AN ALGORITHMIC MORPHOLOGY MATRIX FOR AIRCRAFT FUEL SYSTEM CONCEPTUAL DESIGN

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Abstract

An important step in the conceptual design phase is the synthesis of principal solutions into many concepts. The use of morphological maps is one way to make the synthesis straightforward, so that many alternative concepts are easily generated. However, it is the large number of possible concept combinations that is considered to be the principal drawback of the method.

This paper describes how the morphological matrix has been quantified, thus creating the foundation for an algorithmic approach which effectively minimizes the number of concepts selected for further analysis. The paper gives an illustrative example showing the conceptual synthesis of an aircraft fuel system.

1 General Introduction

Conceptual analysis is often considered as the most important step in the design of a new product. For example, Pahl and Beitz [7] states: “*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 principle than from concentration on technical detail*”.

An important step in the conceptual design phase is the synthesis of principal solutions into many concepts. The use of morphologic maps is one way to make the synthesis straightforward, so that many alternative concepts are easily generated. However, it is the large number of possible concept combinations that is considered to be the principal drawback of the method.

This paper describes how the morphological matrix has been quantified, thus creating the foundation for an algorithmic approach which effectively minimizes the number of concepts selected for further analysis. The paper gives an illustrative example showing the conceptual synthesis of an aircraft fuel system. This technique opens up to the use of optimization algorithms and Pareto optimization to reduce of the number of concept proposals that is pursued into to more detailed analysis.

Furthermore, it is important “*to extend the view on aircraft system design beyond the preliminary aircraft design level*” as stated by Scholtz in [8]. The importance of aircraft system design is also motivated by the fact that for medium range civil transport, systems accounts for about one third of the aircraft’s empty mass as well as one third of the development and production costs, and this ratio is even higher for military aircraft.

The paper is organized as follows: First there is a description of a/c fuel system fundamentals. This is necessary to understand the example presented later. This is followed by a general description of the morphological matrix. The next section describes in detail how the matrix has been quantified, together with an illustrative example. The final section consists of a discussion, followed by the conclusions that can be drawn.

2 Background

2.1 Fuel system fundamentals

Most a/c fuel systems consist of several tanks for structural, slosh, center of gravity (CG) management or safety reasons. The tank configuration of the Saab Gripen fighter is shown in Figure 1.

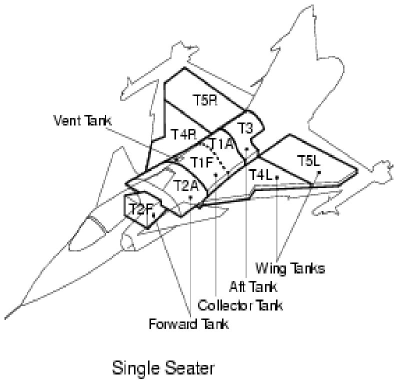


Figure 1: The tank layout of the Saab 39 Gripen

The general fuel system layout consists of one or more boost pumps that feed fuel to the engine from a collector tank, usually a fuselage tank placed close to the CG. The collector tank is refilled by a fuel transfer system that pumps fuel from the source tanks. Source tanks may be other fuselage, wing or drop tanks. The system might be pressurized to avoid engine feed cavitation at high altitude and to aid or provide the means for the fuel transfer.

The fuel system complexity varies from the small home built a/c with no system complexity up to the modern fighter where the fuel system might be critical for CG reasons and therefore very extensive with triple redundancy. If pressure refueling is required, a refueling system of some complexity must be added. The fuel may also sometimes serve as a heat sink, which adds a subsystem for cooling.

Some of the fuel subsystems that may be identified in modern a/c are:

- Engine Feed system
- Fuel Transfer system
- Vent and Pressurization system
- Refueling system
- Measurement and Management system
- Cooling System
- Explosion Protection System

2.1.1 Engine feed

The engine feed is by far the most important task of the fuel system. The engine feed is defined as part of the airframe systems and is not to be confused with the engine's own internal fuel system. There are several methods to ensure fuel to the engine at all conditions.
The engine feed requirement is to keep the fuel pressure (boost the pressure) in the interface within limits under all flow conditions according to ref. JSSG [5]. The purpose of this is to avoid cavitation in the engine's own fuel system.

2.1.2 Fuel Transfer

The simplest way of transferring fuel is by gravity. This method is used in general aviation and commercial a/c dependent on tank configuration. An example of an a/c with gravity transfer is the Saab 2000, shown in Figure 2, where the dihedral transfers the fuel from the outboard to the inboard tank

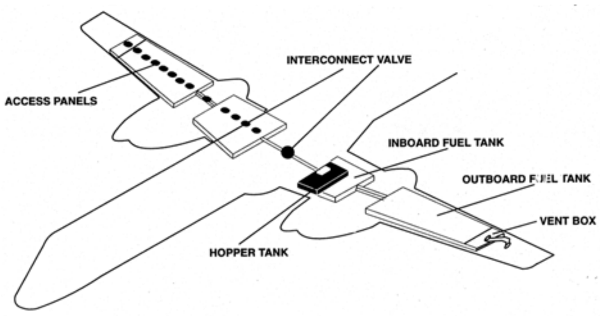


Figure 2: Dihedral gravity transfer of fuel from outboard to inboard wing tank

A more complex method is siphoning, shown in Figure 3 Generally, it is engine bleed air, directly or conditioned by the environmental control system, which supplies the air via a pressure regulator.

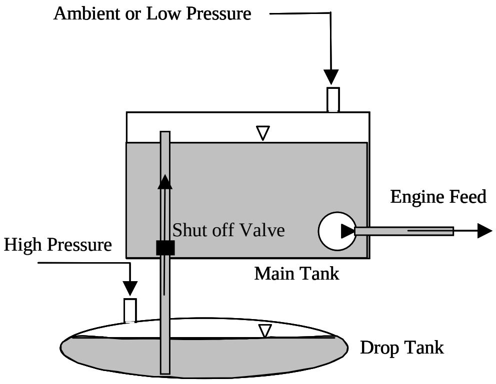


Figure 3: Siphoning of fuel from drop tank to main tank

Pump transfer may be of two principally different types, inline or distributed, see Figure 4. The inline pump is often a centrally placed pump performing transfer from several tanks. This is lightweight and compact, but susceptible to cavitation in suction lines due to pressure drop. Distributed pumps are located in the transfer tank thus minimizing suction head and cavitation. A more detailed description of fuel transfer can be found in Gavel [4].

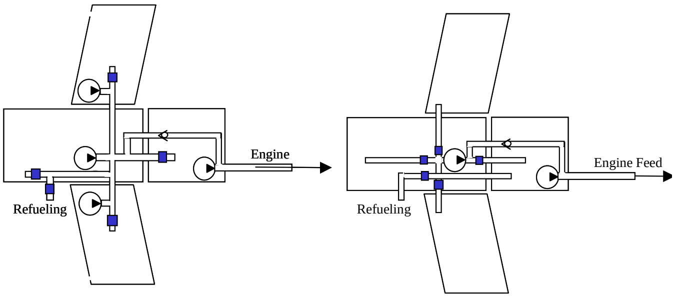


Figure 4: Pump transfer, distributed and centralized.

Pumps used for fuel transfer are generally rotary pumps or jet pumps. Figure 5 shows the principal difference between a jet pump and a centrifugal pump.

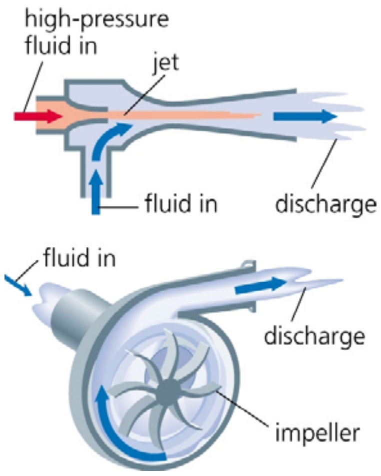


Figure 5: A jet pump (top) and a centrifugal pump (Source: Precision Graphics)

2.1.3 Vent and Pressurization

The vent system must keep the tank pressure within allowable limits during maneuvering and refueling, ingest gas during dive or defueling, expel gas during climb or refueling, and ensure limit pressure in case of refueling overshoot. At high altitude it may be desired to pressurize the tanks to avoid fuel boiling.

The vent and pressurization systems may be of three principally different types. Open, semi open (ejector) or closed.

2.1.4 Refueling

Aircraft with small fuel tanks like general aviation a/c has according to McKinley [3], gravity refueling with manual shut off. As size of the tanks increase, pressure refueling through a sealed single connector is used. Large a/c may have two or more connections. The desire to keep turn around times short drives requirements on high refueling flow rates.

Furthermore, there are also air to air refueling systems.

2.1.5 Fire prevention and explosion suppression

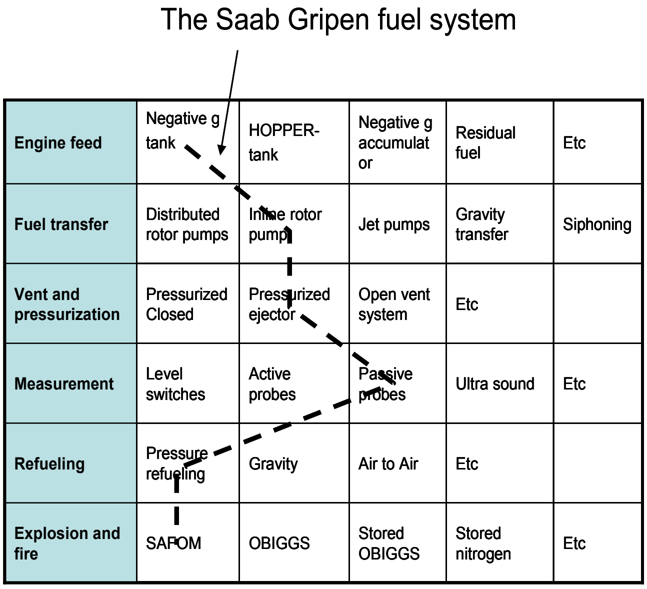
The fuel tanks can be injected with inert gas in order to decrease the oxygen content (below 9 %) and thus creating an inert environment in the ullage. There are several types of systems to do this, both stored and on demand systems

If a fire occurs in a fuel tank, it might be possible to avoid an explosion by having a three-dimensional latticework installed (tank foam a.k.a. SAFOM, which is actually a brand). The tank foam will quench the explosion by removing the energy from the combustion zone.

2.2 Synthesis of concept with a morphological matrix

The generation of concept solutions is the central aspect of designing. The focus of much writing and teaching is therefore on novel products or machines. However, this overlooks the fact that most designs are actually modifications of an already existing product, as stated in [3]. The morphological chart exploits this and encourages the designer to identify novel combinations of components or subsystems.

The morphological matrix is created by decomposing the main function of the product into subfunctions which are listed on the vertical axis of the matrix. Different possible solution principles for each function are then listed on the horizontal axis. Concepts are created by combining different sub-solutions to form a complete system concept. An example of a morphological matrix for an aircraft fuel system is shown in Figure 6.



Engine feed	Negative g tank	HOPPER-tank	Negative g accumulator	Residual fuel	Etc
Fuel transfer	Distributed rotor pumps	Inline rotor pump	Jet pumps	Gravity transfer	Siphoning
Vent and pressurization	Pressurized Closed	Pressurized ejector	Open vent system	Etc	
Measurement	Level switches	Active probes	Passive probes	Ultra sound	Etc
Refueling	Pressure refueling	Gravity	Air to Air	Etc	
Explosion and fire	SAFOM	OBIGGS	Stored OBIGGS	Stored nitrogen	Etc

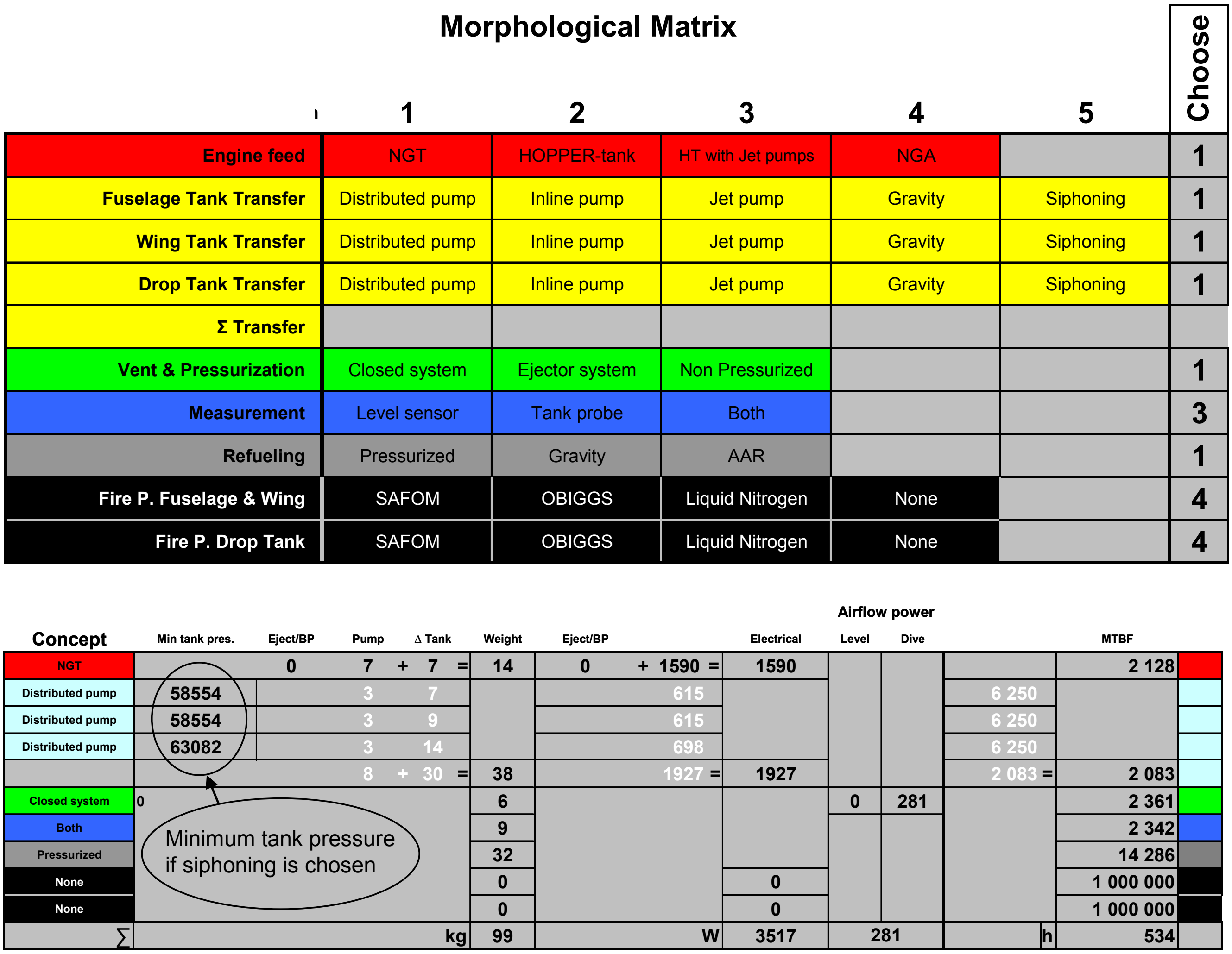
Figure 6: Morphological matrix showing the fuel sub system combination of the Saab Gripen.

Morphology is a way of thinking which was introduced by the astrophysicist Fritz Zwicky (1898-1974). One of the ideas of morphology is to systematically search for a solution to a problem by trying out all possible combinations in a matrix. Zwicky named the matrix a 'morphologic box'; other names are morphological matrix or morphological chart. The fact that the search will also reveal unorthodox combinations is one of the basic ingredients of creativity; there are similarities here with the theory of inventive problem solving [1]. Zwicky’s early work can be found, for example, in [14], [15] and [16]. Many attempts have been made, most often successfully, to refine and improve the use of morphology charts, for instance [13].

The major deficiency of the morphological matrix method is the large number of possible concepts, whereas the number of variants that a designer is capable of evaluating is obviously limited. The relatively small matrix in Figure 6 already gives the designer no less than 2,880 possible concept combinations.

3 The interactive 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-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 by automating the morphological matrix, thus facilitating both the synthesis and the first concept screening. The quantified matrix is a conventional morphological matrix that has built-in mathematical models of the solution elements. The implementation is made in MS Excel and gives an immediate response to change in top-level requirements or design parameter and is therefore considered to be interactive in this sense.



Morphological Matrix

	1	2	3	4	5	Choose
Engine feed	NGT	HOPPER-tank	HT with Jet pumps	NGA		1
Fuselage Tank Transfer	Distributed pump	Inline pump	Jet pump	Gravity	Siphoning	1
Wing Tank Transfer	Distributed pump	Inline pump	Jet pump	Gravity	Siphoning	1
Drop Tank Transfer	Distributed pump	Inline pump	Jet pump	Gravity	Siphoning	1
Σ Transfer						
Vent & Pressurization	Closed system	Ejector system	Non Pressurized			1
Measurement	Level sensor	Tank probe	Both			3
Refueling	Pressurized	Gravity	AAR			1
Fire P. Fuselage & Wing	SAFOM	OBIGGS	Liquid Nitrogen	None		4
Fire P. Drop Tank	SAFOM	OBIGGS	Liquid Nitrogen	None		4

Concept	Min tank pres.	Eject/BP	Pump		Δ Tank		Weight	Eject/BP		Electrical	Airflow power Level	 Dive			MTBF
NGT		0	7	+	7	=	14	0	+ 1590 =	1590					2 128
Distributed pump	58554		3		7				615				6 250		
Distributed pump	58554		3		9				615				6 250		
Distributed pump	63082		3		14				698				6 250		
			8	+	30	=	38		1927 =	1927			2 083 =		2 083
Closed system	0						6				0	281			2 361
Both							9								2 342
Pressurized							32								14 286
None							0			0					1 000 000
None							0			0					1 000 000
∑						kg	99		W	3517	281			h	534

Minimum tank pressure if siphoning is chosen

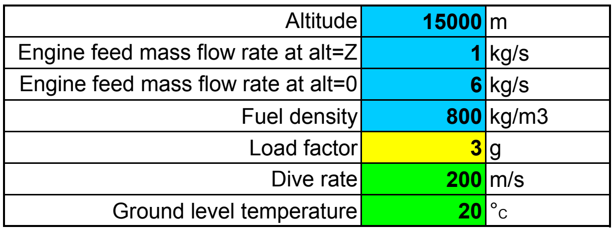
Figure 7. The morph matrix is shown above and the quantified system properties are shown below.

Pahl and Beitz [7] states on page 168 that: *"Combining solutions using mathematical methods is only possible for working principles whose properties can be quantified. However, this is seldom possible at this early stage."* In the framework presented here we focus on properties that can be quantified, such as weight, cost, power consumption and Mean Time Between Failure (MTBF). Furthermore, it is the authors' opinion that quantified models should be used as early as possible in the design process.

The matrix is also useful for a first assessment of fuel system characteristics in the conceptual phase of the a/c itself. This is usually done today by statistically based equations as described by for instance Raymer [10], Berry [2] or Torenbeek [11] to name just a few.

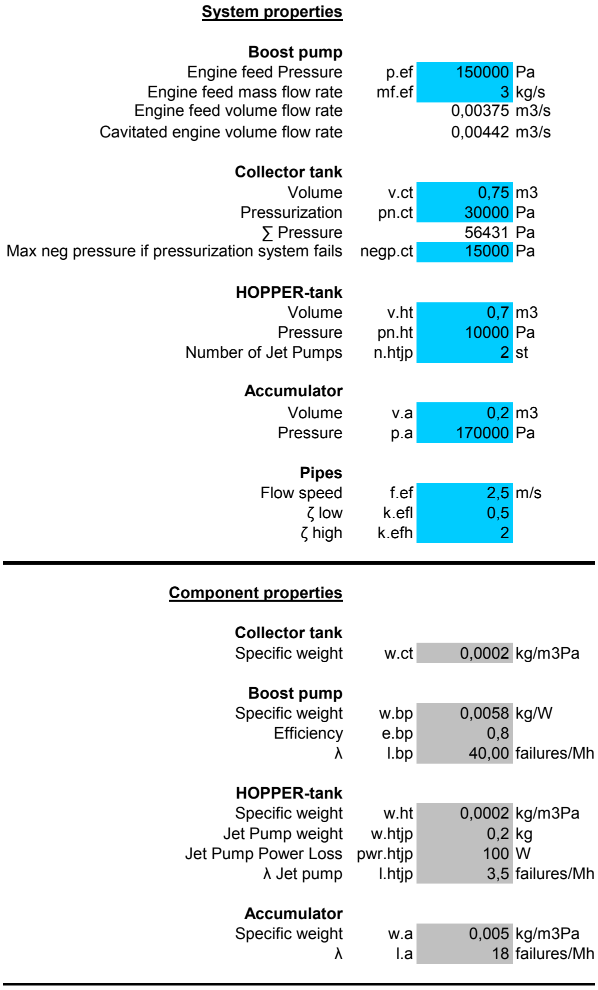
The actual equations, their origin, and the implementation in MS Excel are described in depth in Svahn [9].

Let us first take a glance at the morph chart shown in Figure 7. The upper matrix shows a morphological matrix for a/c fuel systems, similar to the one shown in Figure 6. The column to the left shows a proposed system combination for a small or mid size combat a/c. The lower matrix shows the model outcome, weight, power consumption etc, as described earlier. The top-level requirements are shown in Figure 8 These need to be filled with data for altitude, descent rate, engine fuel consumption, load factor, and density of the fuel used.



Altitude	15000	m
Engine feed mass flow rate at alt=Z	1	kg/s
Engine feed mass flow rate at alt=0	6	kg/s
Fuel density	800	kg/m3
Load factor	3	g
Dive rate	200	m/s
Ground level temperature	20	°c

Figure 8. Top-level requirement



System properties			
Boost pump			
Engine feed Pressure	p.ef	150000	Pa
Engine feed mass flow rate	mf.ef	3	kg/s
Engine feed volume flow rate		0,00375	m3/s
Cavitated engine volume flow rate		0,00442	m3/s
Collector tank			
Volume	v.ct	0,75	m3
Pressurization	pn.ct	30000	Pa
∑ Pressure		56431	Pa
Max neg pressure if pressurization system fails	negp.ct	15000	Pa
HOPPER-tank			
Volume	v.ht	0,7	m3
Pressure	pn.ht	10000	Pa
Number of Jet Pumps	n.htjp	2	st
Accumulator			
Volume	v.a	0,2	m3
Pressure	p.a	170000	Pa
Pipes			
Flow speed	f.ef	2,5	m/s
ζ low	k.efl	0,5	
ζ high	k.efh	2	
Component properties			
Collector tank			
Specific weight	w.ct	0,0002	kg/m3Pa
Boost pump			
Specific weight	w.bp	0,0058	kg/W
Efficiency	e.bp	0,8	
λ	l.bp	40,00	failures/Mh
HOPPER-tank			
Specific weight	w.ht	0,0002	kg/m3Pa
Jet Pump weight	w.htjp	0,2	kg
Jet Pump Power Loss	pwr.htjp	100	W
λ Jet pump	l.htjp	3,5	failures/Mh
Accumulator			
Specific weight	w.a	0,005	kg/m3Pa
λ	l.a	18	failures/Mh

Figure 9. Parameter sheet for the engine feed sub systems alternatives

In the spreadsheet, there are underlying sheets with design parameters that need to be chosen. These might be pipe diameters, pressurization levels, pump characteristics, tank volumes etc. Figure 9 shows, for the purposes of illustration, the design parameter sheet for the engine feed subsystem alternatives. There are similar sheets connected to every subsystem domain in the morph matrix.

4. Illustrative example

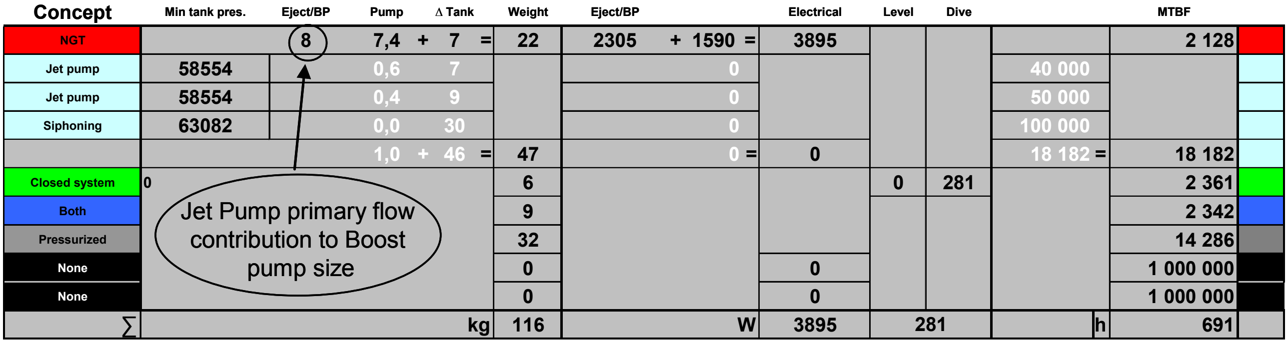
Let us analyze the Figure 7 system proposal in more detail.

The engine feed sub system is a conventional negative g tank (NGT) with a boost pump. It can be seen that the pump weight is estimated to be 7 kg and the structure weight penalty due to tank pressurization is 7 kg. The power consumption is 1.59 kW and the MTBF is 2128 hours

The transfer system consists of a centrifugal pump in each transfer tank, including the drop tank. This type of system is here called a distributed pump system.

Something that is not shown in the top-level model spreadsheet is that all tanks are pressurized at 25 kPa in order to suppress cavitation. This adds to the structural weight. The vent and pressurization system is of the closed type and needs 281 W of compressed air to maintain tank pressure during a maximum dive, and nothing at level flight.

If the complete system proposal is summed up it is possible to see that the estimated weight is 99 kg, the estimated power consumption is 3.5 kW electricity and 281 W compressed air, and the estimated system MTBF is 534 hours.



Concept	Min tank pres.	Eject/BP	Pump	Δ Tank	Weight	Eject/BP	Electrical	Level	Dive		MTBF	
NGT		8	7,4 +	7 =	22	2305 + 1590 =	3895				2 128	🟥
Jet pump	58554		0,6	7		0				40 000		
Jet pump	58554		0,4	9		0				50 000		
Siphoning	63082		0,0	30		0				100 000		
			1,0 +	46 =	47	0 =	0			18 182 =	18 182	
Closed system	0				6			0	281		2 361	🟩
Both					9						2 342	🟦
Pressurized					32						14 286	▨
None					0		0				1 000 000	■
None					0		0				1 000 000	■
∑				kg	116	W	3895	281		h	691	

Figure 10. Quantified system performance of competing system proposal.

4.1 Change in the system objective

Let us do a trade study where the system objective is switched from low weight to robustness.

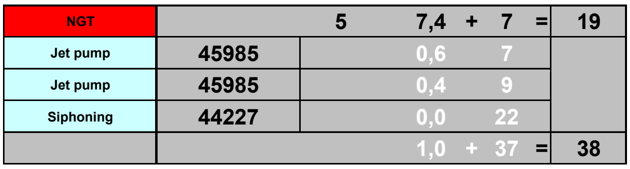
Figure 10 shows a competing system proposal. The distributed pump system for fuel transfer is changed to jet pump from fuselage and wing tanks. The drop tank fuel is transferred by siphoning.

Although the jet pumps themselves are less heavy than centrifugal pumps, the primary flow adds to the boost pump size which makes the system heavy. Siphoning from the drop tank requires a higher tank pressure than the pump alternative; the pressure level is suggested by the model, here 63 kPa, which adds to the structural weight.

All in all, we end up with a heavier, more power consuming system, but on the other hand one that is more robust, as indicated by the estimated MTBF, which is 157 hours longer.

4.2 Change in top- level requirements

It is also possible to make trade studies between system performance and top level requirements. If the top level requirements are altered by changing the load factor from three to one (the load factor level at which the transfer system has to deliver requested transfer flow), the required pressure level for siphoning from the drop tank is lowered from 63 to 44 kPa. This is because the fuel head is decreased to one third and this yields a 9 kg lighter structure as shown in Figure 11.



NGT		5	7,4 +	7 =	19
Jet pump	45985		0,6	7	
Jet pump	45985		0,4	9	
Siphoning	44227		0,0	22	
			1,0 +	37 =	38

Figure 11: Lower system weight due to lower load factor requirement.

5. Discussion and conclusions

The framework presented in this paper is one step towards more formal methods in conceptual design. In conceptual design, there are many activities that cannot be formalized. However, automating activities that could be formalized is an important step towards increasing efficiency in the design process. More time is thereby made available for activities that cannot be formalized. Furthermore, the outcome of the modeling is not the only important result. Important knowledge is also gained during the process of quantifying the matrix and formulating the problem.

Objective function formulation is a central issue in conceptual design, where models are rough and requirements are vague. It is not realistic to believe that one optimal solution could be found at this stage. The advantage is rather to be able to find a group of concepts that is promising for further evaluation. The objectives are also often conflicting ones, and it is not clear which objective is the most important. The quantified matrix is useful at the beginning of the conceptual design phase, as shown in Figure 12. Making more detailed models is not meaningful at this stage due to the large number of assumptions and uncertainties. As the number of evaluated concept decreases later in the conceptual phase, more refined evaluation techniques and models are more appropriate.

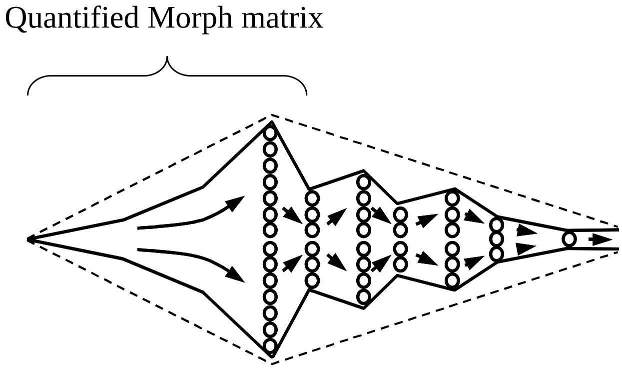


Figure 12: The quantified morph matrix related to concept generation and selection as described by [12]

Quantifying the morph matrix as described in this paper has the following advantages:

- It is a way to introduce automation early on in the design process and thus rationalize the conceptual work and at the same time increase understanding of the design problem
- It minimizes the number of concepts derived by the use of morphology that have to be pursued into more detailed analysis.

Quantification of the matrix opens up for optimization as stated in the general introduction paragraph. There is ongoing work with the aim to further reduce development time and at the same time increase number of investigated concept proposals by use of optimization algorithms.

Results for this work will be presented in the near future.

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