
</tr>
<tr>
<td>$\Delta p_{cf}$</td>
<td>Pressure difference over engine feed system</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$\Delta p_{ct}$</td>
<td>Collector tank pressurization</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>$\Delta p_{bp}$</td>
<td>Boost pump pressurization</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>$P_{cf}$</td>
<td>Engine feed pressure</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>$\Delta p_f$</td>
<td>Pressure loss due to friction</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$\Delta p_{f,\text{low}}$</td>
<td>Pressure loss due to friction on the low pressure side of the boost pump</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{acc}$</td>
<td>Accumulator pressure</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{inlet}$</td>
<td>Pressure at inlet of transfer pump</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{R=0}$</td>
<td>Pressure at which cavitation is fully developed</td>
<td>17000</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{R=1}$</td>
<td>Pressure at which cavitation is starting to develop</td>
<td>70000</td>
<td>Pa</td>
</tr>
<tr>
<td>$\Delta p_{\text{Fuelhead}}$</td>
<td>Fuelhead pressure</td>
<td>10000</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{atm}$</td>
<td>Atmospheric pressure</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$p_{\text{Inlet}}$</td>
<td>Boost pump inlet pressure</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
<tr>
<td>$\lambda_{bp}$</td>
<td>Boost pump failure frequency</td>
<td>470 [15]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{nrv}$</td>
<td>NRV failure frequency</td>
<td>3 [15]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Value</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
<td>-------</td>
<td>--------------</td>
</tr>
<tr>
<td>(\lambda_{\text{acc}})</td>
<td>Accumulator failure frequency</td>
<td>18 [11]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>(\lambda_{\text{hjp}})</td>
<td>HOPPER tank jet pump failure frequency</td>
<td>5</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>(\dot{m}_{\text{ef}})</td>
<td>Engine feed mass flow rate</td>
<td>Input</td>
<td>kg/s</td>
</tr>
<tr>
<td>(V_{\text{ef}})</td>
<td>Engine feed volume flow rate</td>
<td>Calculated</td>
<td>m³/s</td>
</tr>
<tr>
<td>(v_{\text{ef}})</td>
<td>Engine feed flow rate</td>
<td>Input</td>
<td>m/s</td>
</tr>
<tr>
<td>(L_{\text{ef}})</td>
<td>Engine feed system pipe length</td>
<td>Input</td>
<td>m</td>
</tr>
<tr>
<td>(m_{\text{t}})</td>
<td>Specific tank weight</td>
<td>0.0002 [5]</td>
<td>kg/ m³·Pa</td>
</tr>
<tr>
<td>(m_{\text{bp}})</td>
<td>Specific boost pump weight</td>
<td>0.0043 9.1</td>
<td>kg/ W</td>
</tr>
<tr>
<td>(m_{\text{jph}})</td>
<td>HOPPER tank jet pump weight</td>
<td>0.2 MG37</td>
<td>kg</td>
</tr>
<tr>
<td>(m_{\text{nrvt}})</td>
<td>NRV weight</td>
<td>0.2 [17]</td>
<td>kg</td>
</tr>
<tr>
<td>(m_{\text{acc}})</td>
<td>Specific accumulator weight</td>
<td>0.0005</td>
<td>kg/ m³·Pa</td>
</tr>
<tr>
<td>(m_{\text{ef}})</td>
<td>Specific engine feed pipe weight</td>
<td>0.3 [6]</td>
<td>kg/ m</td>
</tr>
<tr>
<td>(\eta_{\text{bp}})</td>
<td>Boost pump efficiency</td>
<td>0.8 [15]</td>
<td></td>
</tr>
<tr>
<td>(n_{\text{nrvt}})</td>
<td>Number of NRV:s</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>(n_{\text{jph}})</td>
<td>Number of HOPPER tank jet pumps</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>(M_{\text{ht}})</td>
<td>HOPPER tank weight</td>
<td>5</td>
<td>kg</td>
</tr>
<tr>
<td>(M_{\text{nrvt}})</td>
<td>NRV weight</td>
<td>0.2 MG37</td>
<td>kg</td>
</tr>
<tr>
<td>(M_{\text{jph}})</td>
<td>HOPPER tank jet pump weight</td>
<td>0.2</td>
<td>kg</td>
</tr>
<tr>
<td>(M_{\text{i}}^{\text{bp}})</td>
<td>Initial boost pump structure weight</td>
<td>1.89 9.1</td>
<td>kg</td>
</tr>
<tr>
<td>(M_{\text{X}}^{\text{p}})</td>
<td>Pump weight for the chosen solution</td>
<td>Output</td>
<td>kg</td>
</tr>
<tr>
<td>(M_{\text{X}}^{\text{t}})</td>
<td>Tank weight for the chosen solution</td>
<td>Output</td>
<td>kg</td>
</tr>
<tr>
<td>(P_{\text{jph}})</td>
<td>Jet pump power loss (HOPPER)</td>
<td>100 [15]</td>
<td>W</td>
</tr>
<tr>
<td>(P_{\text{X}})</td>
<td>Required electrical power</td>
<td>Output</td>
<td>W</td>
</tr>
<tr>
<td>(c_{p}^{\text{ef}})</td>
<td>Cavitation propensity</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$\zeta_{ef}$</td>
<td>Loss factor for engine feed system</td>
<td>4 [15]</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>$\zeta_{Low,ef}$</td>
<td>Low pressure side loss factor for e.f. system</td>
<td>0.5 [15]</td>
<td></td>
</tr>
<tr>
<td>$\rho_{Fuel}$</td>
<td>Fuel density</td>
<td>800 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>$R_{ef}$</td>
<td>Reduction factor to simulate cavitation</td>
<td>Calculated</td>
<td></td>
</tr>
</tbody>
</table>

### 4.3.2 Common equations

Both the weight and power consumption of the engine feed system are calculated from the same basic equation, the power consumption of the boost pump. The power consumed by the boost pump is calculated by the mass flow rate requested by the jet engine in a given case, the pressure difference over the boost pump and a cavitation factor that simulates cavitation.

#### 4.3.2.1 Power

The peak fuel mass flow rate the fuel system and the boost pump have to deliver occurs at ground level. This is because of the air, and the fact that the density of the air and hence the density of the oxygen is as highest at the lowest possible altitude. Above this level the oxygen density of the air decreases and with it the usable fuel flow rate. However at higher altitudes the decreased pressure may induce cavitation in the fuel pumps which forces the pumps to work harder for the same amount of fuel. In certain cases a pump may be dimensioned by flight at higher altitudes, where the pump consumes more power for less fuel mass flow due to severe cavitation. Investigation of the worst case scenario is ensured by the calculation of the fuel mass flow rate at ground level and at altitude $z$. The highest one of these two are then inserted in the formulas to calculate pump weight and power consumption. The calculations are identical, except that cavitation is neglected at ground level. The two different calculations will not be presented separately in this description of the model.
The power consumption is calculated by

\[ P_{ef} = \frac{\dot{V}_{ef} \cdot \Delta P_{ef}}{R_{ef}} \]  

where

\[ \dot{V}_{ef} = \frac{\dot{m}_{ef}}{\rho_{Fuel}} \]

\[ \Delta P_{ef} = p_{ef} - \Delta p_{ct} - p_{atm} + \frac{\zeta_{ef} \cdot \rho_{Fuel} \cdot \dot{V}_{ef}^2}{2} - \frac{10000}{\Delta P_{fuelhead}} \]

\[ R_{ef} = \frac{\Delta p_{ct} + p_{atm} - \frac{\rho_{Fuel} \cdot \dot{V}_{ef}^2}{2} + \frac{\Delta P_{fuelhead}}{\Delta P_{fuelhead}} \cdot \frac{P_{atm}}{P_{fuelhead}}} {7000 - \frac{10000 - 17000}{P_{fuelhead} - P_{atm}}} \cdot \frac{1}{C_p^{\phi}} \]

The equation (10) for calculating the flow reduction factor \( r \) is based on Hampus Gavel [5]. The resulting \( r \)-value is used to reduce the flow rate in order to simulate cavitation. The square of the formula has been removed because validation showed that the resulting \( r \) was to radically affecting the flow rate. Another variable added to the cavitation simulation formula is the cavitation propensity \( c_p \). It is used to model different pump type’s propensity to cause cavitation.

### 4.3.2.2 Weight

The standard boost pump weight of an engine feed system is a derivate of the power consumption. A specific pump weight tells how large the boost pump has to be in order to deliver the demanded pump power. There is also an initial structure weight in the pump, present without regard to the power consumption. This could be called a minimum weight.

The basic pump weight of an engine feed system is calculated by

\[ M_{ef}^p = M_{bp}^p + P_{ef} \cdot m_{bp} \]

The basic tank weight is calculated with the size of the tank, the pressure the tank must withstand and a specific tank weight.
The basic tank weight of an engine feed system is calculated by

\[ M'_{ef} = L_{ef} \cdot m_{ef} + V_{ct} \cdot \Delta p_{ct} \cdot m_t \]

### 4.3.2.3 MTBF

MTBF is calculated by

\[ MTBF = \frac{1}{\lambda} \]

MTBF for a system or a composite detail consisting of n parts is the inverted sum of the parts \( \lambda \) values.

\[ MTBF_{Composite} = \frac{1}{\sum_{i=1}^{n} \lambda_i} \]

### 4.3.3 NGT/Negative gravity tank

#### 4.3.3.1 Power

The power consumption of a NGA engine feed system is calculated with the basic power equation with one exception, the efficiency of the boost pump, which makes the formula look like this.

\[ P_{ngt} = \frac{\dot{V}_{ef} \cdot \Delta p_{ef}}{R_{ef} \cdot \eta_{bp}} \]

#### 4.3.3.2 Weight

The pump weight of the NGT system is calculated with the basic weight equation based on the power consumption, an initial structure weight and a specific weight per power unit.

\[ M'_{ngt} = M'_{bp} + P_{ngt} \cdot m_{bp} \]

The weight of the collector tank is calculated with the basic formula for the collector tank weight.

\[ M'_{ngt} = L_{ef} \cdot m_{ef} + V_{ct} \cdot \Delta p_{ct} \cdot m_t \]
4.3.3.3 MTBF

The MTBF for the NGT engine feed system is calculated by.

\[
MTBF_{nrg} = \frac{1}{\lambda_{bp}}
\]

4.3.4 NGA/Negative gravity accumulator

4.3.4.1 Power

The electrical power consumption of the NGA engine feed system is calculated by

\[
P_{nga} = \frac{V_{ef} \cdot \Delta p_{ef}}{R_{ef} \cdot \eta_{bp}}
\]

It could be noted that the power for filling the accumulator is taken into account but does not affect the long term power consumption. This is because the power is recycled when the accumulator is used and the boost pump is not loaded.

4.3.4.2 Weight

The pump weight for the NGA engine feed system is calculated by.

\[
m_{nga}^p = m_{bp}^i + P_{nga} \cdot m_{bp}
\]

The tank weight for the NGA engine feed system is calculated by the mass of the collector tank and the accumulator like this.

\[
m_{nga}^t = L_{ef} \cdot m_{ef} + V_{ct} \cdot \Delta p_{ct} \cdot m_{ct} + V_{acc} \cdot p_{acc} \cdot m_{acc}
\]

4.3.4.3 MTBF

The MTBF for the NGA engine feed system is calculated by

\[
MTBF_{nga} = \frac{1}{\lambda_{bp} + \lambda_{acc}}
\]
4.3.5 HOPPER tank with NRV

4.3.5.1 Power
The electrical power consumption of the HOPPER tank/NRV engine feed system is calculated by

\[
P_{\text{hrv}} = \frac{\dot{V}_{\text{ef}} \cdot \Delta p_{\text{ef}}}{R_{\text{ef}} \cdot \eta_{\text{hp}}}
\]

4.3.5.2 Weight
The pump weight for the HOPPER tank/NRV engine feed system is calculated by

\[
M^p_{\text{hrv}} = M^i_{\text{hp}} + P_{\text{hrv}} \cdot m_{\text{hp}}
\]

The tank weight for the HOPPER tank/NRV engine feed system is calculated by

\[
M^i_{\text{hrv}} = L_{ef} \cdot m_{ef} + \dot{V}_{\text{et}} \cdot \Delta p_{\text{et}} \cdot m_t + M_{ht} + n_{\text{avv}} \cdot M_{avv}
\]

4.3.5.3 MTBF
The MTBF for the HOPPER tank/NRV engine feed system is calculated by

\[
MTBF_{\text{hrv}} = \frac{1}{\lambda_{\text{hp}} + n_{\text{avv}} \cdot \dot{\lambda}_{\text{avv}}}
\]

4.3.6 HOPPER-Tank with jet pumps

4.3.6.1 Power
The electrical power consumption of the HOPPER tank/Jet pump engine feed system is calculated with the basic power equation except that the boost pump is also loaded with the drive flow of the jet pumps. The total output power of the boost pump is divided by the efficiency of the boost pump in order to get the electrical power required to get the work done.

\[
P_{\text{hip}} = \frac{\dot{V}_{\text{ef}} \cdot \Delta p_{\text{ef}} + n_{\text{hip}} \cdot P_{\text{hip}}}{R_{\text{ef}} \cdot \eta_{\text{hp}}}
\]
4.3.6.2 Weight
The pump weight for the HOPPER tank/Jet pump engine feed system is calculated by.

\[
M_{hijp}^p = M_{hijp}^p + P_{hijp} \cdot m_{hijp} + n_{hijp} \cdot M_{hijp}
\]

The tank weight for the HOPPER tank/Jet pump engine feed system is calculated by.

\[
M_{hijp}^t = L_{ef} \cdot m_{ef} + V_{ct} \cdot p_{ct} \cdot m_{t} + M_{kt}
\]

4.3.6.3 MTBF
The MTBF for the HOPPER tank/Jet pump engine feed system is calculated by

\[
MTBF_{hijp} = \frac{1}{\lambda_{hijp} + n_{hijp} \cdot \lambda_{hijp}}
\]

4.4 Fuel transfer
Fuel transfer is actually separately calculated for three different parts of the fuel system in the aircraft at the same time. Fuselage tanks, wing tanks and drop tanks have been separated in order to give a more precise description of the fuel system to be investigated. However the calculations are the same for the different parts of the system and no discrimination will be done in this description. There will only be description of a general system.

4.4.1 Fuel transfer variables
Previously defined variables are colored grey.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{tt})</td>
<td>Fuel transfer tank volume</td>
<td>Input</td>
<td>m³</td>
</tr>
<tr>
<td>(\Delta p_t)</td>
<td>Fuel transfer tank pressurization</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>(\Delta p_f)</td>
<td>Pressure difference over transfer system</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>(\Delta p_{ct})</td>
<td>Collector tank pressurization</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>(\Delta p_f)</td>
<td>Pressure loss due to friction</td>
<td>Calculated</td>
<td>Pa</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p_{l_{\text{low}}}$</td>
<td>Pressure loss due to friction on the low pressure side of the transfer pump</td>
<td>Calculated Pa</td>
</tr>
<tr>
<td>$\Delta p_z$</td>
<td>Pressure loss due to difference in height</td>
<td>Calculated Pa</td>
</tr>
<tr>
<td>$p_{\text{Inlet}}$</td>
<td>Pressure at inlet of transfer pump</td>
<td>Calculated Pa</td>
</tr>
<tr>
<td>$p_{R=0}$</td>
<td>Pressure at which cavitation is fully developed</td>
<td>17000 Pa</td>
</tr>
<tr>
<td>$p_{R=1}$</td>
<td>Pressure at which cavitation is starting</td>
<td>70000 Pa</td>
</tr>
<tr>
<td>$p_{\text{aim}}$</td>
<td>Atmospheric pressure</td>
<td>Calculated Pa</td>
</tr>
<tr>
<td>$\lambda_{fp}$</td>
<td>Fuel transfer pump failure frequency</td>
<td>75 [15] failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{jp}$</td>
<td>Jet pump failure frequency</td>
<td>5 [15] failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{tv}$</td>
<td>Transfer valve failure frequency</td>
<td>10 [15] failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{itp}$</td>
<td>Inline pump failure frequency</td>
<td>100 [15] failures/Mh</td>
</tr>
<tr>
<td>$m_{fi}$</td>
<td>Fuel transfer mass flow rate</td>
<td>Input kg/s</td>
</tr>
<tr>
<td>$V_{fi}$</td>
<td>Fuel transfer volume flow rate</td>
<td>Calculated m³/s</td>
</tr>
<tr>
<td>$v_{fi}$</td>
<td>Fuel flow rate</td>
<td>Input m/s</td>
</tr>
<tr>
<td>$L_{ft}$</td>
<td>Fuel transfer system pipe length</td>
<td>Input</td>
</tr>
<tr>
<td>$m_{ft}$</td>
<td>Fuel transfer system pipe length density</td>
<td>Input</td>
</tr>
<tr>
<td>$m_t$</td>
<td>Specific tank weight</td>
<td>0.0002 [5] kg/ m³·Pa</td>
</tr>
<tr>
<td>$m_{tp}$</td>
<td>Specific transfer pump weight</td>
<td>0.0069 kg/ W</td>
</tr>
<tr>
<td>$m_{jp}$</td>
<td>Jet pump weight</td>
<td>0.2 [15] kg</td>
</tr>
<tr>
<td>$n_{dp}$</td>
<td>Number of distributed fuel transfer pumps</td>
<td>Input</td>
</tr>
<tr>
<td>$n_{jp}$</td>
<td>Number of fuel transfer jet pumps</td>
<td>Input</td>
</tr>
<tr>
<td>$\eta_{tp}$</td>
<td>Fuel transfer pump efficiency</td>
<td>0.6 [15]</td>
</tr>
<tr>
<td>$\eta_{jp}$</td>
<td>Jet pump efficiency</td>
<td>0.23</td>
</tr>
<tr>
<td>$\eta_{bp}$</td>
<td>Boost pump efficiency</td>
<td>0.8 [15]</td>
</tr>
<tr>
<td>$M_X^p$</td>
<td>Pump weight for the chosen solution</td>
<td>Output kg</td>
</tr>
</tbody>
</table>
### 4.4.2 Common equations

Fuel transfer modeling is initiated the same way as engine feed, with the power necessary to fulfill the demands set by the system parameters. A difference compared to the engine feed system is that transfer might be achieved by siphoning, which set certain demands on the pressurization system.

There might also be a noticeable difference in height between the inlet of the transfer pipe in the transfer tank and the outlet of the transfer pipe in the collector tank. When the transfer system is exposed to greater levels of gravity this difference in height may drastically affect the power needed for transfer to take place and hence the size of the transfer pump or transfer pumps.
4.4.2.1 Power

The power is calculated by

\[ P_\beta = \frac{\dot{V}_\beta \cdot \Delta p_{\beta}}{R_\beta} \]  

(31)

(32)

where

\[ \dot{V}_\beta = \frac{m_\beta}{\rho_{Fuel}} \]  

(33)

\[ \Delta p_{\beta} = \Delta p_{ct} - \Delta p_a + \zeta \cdot \rho_{Fuel} \cdot v_{\beta}^2 \cdot \frac{1}{2} + \rho_{Fuel} \cdot 9.82 \cdot N_z \cdot z_{\beta} \]  

(34)

\[ R_\beta = \frac{\Delta p_a + p_{atm} - c^{Low}_{\beta} \cdot \rho_{Fuel} \cdot v_{\beta}^2 \cdot \frac{1}{2} - 1700}{7000 - 1700} \cdot \frac{1}{c_p^\beta} \]  

(35)

4.4.2.2 Weight

The pump weight is calculated by

\[ M_\beta = P_\beta \cdot m_p \]  

(36)

Because there are often more than one transfer tank the tank weight is calculated by

\[ M'_t = L_t \cdot m_t + \sum V_a \cdot \Delta p_a \cdot m_t \]  

(37)

4.4.2.3 MTBF

MTBF for a system or a composite detail consisting of n parts is the inverted sum of the parts \( \lambda \) values.

\[ MTBF_{Composite} = \frac{1}{\sum \lambda_i} \]  

(38)
4.4.3 Distributed pump

4.4.3.1 Power
The electrical power consumption of the distributed pump transfer system if calculated by

\[ P_{\text{Distributed}} = \frac{\dot{V}_\beta \cdot \Delta p_\beta}{R_\beta \cdot \eta_\beta} \]  (39)

4.4.3.2 Weight
The pump weight of the distributed pump transfer system is calculated by.

\[ M_{\text{Distributed}} = P_{\text{Distributed}} \cdot m_\beta \]  (40)

The tank weight of the distributed pump transfer system is calculated by.

\[ M_{\text{Distributed}}' = L_\beta \cdot m_\beta + \sum V_n \cdot p_n \cdot m_i \]  (41)

4.4.3.3 MTBF
The MTBF for the distributed pump transfer system is calculated by.

\[ MTBF_{\text{Distributed}} = \frac{1}{n_\beta \cdot \lambda_{\text{op}} + \lambda_{\text{pv}}} \]  (42)

4.4.4 Inline pump

4.4.4.1 Power
The electrical power consumption of the inline pump transfer system if calculated by

\[ P_{\text{Inline}} = \frac{\dot{V}_\beta \cdot \Delta p_\beta}{R_\beta \cdot \eta_\beta} \]  (43)

4.4.4.2 Weight
The pump weight of the inline pump transfer system is calculated by.

\[ M_{\text{Inline}} = P_{\text{Inline}} \cdot m_\beta \]  (44)
The tank weight of the inline pump transfer system is calculated by.

\[ M_{\text{Inline}}^t = L_{\beta} \cdot m_{\beta} + \sum V_n \cdot p_n \cdot m_i \]  

4.4.4.3 MTBF

The MTBF for the inline pump transfer system is calculated by.

\[ MTBF_{\text{Inline}} = \frac{1}{\lambda_{\text{ip}} + \lambda_{\text{rv}}} \]

4.4.5 Jet pump

Fuel transfer by jet pumps is executed by the jet pumps but driven by a high pressure flow from another pump. An idea could be to run the jet pump with the flow from the boost pump since it already exists and probably can produce enough high pressure flow. However if the boost pump is used for operating the jet pumps at the same time as the pilot gives full thrust it must be enlarged in order to withstand the additional load of the jet pumps.

4.4.5.1 Power

Because the jet pumps are driven by the boost pump the electrical power consumption of the fuel transfer system is calculated by

\[ P_{\text{Jet}} = \frac{\dot{V}_R \cdot \Delta p_R}{R_{\beta} \cdot \eta_{\text{ep}} \cdot \eta_{\text{jp}}} \]

Note that this is the load on the boost pump; the transfer system in itself does not consume any electrical power since the jet pumps are driven by the boost pump.

4.4.5.2 Weight

The pump weight of the jet pump fuel transfer system is calculated by.

\[ M_{\text{Jet}}^p = \frac{\dot{V}_R \cdot \Delta p_R \cdot m_{\text{bp}}}{R_{\beta} \cdot \eta_{\text{ep}}} + \frac{n_{\text{jp}} \cdot m_{\text{jp}}}{\text{Fuel transfer system weight}} \]

The tank weight of the jet pump fuel transfer system is calculated by.

\[ M_{\text{Jet}}^t = L_{\beta} \cdot m_{\beta} + \sum V_n \cdot p_n \cdot m_i \]
4.4.5.3 MTBF
The MTBF for the jet pump fuel transfer system is calculated by.

\[ MTBF_{inline} = \frac{1}{n_{jp} \cdot \lambda_{jp} + \lambda_{re}} \]  

4.4.6 Gravity
Since gravity transfer does not require any pressurization or any pump there is no increase in weight and no power consumption.

4.4.6.1 MTBF
The effect on the total MTBF from a gravity driven transfer system with no moving parts and no electronics in a concept study like this is assumed to be negligible.

\[ MTBF_{Gravity} = 1 \]

4.5 Ventilation and pressurization
The pressurization power is a bit hard to model because of a few reasons. The semi-closed or ejector system could be called indirect. The tanks are pressurized partly by an air flow from the surrounding air and partly by a controlled pressurization-air-flow that is also inducing a flow from the surrounding air. This makes it hard to approximate how much power that is needed from the pressurization system and how much that comes from the naturally varying pressure surrounding the aircraft. (This is discussed in Appendix 9.5) On top of this, RAM air, or in this case bleed air, is often used for pressurization because it is an existing air flow with high pressure. Hence there is no electrical power involved which is the case in the other parts of the fuel system. However the bleed air may vary in pressure and flow rate depending on flight mode, thrust setting and air properties. However in this thesis the pressure and flow rate of the bleed air is assumed to be sufficient and the power loss due to the air bleeding from the engine is left out of the model.

The required electrical power used as measure of merit in earlier function solutions is here replaced by the pressurization air mass flow rate. This is because of the dynamic nature of the pressurization which makes it hard to model and the

In this concept synthesis tool the pressurization modeling is, due to reasons of extent, restricted to bleed air pressurization.
### 4.5.1 Variables

Table 6 – Pressurization system variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{pv}$</td>
<td>Pressure valve failure frequency</td>
<td>3,5 [15]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{ep}$</td>
<td>Ejector pump failure frequency</td>
<td>2 [15]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{cu}$</td>
<td>Control unit failure frequency</td>
<td>4200 [15]</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\dot{z}$</td>
<td>Descent rate</td>
<td>Input</td>
<td>m/s</td>
</tr>
<tr>
<td>z</td>
<td>Altitude</td>
<td>Input</td>
<td>m</td>
</tr>
<tr>
<td>r</td>
<td>Ejector</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$L_{pm}$</td>
<td>Pressurization system pipe length</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$m_{pm}$</td>
<td>Pressurization system pipe length density</td>
<td>0,3 [6]</td>
<td></td>
</tr>
<tr>
<td>$m_E$</td>
<td>Ejector pump weight</td>
<td>0,2 [15]</td>
<td>kg</td>
</tr>
<tr>
<td>$m_V$</td>
<td>Specific pressurization valve weight</td>
<td>0,4 [15]</td>
<td>kg/m3</td>
</tr>
<tr>
<td>$M_{pv}$</td>
<td>Pressurization valve weight</td>
<td>Output</td>
<td>kg</td>
</tr>
<tr>
<td>$M_{ej}$</td>
<td>Ejector pump weight</td>
<td>Output</td>
<td>kg</td>
</tr>
<tr>
<td>$V_{tt}$</td>
<td>Transfer tank volume</td>
<td>Input</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$V_{ct}$</td>
<td>Collector tank volume</td>
<td>Input</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\rho_{Air}$</td>
<td>Air density</td>
<td>Calculated</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$m^{\text{Dive}}$</td>
<td>pressurization flow rate at descent</td>
<td>Output</td>
<td>kg/s</td>
</tr>
<tr>
<td>$m^{\text{Level flight}}$</td>
<td>pressurization flow rate at level flight</td>
<td>Output</td>
<td>kg/s</td>
</tr>
<tr>
<td>$M_X$</td>
<td>weight for a specific solution</td>
<td>Output</td>
<td>kg</td>
</tr>
<tr>
<td>$r_{ej}$</td>
<td>Air flow ratio in ejector pump</td>
<td>Calculated</td>
<td></td>
</tr>
</tbody>
</table>
4.5.2 Closed system

4.5.2.1 Mass flow rate

A closed pressurization system has only to compensate for the decrease of pressure caused by the fuel volume flow out of the fuel system created by engine feed. This pressure difference is assumed to be relatively small and fall within the margin of error in this model. Volume differences coming from fuel transfer between tanks does not affect the pressurization system as a whole.

\[
\dot{m}_{\text{Closed system}}^{\text{Level flight}} = 0
\]

At dive however a closed pressurization system has to generate the amount of air that is needed to keep the pressure in the tank at the same level, regardless of the surrounding atmospheric pressure changes. According to Hampus Gavel [5] the airflow needed to maintain the pressure in the tank during dive can be approximate with this formula.

\[
\dot{V} = V \cdot \frac{\dot{z}}{10000}
\]

According to Hans Ellström [18] the number 10000 is an approximation of a quote

\[
10000 \approx \frac{P_{\text{atm}}}{\frac{\partial P_{\text{atm}}}{\partial z}}
\]

Which it if is actually calculated contributes to the formula for pressurization mass flow rate at dive like this

\[
\dot{m}_{\text{Closed system}}^{\text{Dive}} = \frac{V \cdot \dot{z}}{P_{\text{atm}}} \cdot \rho_{\text{Air}}
\]

The use of the formula for pressurization air volume flow rate is discussed in Chapter 9.4.

4.5.2.2 Weight

\[
M_{\text{Closed system}} = L_{\text{pn}} \cdot m_{\text{pn}} + M_{\text{pv}}
\]

4.5.2.3 MTBF

The complete MTBF for a pressurization system is calculated with a \( \lambda \) contribution from the air flow control unit as a part of the system.

\[
MTBF_{\text{Inline}} = \frac{1}{\lambda_{\text{pv}} + \lambda_{\text{cu}}}
\]
4.5.3 Ejector system or semi closed system

4.5.3.1 Mass flow rate

In an ejector system where the pressure in the tank has to be constantly maintained by an air flow there is, at level flight, an equilibrium when no air is going in or out of the tank. This creates a balance of force in the mixture pipe of the ejector which can be described by this equation. The air mass flow rate and the velocity of the air flow creates a force equal to the one created by the area of the pressurization pipe and the pressure difference over the area. Hence the pressurization air mass flow rate is calculated by.

\[
\dot{m}_{\text{Level flight}}^{\text{Ejector system}} = \frac{a_{\text{Pipe}} \cdot \Delta p_{\text{Pressurization}}}{v_{\text{Sound}}}
\]

Where the pressurization pipe area

\[
a_{\text{Pipe}} = \sqrt{\frac{m_{\text{Pipe}}^2 \cdot \zeta_{\text{Pipe}}}{2 \cdot \rho_{\text{Air}} \cdot \Delta p_{\text{neg}}}}
\]

is the dimension of the pressurization pipe based on how much negative pressure the tanks can withstand during dive if the pressurization system brakes down. If there is no pressurizing air flow present the flow pipes must be wide enough to let air flow into the tank with no greater pressure difference than \(\Delta p_{\text{neg}}\) which is the limit for how much negative pressure the tanks can withstand at given dive rate.

The controlled mass flow rate thru the ejector at dive is calculated as the total mass flow needed for upholding the amount of air in the tanks adjusted by a factor that models the quotient of air coming from the drive flow divided by the air flow coming from the surrounding atmosphere.

\[
\dot{m}_{\text{Dive}}^{\text{Ejector system}} = \frac{m_{\text{Dive}}^{\text{Closed system}}}{r_{ej} + 1} = \frac{V \cdot \dot{z} \cdot \rho_{\text{Air}}}{p \frac{\partial \rho_{\text{Air}}}{\partial z}} = \frac{r_{ej} + 1}{r_{ej} + 1}
\]

4.5.3.2 Weight

\[
M_{\text{Closed system}} = L_{pn} \cdot m_{pn} + M_{po} + M_{ej}
\]

4.5.3.3 MTBF

\[
MTBF_{\text{inline}} = \frac{1}{\lambda_{ej} + \lambda_{cu}}
\]
4.5.4 Non pressurized system

A non pressurized system has no controlled pressurization mass flow rate, no added weight and does not decrease the fuel system reliability.

4.6 Measurement

The weight and MTBF for the measurement system is calculated trivially with a specific weight per probe plus added cable weight. MTBF is also calculated in the normal way with the inverted sum of the parts $\lambda$ values.

The power consumption for measurement is assumed to be a lesser part of the total power consumption and fall within the margin of error in this model and is therefore neglected.

4.6.1 Measurement variables

Table 7 – Measurement system variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_s$</td>
<td>Level switch failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_p$</td>
<td>Capacitive probe failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$m_s$</td>
<td>Specific level switch weight</td>
<td>0.1[15]</td>
<td>kg/each</td>
</tr>
<tr>
<td>$m_p$</td>
<td>Capacitive probe weight</td>
<td>0.25[15]</td>
<td>kg/each</td>
</tr>
<tr>
<td>$n_s$</td>
<td>Number of level switches per tank</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$n_p$</td>
<td>Number of capacitive probes per tank</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$n_t$</td>
<td>Number of tanks</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$M_c$</td>
<td>Cable weight</td>
<td>0.5[15]</td>
<td>kg</td>
</tr>
</tbody>
</table>
4.6.2 Level switches

The weight and MTBF of a measurement system with level switches is trivially calculated as follows.

\[ M_{\text{level switches}} = n_S \cdot n_i \cdot m_S + M_C \]  

\[ MTBF = \frac{1}{n_S \cdot n_i \cdot \lambda_S} \]

4.6.3 Capacitive probes

The weight and MTBF of a measurement system with capacitive probes is trivially calculated as follows.

\[ M_{\text{capacitive probes}} = n_p \cdot n_i \cdot m_p + M_C \]  

\[ MTBF = \frac{1}{n_p \cdot n_i \cdot \lambda_p} \]

4.6.4 Both level switches and capacitive probes

The weight and MTBF of a measurement system with both level switches and capacitive probes is trivially calculated as follows.

\[ M_{\text{capacitive probes}} = n_p \cdot n_i \cdot m_p + M_C + n_S \cdot n_i \cdot m_S + M_C \]  

\[ MTBF = \frac{1}{n_S \cdot n_i \cdot \lambda_S + n_p \cdot n_i \cdot \lambda_p} \]

4.7 Refueling

If refueling is performed by gravity all that is needed is a refueling valve and pipes that leads the fuel to the tanks. The pipes however are assumed to already be there since the fuel is supposed to be transferred between the tanks and fed into the engine. Hence all pipe mass is added in transfer and pressurization and no mass is added from pipes in the refueling part of the matrix.

If pressurized refueling is used the tanks must be able to withstand the pressure peaks that may be induced during refueling. The tanks are in most cases already reinforced in order to
cope with higher values of $N_z$. However this reinforcement is only focused on the lower part of the tank. When the tank is refueled the pressure brought by the refueling system affects the whole tank and hence also the upper part which may have to be reinforced with the only purpose to withstand pressurized refueling.

![Diagram of reinforced fuel tank]

The power consumption in the aircraft during refueling is assumed to be minor and is left out of this model.

### 4.7.1 Refueling variables

Table 8 – Refueling system variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_g$</td>
<td>Pressurized refueling valve failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_p$</td>
<td>Gravitation refueling valve failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_{aar}$</td>
<td>AAR boom failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$l_{pipe}$</td>
<td>Total pressurization pipe length</td>
<td>Input</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta p_r$</td>
<td>Refueling pressure</td>
<td>Input</td>
<td>Pa</td>
</tr>
<tr>
<td>$M_p$</td>
<td>Pressurized refueling valve weight</td>
<td>2.5[15]</td>
<td>kg</td>
</tr>
<tr>
<td>$m_{pipe}$</td>
<td>Specific pipe weight per m</td>
<td>Input</td>
<td>kg/m</td>
</tr>
<tr>
<td>$m_g$</td>
<td>Gravitation refueling valve weight</td>
<td>1[15]</td>
<td>kg</td>
</tr>
<tr>
<td>$m_{aar}$</td>
<td>AAR boom weight</td>
<td>40[15]</td>
<td>kg</td>
</tr>
<tr>
<td>$n_t$</td>
<td>Number of tanks</td>
<td>Input</td>
<td></td>
</tr>
</tbody>
</table>
4.7.2 Gravity refueling

Gravity refueling only adds the mass of the refueling valves to the aircrafts total weight.

\[ M_{\text{Gravity}} = n_v \cdot m_g \]  \hspace{1cm} (69)

The reliability of the gravity refueling system is calculated by

\[ MTBF = \frac{1}{\lambda_g} \]  \hspace{1cm} (70)

4.7.3 Pressurized refueling

The weight of a pressurized refueling system is calculated by

\[ M_{\text{Pressurized}} = M_p + n_i \cdot m_g + V_i \cdot \Delta p_r \cdot m_i \cdot \frac{\lambda}{4} \]  \hspace{1cm} (71)

The reliability of the pressurized refueling system is calculated by

\[ MTBF = \frac{1}{\lambda_p} \]  \hspace{1cm} (72)

4.7.4 Air-to-air refueling

The weight of an air to air refueling system is calculated by

\[ M_{\text{Air}} = M_{\text{Air}} + M_p + n_i \cdot m_g + V_i \cdot p_r \cdot m_i \cdot \frac{\lambda}{4} \]  \hspace{1cm} (73)

The reliability of the air to air refueling system is calculated by

\[ MTBF = \frac{1}{\lambda_p + \lambda_{\text{Air}}} \]  \hspace{1cm} (74)
4.8 Fire protection

4.8.1 Fire protection variables

Table 9 – Fire protection system variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_s$</td>
<td>SAFOM failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_o$</td>
<td>OBIGGS failure frequency</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$\lambda_k$</td>
<td>Liquid nitrogen accumulator</td>
<td>Input</td>
<td>failures/Mh</td>
</tr>
<tr>
<td>$V_{tt}$</td>
<td>Transfer tank volume</td>
<td>Input</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$V_{ct}$</td>
<td>Collector tank volume</td>
<td>Input</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$n_t$</td>
<td>Number of tanks</td>
<td>Input</td>
<td></td>
</tr>
<tr>
<td>$m_s$</td>
<td>Specific SAGOM weight</td>
<td>Input</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$M'_o$</td>
<td>Initial OBIGGS structure weight</td>
<td>6 $9.5$</td>
<td>kg</td>
</tr>
<tr>
<td>$m_o$</td>
<td>Specific OBIGGS weight</td>
<td>0.026 $9.5$</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$m_{ln}$</td>
<td>Specific nitrogen accumulator weight</td>
<td>Input</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Specific OBIGGS power consumption</td>
<td>390 $9.5$</td>
<td>W/kg</td>
</tr>
</tbody>
</table>

4.8.2 SAFOM

The passive safom system does not consume any power. The mass is calculated as a function of the volume of the tanks.

\[ M_{\text{safom}} = V_{tt} \cdot m_s \]  

(75)

The reliability of the pressurized refueling system is calculated by

\[ MTBF_{\text{safom}} = \frac{1}{\lambda_s} \]  

(76)
4.8.3 OBIGGS

OBIGGS is the only fire prevention system that consumes power in flight on board the aircraft. The power consumption of an OBIGGS is calculated as the weight of the OBIGGS multiplied by an approximated specific power per weight ratio based on different OBIGGS’s. For details see Appendix 9.5.

\[
P_{\text{OBIGGS}} = M_o' + P_o \cdot m_o \tag{77}
\]

The weight of an OBIGGS fire protection system is calculated as a function of the total volume of the fire protected tanks and the descent rate multiplied by a specific mass.

\[
M_{\text{OBIGGS}} = V_i \cdot \dot{z} \cdot m_o \tag{78}
\]

The reliability of an OBIGGS fire protection system is calculated by

\[
MTBF_{\text{OBIGGS}} = \frac{1}{\lambda_o} \tag{79}
\]

4.8.4 Stored liquid nitrogen

The weight of a liquid nitrogen system is calculated by

\[
M_{\text{ln}} = V_i \cdot m_{\text{ln}} \tag{80}
\]

The reliability of a liquid nitrogen fire protection system is calculated by

\[
MTBF_{\text{ln}} = \frac{1}{\lambda_{\text{ln}}} \tag{81}
\]

4.8.5 No fire protection

If no fire protection system is used there is no power consumption, no added weight and no added decrease of the aircraft’s reliability.
5 The quantified matrix

The usual approach in early conceptual design is to first generate concepts, possibly with the aid of a method or tool for synthesis such as the function and means tree or the morphological matrix. The next step is then to screen inferior concepts by assessment and approximate calculations (where the remaining concepts are pursued into deeper analysis followed by active selection rather than screening).

The approach here is to rationalize these first steps in conceptual design of an aircraft fuel system by automating the morphological matrix, thus facilitating both the synthesis and the first concept screening. The standard morphological matrix is a way of giving structure to a large number of concepts. It is then up to the engineer to screen and score the concepts according to different procedures and techniques.

The quantified matrix is a conventional morphological matrix that also has a built-in mathematical model of the subsystem alternatives. This model gives the engineer immediate access to approximated properties of the product that is to be designed. The matrix is also useful for a first assessment of fuel system characteristics in the conceptual phase of the aircraft itself. This is usually done today by statically based equation as described in Daniel P. Raymer [16] and others.

The quantified matrix described here is implemented in the spreadsheet program MS Excel. Every potential subsystem concept solution is described either with physical or statistical equations, or a combination thereof. Useful measures of merits are quantified and then by choosing subsystem combinations, a quantified value of the complete system is obtained. In this case, system weight penalty, electrical power consumption, air bleed from the main engine and Mean Time Between Failure (MTBF) has been used as measure of merit. The actual equations, their origin and the implementation in MS Excel are thoroughly described in Chapter 4.

5.1 Quantified morphological matrix for aircraft fuel systems

A morphological matrix for aircraft fuel systems may look like this. The functions of the system are lined up in the first column and the means for each function are lined up as rows after each function. By choosing a means for each and every function concepts are put together.
The quantified matrix has mathematical models for each means “behind” every cell that calculates and presents values of the requested properties. These values can be summarized according to the engineer’s choice of concept. As a result the concepts approximated measures of merit are instantly presented for evaluation.

Table 10 – A convention morphological matrix

<table>
<thead>
<tr>
<th>Engine feed</th>
<th>NGT</th>
<th>HOPPER Tank</th>
<th>Jet pump</th>
<th>NGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel transfer</td>
<td>Distributed pump</td>
<td>Inline pump</td>
<td>Jet pump</td>
<td>Gravity</td>
</tr>
<tr>
<td>Pressurization</td>
<td>Closed system</td>
<td>Ejector system</td>
<td>Non Pressurized</td>
<td></td>
</tr>
<tr>
<td>Measurement</td>
<td>Level sensor</td>
<td>Tank probe</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td>Refueling</td>
<td>Pressurized</td>
<td>Gravity</td>
<td>AAR</td>
<td></td>
</tr>
<tr>
<td>Fire protection</td>
<td>SAFOM</td>
<td>OBIGGS</td>
<td>Liquid Nitrogen</td>
<td>None</td>
</tr>
</tbody>
</table>

5.2 Implementation in Excel

5.2.1 Variables

5.2.1.1 Naming

The default designation of a cell in Excel is based on the cells position in the worksheet, a letter for the column and a number for the row. If large formulas like the ones used in this fuel system model are to be implemented the equations will look like hard-to-understand sequences of combinations of letters and numbers, even harder to troubleshoot. In order to avoid this, the designation of the cells has been replaced by names. Every vital value in the excel workbook has an individual name and all of the vital formulas are built up with names. The names describes the nature of the value, not the position of the cell. This also makes the model immune to replacing of cells in the worksheet. The naming may not be perfectly stringent but the names have been chosen as intuitive as possible.

The limitations of naming of cells in excel are, among others, that only small letters are allowed and a highly limited amount of special signs are allowed. Every name in the implemented model is built up of two positions, one for the type of quantity in question and one for a more specific indication of where and when the quantity is valid. The point “.” has been chosen to indicate the mark between the quantity and the specification. In the Excel program, a name key which gives a full explanation of all names, is provided.
Example 1

**Accumulator**
- Volume: v.a 0.2 m³
- Pressure: p.a 170000 Pa

Figure 16 – Some accumulator variables in Excel

This is an example of naming where v.a means the volume of the accumulator and p.a means the pressure in the accumulator.

Example 2

**HOPPER-tank**
- Weight: w.ht 4 kg
- Jet Pump weight: w.htjp 0.2 kg
- NRV weight: w.htrnv 0.1 kg

Figure 17 – Some HOPPER tank variables in Excel

In this naming example the weight of the HOPPER tank is called w.ht. The weight of the HOPPER tank jet pump is called w.htjp, and the weight of the HOPPER tank non return valve is named w.htrnv.

5.2.1.2 Top requirements

These figures, called the top requirements, stores information about where in the flight envelop the simulation is done.

**Table 11 – Top requirements**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Approx. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>Altitude</td>
<td>Input</td>
<td>m</td>
</tr>
<tr>
<td>$\dot{z}$</td>
<td>Descent rate</td>
<td>Input</td>
<td>m/s</td>
</tr>
<tr>
<td>$T_{GROUND}$</td>
<td>Ground level temperature</td>
<td>0.1</td>
<td>°C</td>
</tr>
<tr>
<td>$G$</td>
<td>Gravity factor</td>
<td>0.25</td>
<td>g</td>
</tr>
<tr>
<td>$\rho_{FUEL}$</td>
<td>Fuel density</td>
<td>4</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity</td>
<td>2</td>
<td>M</td>
</tr>
<tr>
<td>$Q_{CT}$</td>
<td>Collector tank fuel amount</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>$Q_{FT}$</td>
<td>Fuselage tank fuel amount</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>$Q_{WT}$</td>
<td>Wing tank fuel amount</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>$Q_{DT}$</td>
<td>Drop tank fuel amount</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

In Excel some of the top requirements are placed in a table like this.
This is some of the top requirements from the Excel workbook. With these values the fuel system produces a mass flow of 1 kg/s at ground level or 6 kg/s at an altitude of 5000 m. The maneuvering of the aircraft is currently inducing an $N_z=3$, more commonly known as G-force, The fuel density is 800 kg/m$^3$, the dive rate is 150 m/s and the temperature at ground level is 15°C.

5.2.1.3 System parameters

The system parameters are input variables given by the user. They set the requirements for the system.

This is an example of system parameters in the Excel workbook. Here the pressure on the high pressure side of the boost pump is set to 200 kPa, the collector tank volume is set to 750 liters and the pressure in the collector tank is set to 50 kPa.

The system parameters are color coded light blue in Excel

Example 5

The collector tank pressurization is set to 50 kPa. For example the weight of the collector tank, boost pump and transfer pump as well as the power consumption of the boost pump, the transfer pump and the pressurization system is depending on this value.
5.2.1.4 **Design parameters**

The design parameters are the “key values” of the quantified morphological matrix. It is with these values and the input variables that derived values and results are calculated.

**Example 6**

<table>
<thead>
<tr>
<th>Electric Transfer pump</th>
<th>w.tp</th>
<th>0.0069 kg/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>e.tp</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Figure 20 – Some design parameters in Excel*

These are some of the design parameters in the excel workbook. They state that the electric transfer pump weights 0.0069 kg for every watt of pump power it produces. It also states that the electric transfer pump has an efficiency of 0.6. For every watt of pump power it produces it requires $\frac{1}{0.6} \approx 1.67$ watts of electrical power.

The design parameters are color coded light grey in Excel.

5.2.1.5 **Results**

These values are the result of the system parameters and the design parameters. They are presented separately for each concepts every function and also summarized for the whole chosen concept. The results make up the measures of merit for each concept.

**Example 7**

<table>
<thead>
<tr>
<th>Wing Tanks</th>
<th>p.wt</th>
<th>54015 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank pressure</td>
<td>dpf.wt</td>
<td>7350 Pa</td>
</tr>
</tbody>
</table>

*Figure 21 – Some results in Excel*

This is an example of some calculated results. In this case they present the absolute tank pressure in the wing transfer tanks and the pressure loss associated with wing tank fuel transfer due to friction.

The end results that are presented just before summarization in the interactive morphological matrix are color coded white. These values are the specific functions contribution to the measure of merits for the whole concept.
5.2.2 Calculations

The calculations that give the results are often divided into smaller parts in several cells instead of one big formula in one cell. This is to increase the readability of the formulas and to present many small steps of every calculation. If smaller steps are presented it is easier to backtrack thru the calculation steps and find the origin of any abnormal values.

Example 8

Depending on the current altitude and pressurization of the tanks the cavitation may differ widely. A large transfer pump with equally large power consumption could be the result of cavitation and not only a large pressure difference over the pump. The difference becomes clear when the causes and their remedies are investigated. Cavitation is remedied only by increasing the pressure on the low pressure side of the pump and not by lowering the pressure on the high pressure side, which could be a remedy for a large pressure difference over the pump. Lowering the pressure on the high pressure side could instead result in increased cavitation further down the fuel system in the boost pump. The separate presentation of the cavitation informs the user of the circumstances in the pump.

5.2.3 Structure

5.2.3.1 The first page - The matrix

The interactive morphological matrix is presented on the first worksheet in excel. Every function has been color coded.

Figure 22 – The morphological matrix
The colors for the different functions are listed below.

### Table 12 – The function color coding

<table>
<thead>
<tr>
<th>Function</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine feed</td>
<td>Red</td>
</tr>
<tr>
<td>Fuel transfer</td>
<td>Yellow</td>
</tr>
<tr>
<td>Pressurization and ventilation</td>
<td>Green</td>
</tr>
<tr>
<td>Measurement</td>
<td>Blue</td>
</tr>
<tr>
<td>Refueling</td>
<td>Grey</td>
</tr>
<tr>
<td>Fire protection</td>
<td>Black</td>
</tr>
</tbody>
</table>

#### 5.2.3.2 The sheets - The functions

On the following sheets the different functions of the fuel system are represented. Each one has its own sheet with a color coded tab. All with their respective solutions and a complete presentation of the resulting measures of merit for the solutions. On the first page, in the morphological matrix, a concept is chosen and according to the choices the measures of merits are collected from the underlying sheets. The results are summarized and presented as the fuel systems total weight, power consumption and MTBF in the interactive matrix. For pressurization the mass flow rate is presented instead of consumed power due to reasons discussed in 4.5.

Every worksheet is built up with some or all of the variables described above. The structure of a typical worksheets is described in Figure 23.

![Figure 23 – A typical worksheet](image-url)
5.2.4 The envelop

The possibility to quickly perform a “simulation” in different places in the flight envelop makes it possible to investigate the fuel system in different situations and to provoke it to reveal deviant properties. This may be a time saving advantage with an automated morphological matrix.

Example 9

The meaning with a semi closed pressurization system is clearly visible when steep dive is investigated but not so obvious at level flight. The properties of a closed or a semi closed pressurization system can quickly be investigated at both level flight and at various dive rates.

5.2.5 Side effects of concept choices

Different combinations of concept choices sometimes interact with each other in less expected ways.

5.2.5.1 Jet pump transfer

In a jet pump transfer system the jet pumps are transferring the fuel but they are in turn driven by the boost pump. Hence the power consumed by the jet pumps loads the boost pump and increases its size and power consumption. This power consumption and added weight is presented in the red engine feed function row in the matrix (the top row), but is color coded yellow (here underlined due to lack of color print) as in fuel transfer.

<table>
<thead>
<tr>
<th>Function</th>
<th>Min tank pres.</th>
<th>Eject/BP</th>
<th>Pump</th>
<th>Δ Tank</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine feed</td>
<td>2</td>
<td>7</td>
<td></td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>Fuselage Tank Transfer</td>
<td>1</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wing Tank Transfer</td>
<td>0</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drop Tank Transfer</td>
<td>0</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Σ Transfer</td>
<td>1</td>
<td>30</td>
<td></td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

Figure 24 – An example of concept choice side effects.
5.2.5.2 Fuel transfer by siphoning

If siphoning is chosen as a means of fuel transfer there is no need for a transfer pump. However all the demands that should have been set on the transfer pump are now set on the pressurization system. Therefore the pressurization required for fuel transfer to occur are presented in the matrix. When these pressures are inserted by the user, the pressurization system is instantly dimensioned for producing them.

5.2.5.3 Impossible choices

There is one combination of means that is impossible. Fuel transfer by siphoning must be combined with a pressurization system and therefore “Non pressurized” can not be chosen at the same time as “Siphoning”. If this combination is chosen the interactive matrix displays the message “Not allowed with siphoning!” next to the pressurization choice.

5.3 Validation

5.3.1 JAS 39 Gripen

Because this morphological matrix is made at SAAB AB it is more or less built up with the parameters of Gripen from scratch. Many of the parameters of current interest regarding fuel systems of newer aircraft are however secret or evidently hard to come over. This makes small scale validation a time consuming task and complete validation even grander. Due to the extent of the validation task and some miscalculation of the time at hand the numerical validation will be more or less left out of this report.

A way of validating the structure of the quantified matrix is to ensure that result of the matrix built up by Gripen also reflects the properties of Gripen.

5.3.2 Some general conclusions

5.3.2.1 Weight

The transfer pump is according to the quantified matrix very small or not necessary at any altitude or any speed if not transfer between transfer tanks is of interest (If the transfer pump only transfers the fuel the engine consumes to the collector tank). This is entirely correct and confirms the validity of the matrix. The pressurization of the tanks gives enough pressure difference to let the fuel flow by itself from the transfer tanks to the collector tank. However at greater altitudes and when other levels of gravity are investigated the demands on the transfer pump increases.
The engine feed and fuel transfer functions in the matrix have both pump and tank weight as output. The tank weight is based on an attempt to isolate the weight added to the aircrafts structure due to pressurization reinforcement of the tanks.

The real gross weight of the tanks due to pressurization is not available at this time and validation is therefore relying on the accuracy of the original value found in Hampus Gavel [6].

The calculated structural weights of measurement and pressurization systems of less than 2 kg each are negligibly small compared to the earlier discussed systems. It is assumed to fall within the margin of error for the system as a whole.

The total calculated weight of the fuel system under a set of demanding circumstances is 102 kg. This value, including the special tank weight, is not currently available for the real Gripen.

5.3.2.2 Power

Jet pump transfer is a robust but power consuming way of transferring fuel. The matrix shows this by presenting nothing but higher power consumptions for the jet pump transfer solution compared to the transfer solutions driven by electric motors.

Siphoning is another indirect way of generating fuel transfer that is motivated by other reasons than power consumption. Any siphoning system is at the end heavier than any electrically driven transfer pump solution.

5.3.2.3 MTBF

The jet pump case, just as siphoning, gives higher reliability than any electrically driven transfer pump solution.

Another notable property is that any transfer system with distributed pumps is less reliable than any transfer system with distributed pumps due to the increased number of electric moving parts.
6 Conclusions

6.1 The model

As said before, there is one sure fact about every mathematical model simulating any physical system, it is wrong. How well the model fills its purpose can be measure with how less wrong it is.

In this quantified morphological matrix the purpose has been to rationalize the concept generating process. Because it is a process prior to the concept analyzing process the main objective is to put together potential concepts, not to strictly evaluate them. However, there is a degree of evaluation incorporated in using this quantified morphological matrix but it is based on approximation and the aim is to discard obviously bad concepts, not to compare the concepts with each other.

Further limitations in the model are the chosen measures of merit. The concepts are not evaluated in any other areas than the weight, power consumption and MTBF. Other measures of merit might be price, complexity and installation and service properties. Also reliability has huge possibilities for even more precise prediction of future products including other quantities to describe quality.

However it must be remembered that a too detailed analysis might not be the most efficient way of early evaluation. The extra precision has no meaning in prediction stages far from detailed design or final concepts selection. Experience drawn from the creation of this model shows that with these three measures of merit, as the complexity of the model grows, and the learning curve gets steeper the usage of the tool might be slowed down. The value of a good synthesis rationalization tool is as highest at a moderate level of complexity. Beyond this point further precision does not increase the accuracy. A lesson well learned during the development of this automized morphological matrix.
6.2 For the future

6.2.1 Expansion

This tool is made with flexibility in mind. The consistent naming system combined with an open and simple structure of most formulas makes it possible to use this tool as more than a permanent static model. The idea is that as the tool is used and as further validation is made it should be updated both regarding values and structure.

There is also a possibility to expand this model towards analysis of concepts. For use on a simpler product or with a more accurate set of models the result can be closer to reality and may also be usable during the selection of fitting concepts. A process that takes place later in the concept phase.

6.2.2 Implementation

A good idea for long term use of a quantified interactive morphological matrix model might be to implement it in another, more user friendly program than MS Excel, regarding interactive concept generation.

6.2.3 Validation

Despite the approximate nature of this model the goal is still to make a good prediction. This goal might be better achieved by more extensive validation than the small example showed in this report. One of the reasons for this small scale validation is the fact that it is very hard or impossible to acquire this kind of properties from many aircraft manufacturers.

The Gripen aircraft has had major influence on this model and the model may therefore be more valid for single engine fighters than for multi engine or civil aircraft. However to state how well it fits different aircraft types, more validation has to be performed.

It has been learned during the work with this model that after a moderate level of complexity of the model set strictly by the user friendliness; instead of chasing accuracy by precision, it should be acquired by validation.
6.2.4 Optimization

There is a possibility for optimization to be connected to this morphological matrix. However, the limitations of this interactive tool make some solutions seemingly superior, regardless of the demands of the system. Fuel transfer by gravity is such an example. It is, according to the model, the best choice because it is the lightest, least power consuming and safest approach to fuel transfer. That is true, except that it can not deal with uncoordinated flight. Therefore there may have to be an engineer present, with some experience in aircraft design during the optimization, to overlook the process or forbid some obviously unsuitable solutions.
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7.1 Personal references

[17] Mats Gideonsson  
SAAB Aircraft

[18] Hans Ellström  
SAAB Aerosystems
8 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ram-air</td>
<td>Air inlet originating in the atmosphere.</td>
</tr>
<tr>
<td>Cavitation</td>
<td>Boiling in the fuel due to rapid pressure decreasing</td>
</tr>
<tr>
<td>Ullage</td>
<td>The tank space not occupied by fuel</td>
</tr>
<tr>
<td>NRV</td>
<td>Non Return Valve</td>
</tr>
<tr>
<td>NEA</td>
<td>Nitrogen Enriched Air</td>
</tr>
<tr>
<td>OBIGGS</td>
<td>On Board Inert Gas Generating System</td>
</tr>
<tr>
<td>CG</td>
<td>Center of gravity</td>
</tr>
<tr>
<td>Ram-air</td>
<td>Air inlet originating in the atmosphere.</td>
</tr>
</tbody>
</table>
9 Appendix

9.1 Boost pump sizing

A weight to power ratio has been approximated from a group of boost pumps to $0.0043\text{kg/W} + 1.89\text{kg}$.

Figure 25 – Boost pump weight per performed power unit.
9.2 Transfer pump sizing

A weight to power ratio has been approximated from a group of transfer pumps to 0.0069 kg/W.

Figure 26 - Transfer pump weight per performed power unit

y = 0.0069x
9.3 Jet pump efficiency

To approximate the efficiency of a typical jet pump three simulations where done in a well calibrated and tested simulation model. These are the resulting graphs made from three levels of pressure on the drive flow. Along the simulation of each pump the primary drive flow pressure was held constant whilst the surrounding pressure at the outlet was varied. The maximum efficiency can be approximated to be 0.23 independent of the drive flow pressure.

![Graph showing the efficiency of a jet pump at 50 kPa drive flow.](image)

Figure 27 – Jet pump efficiency at 50 kPa drive flow.
Figure 28 – Jet pump efficiency at 150 kPa drive flow.

Figure 29 – Jet pump efficiency at 250 kPa drive flow.
9.4 Quotient in dive power for closed system

It can be questioned if it is necessary with a more specific formula to calculate which already is an approximation. However the creator of this matrix felt it was a small investment of time worth the eventual increase of accuracy it might bring, especially since it does not change the process of using the quantified matrix.

The quotient between ambient pressure and ambient pressure change rate has been calculated for use in the formula that approximates the volume flow rate in and out of the pressurized tanks.

\[
\frac{p_{\text{atm}}}{p_{\text{atm}}} \tag{82}
\]

\[
p_{\text{atm}} = 101325 \cdot \left(1-0.002256 \cdot z\right)^{5.256} \tag{83}
\]

\[
\frac{\hat{p}_{\text{atm}}}{\hat{z}} = \left| 101325 \cdot 5.256 \cdot (-0.002256) \cdot (1-0.00002256 \cdot z)^{4.256} \right| \tag{84}
\]

Figure 30 - Quotient in dive power for closed system
9.5 Primary/Secondary flow ratio in pressurization ejector

In order to assess how much of the pressurization air that comes from naturally increasing pressure outside the aircraft and how much comes thru the controlled pressurization flow in the ejector pressurization system a simulation has been done in a well tested simulation program.

![Figure 31 - Primary/secondary flow ratio in pressurization ejector](image)

The simulation was done at ground level and at an altitude of 6 km. The upper dotted line is the ratio at ground level and the lower dotted line is the ratio at an altitude of 6 km. The ratio between the primary and the secondary pressurization flow rates have been plotted together with an approximation line. The approximation shows Equation (85) which is used to approximate the primary/secondary flow ratio.
This approximation is made with a tank volume and ejector properties like those in the Gripen aircraft. Another aircraft may have a different setup that gives other flow ratios in the pressurization ejector. However this is an approximate, early conceptual study and the end result of this approximation is to compare the flow rates with a closed system, not to evaluate the ejector system. What is sought for in this formula is the general shape and not the exact value.

9.6 **OBIGGS sizing**

From [13] a number of OBIGGS’s have been investigated in order to calculate a specific OBIGGS weight per descent rate and tank volume. The OBIGGS’s are presented in Table 13.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Fuel Weight [kg]</th>
<th>Fuel Volume [m³]</th>
<th>Descent rate [m/s]</th>
<th>OBIGGS weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-5</td>
<td>150</td>
<td>187,5</td>
<td>18,2</td>
<td>2278</td>
</tr>
<tr>
<td>KC-135</td>
<td>86</td>
<td>107,5</td>
<td>13,2</td>
<td>323</td>
</tr>
<tr>
<td>C 17</td>
<td>81</td>
<td>101,25</td>
<td>80</td>
<td>973</td>
</tr>
<tr>
<td>Boeing ATF</td>
<td>8,6</td>
<td>10,75</td>
<td>203</td>
<td>117</td>
</tr>
<tr>
<td>Apache</td>
<td>1,1</td>
<td>1,375</td>
<td>25,4</td>
<td>4,8</td>
</tr>
</tbody>
</table>
First a specific OBIGGS weight per tank volume is calculated from Figure 32 and the specific weight per fuel volume is approximated to 10 kg/m³ regardless of descent rate.
The descent rate or flow capacity of the OBIGGSs has also been taken into account and a specific weight per descent rate can be assessed to around 3kgs/m from Figure 33.

The deviant value noted in the upper left corner comes from the C 5 aircraft which is the oldest in the group. Since OBIGGS is a currently developing technology newer systems are often more efficient and the C 5 is assumed to be an outliner in this case.
Finally, in order to assess the weight of an arbitrary OBIGGS the weight has been normalized per cubic meter tank volume in Figure 34.

The result is that an OBIGGS weighs approximately $6 + 0.026 \cdot z \text{ kg/m}^4$. 

Figure 34 – OBIGGS weight per fuel volume and descent rate.
In order to assess the power consumption of the OBIGGS’s, based on the assumption that
the weight and power consumption increases at the same rate with respect to fuel volume
and dive rate, a specific power consumption per OBIGGS weight has been calculated. This
has been done with figures based on different commercial OBIGGS’s as seen in Figure 35.

The result is that an OBIGGS consumes approximately 390W/kg.