On Aircraft Fuel Systems
Conceptual Design and Modeling

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Abstract

THE LARGEST AND most important fluid system in an aircraft is the fuel system. Obviously, future aircraft projects will involve the design of fuel system to some degree. In this project design methodologies for aircraft fuel systems are studied, with the aim of shortening the system development time.

This is done by means of illustrative examples of how optimization and the use of matrix methods, such as the morphological matrix, house of quality and the design structure matrix, have been developed and implemented at Saab Aerospace in the conceptual design of aircraft fuel systems. The methods introduce automation early in the development process and increase understanding of how top requirements regarding the aircraft level impact low-level engineering parameters such as pipe diameter, pump size, etc. The morphological matrix and the house of quality matrix are quantified, which opens up for use of design optimization and probabilistic design.

The thesis also discusses a systematic approach when building a large simulation model of a fluid system where the objective is to minimize the development time by applying a strategy that enables parallel development and collaborative engineering, and also by building the model to the correct level of detail. By correct level of detail is meant the level that yields a simulation outcome that meets the stakeholders' expectations. The experienced gained at Saab in building a simulation model, mainly from the Gripen fuel system, but also the accumulated experience from other system models, is condensed and fitted into an overall process.

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Linköping, December 2006

Hampus Gavel

Papers

T HE FOLLOWING SEVEN papers are appended and will be referred to by their Roman numerals. The papers are printed in their originally published state except for changes in formatting and correction of minor errata.

[I]   GAVEL H., BERRY P., AXELSSON A., "Conceptual design of a new generation JAS 39 Gripen", *44th AIAA Aerospace Sciences Meeting and Exhibit,* paper No AIAA-2006-0031, Reno, USA, 2006.

[II]   GAVEL H., LANTTO B., ELLSTRÖM H., JARELAND M., STEINKELLNER S., KRUS P., ANDERSSON J., "Strategy for Modeling of large A/C fluid systems", *SAE Transactions Journal of Aerospace 2004,* pp 1495-1506, 2004.

[III]   GAVEL H., ANDERSSON J., JOHANSSON B., "An Algorithmic Morphology Matrix for Aircraft Fuel System Design", *25th Congress of the International Council of the Aeronautical Sciences,* paper No ICAS-2006-9.2.2, Hamburg, Germany, 2006.

[IV]   GAVEL H., ÖLVANDER J., JOHANSSON B., KRUS P "Aircraft fuel system synthesis aided by interactive morphology and optimization", *45th AIAA Aerospace Sciences Meeting and Exhibit*, paper No AIAA-2007-0653, Reno, USA, 2007.

[V]   GAVEL H., KRUS P, ANDERSSON J, "Quantification of the Elements in the Relationship matrix. A conceptual study of Aircraft Fuel System", *42nd AIAA Aerospace Sciences Meeting and Exhibit*, paper No AIAA-2004-0538, Reno, USA, 2004.

[VI]   GAVEL H., KRUS P., ANDERSSON J., JOHANSSON B., "Probabilistic design in the conceptual phase of an aircraft fuel system.", *7th AIAA Non-Deterministic Design Forum*, paper No AIAA-2005-2219, Austin, USA, 2005.

[VII]   GAVEL H., ÖLVANDER J., KRUS P., "Optimal Conceptual Design of Aircraft Fuel Transfer Systems" *Journal of Aircraft*, vol.43, No.5, pp 1334-1340, 2006.

The following papers are not included in the thesis but constitute an important part of the background.

[VIII] GAVEL H., "Fuel Transfer System in the Conceptual Design Phase", *SAE World Aviation congress and Display 2002*, Paper No 2002-01-2931, Phoenix, USA, 2002.

[IX] GAVEL H., ANDERSSON J., "Using Optimization as a Tool in Fuel System Conceptual Design", *SAE World Aviation Congress and Display 2003*, Paper No 2003-01-3052, Montreal, Canada, 2003.

[X] LANTTO B., ELLSTRÖM H., GAVEL H., JARELAND M., STEINKELLNER S., JÄRLESTÅL A., LANDBERG M., "Modeling and Simulation of Gripen's Fluid Power Systems" *Recent advances in aerospace actuation systems and components*, Toulouse, France, 2004.

Contents

1
Introduction

IN THE PAST, before the 1980s, new aircraft (a/c) types were developed just a couple of years apart. This was true of both civil and military combat a/c. In those days, there was no shortage of experienced engineers in early design of a new a/c, who knew the important factors when making a choice between different concepts. Today, 20-30 years between new a/c models is not unusual, at least not in the military industry. Although well-educated engineers are available, lack of experience in a/c specific supply systems is becoming an increasing problem for a/c system design.

Making the right design decisions in the early design phase is vital to the success of a project. It can be 100 times more expensive to correct an error late in the design or during production phase compared to correcting it in the planning phase. Retrofitting a modification in operational aircraft is extremely expensive. The importance of useful tools and methods in early design must therefore not be underestimated.

The largest and most important fluid system in an aircraft is the fuel system. Obviously all aircraft projects involve the design of a fuel system to some degree. The objective of this thesis is to describe how the use of design methods may shorten system development time in the conceptual phase by early introduction of design automation. In this way more concepts can be evaluated in the early stages of aircraft design. Every step in the system development process that can be formalized and automated reduces the time needed from days to minutes or even seconds. Consequently, there is an enormous potential for improvement. The objective is also to minimize the number of mistakes by helping the designer increase his or her understanding of how flight conditions impact the low-level design parameters such as pumps, valves, pipes etc. This is done by giving illustrative examples of how optimization and the use of matrix methods, such as the morphological matrix, house of quality and the design structure matrix, have been developed and implemented at Saab Aerospace in the conceptual design of a/c fuel system.

The thesis also discusses a systematic approach when building a large simulation model of a fluid system where the objective is to minimize the development time by applying a strategy that enables parallel development and collaborative engineering and also by building the model to the correct level of detail. By correct level of detail is

meant the level that yields a simulation outcome that meets the stakeholders' expectations. That is, it should be accurate enough to provide a basis for the design decisions at hand. The experienced gained at Saab in building a simulation model, mainly of the Gripen fuel system, but also incorporating the accumulated experience from other system models, is condensed and fitted into an overall process.

The thesis begins with a section that describes engineering design. This includes the design processes in general, the conceptual phase in particular, matrix methods used in engineering design, modeling, optimization and probabilistic design. There then follows a brief example of aircraft system design and an overview of the basics of fuel system design. The fuel system chapter is a condensation of [11] Gavel, in which fuel system fundamentals are described in detail. This is followed by giving the reader examples of how early conceptual design at Saab Aerospace have been facilitated by the use of optimization and matrix methods. A description of a strategy proposal intended for development of large simulation models is also included. The final chapter consists of a discussion and a presentation of the conclusions.

2
Aims

This thesis couples several aspects of aircraft fuel system development. The aim of this research is to contribute to the reduction of fuel system development time. For every step in the system development process that can be formalized and automated, time is reduced from days to minutes or even seconds. Consequently, there is an enormous potential for improvement. A second aim is to reduce the number of mistakes in early phases of design that may necessitate time-consuming late redesign or expensive retro-modifications by increasing understanding of how the top level requirements impact low level practicalities such as an aircraft fuel system. The primary research questions can be formulated as:

- How can the development of aircraft fuel systems be supported in the conceptual design stage?

- How can optimization based on modeling and simulation be used in conceptual design?

- How can it be assured that top-level requirements are handled properly in low-level design?

- How can the development time for large fluid system models be reduced?

The answers to these questions are sought by improving existing and inventing new methods and techniques for design which are then tested and evaluated in development projects at Saab Aerosystems.

3
Engineering Design

IN THIS CHAPTER the theoretical background of the project is presented. First there is a brief overview of design processes. This is followed by an introduction to matrix methods for design. Then modeling and optimization are described and finally there is a section about probabilistic design.

Engineering design is a way to solve problems where a set of often unclear objectives have to be balanced without violating a set of constraints. Based on this statement, it might be said that design is essentially an optimization process, as stated by Herbert Simon [39] as long ago as 1967. By employing modern modeling, simulation and optimization techniques, vast improvements can also be achieved in the conceptual part of the design process. It is, however, recognized that for the foreseeable future there will be parts of the design process that require human or unquantifiable judgment and are thus not suitable for automation.

A great deal of research has been done in the field of engineering design and has led to different design processes and methods. Various authors present different models of the design process, such as for example Cross [7], Pahl& Beitz [31], Suh [44], Ullman [47] and Ulrich and Eppinger [48]. They all describe a phase-type process of different granularity with phases such as Specification, Concept Design, Preliminary Design, Detail Design, Prototype Development, Redesign, and Production (using the names along the bottom of Figure 1). One main focus of the work presented in this thesis is to support the conceptual design phase both in terms of concept generation and concept selection.

Ullman [47] p 13, speaks of the design paradox, where very little is known about the design problem at the beginning but we have full design freedom. As time in the design process increases, knowledge about the problem is gained but the design freedom is lost due to the design decisions made during the process. To further stress the importance of the early phases of the design process, it is here that most of the cost is committed. To summarize: at the beginning of the design process of a new product, we have little knowledge of the problem, but great freedom in decision making, and the decisions we make determine much of the cost induced later in the design process. However, one would wish to be able to obtain more knowledge early on, to maintain the same high

degree of design freedom and postpone the commitment of costs, as illustrated in Figure 1. The work presented in this thesis addresses, among other things, the issue of gaining knowledge early at low cost.
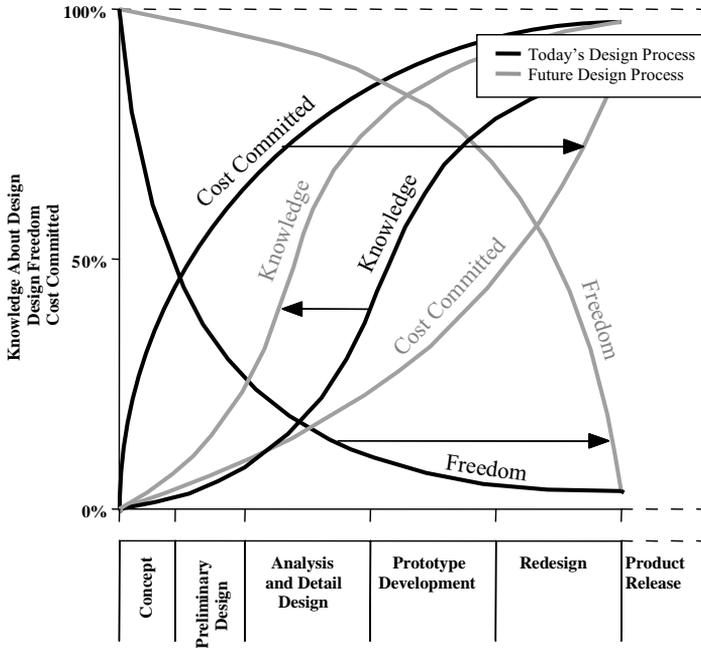
Figure 1: *A paradigm shift in the design process. When knowledge about design is enhanced at an early stage, design freedom increases, and cost committing is postponed. Illustration from [9], [27] and [29].*

3.1 The design process

There have been many attempts to devise maps or models of the design process according to [7] Cross, who continues, "*Some of these models simply describe the sequences that typically occur in designing; other models attempt to prescribe a better or more appropriate pattern of activities.*"

A descriptive process describe the sequence how design activities usually occur in practice and therefore most often focuses on generating concepts, which are then analyzed, further developed, and refined. Descriptive processes are regarded as solution focused. An example of a descriptive design process is the basic design cycle from [34] Roozenburg and Eekels shown in Figure 2.
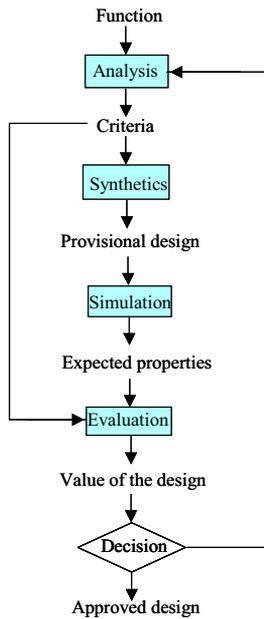
Figure 2: *The basic design cycle as described in [37] Roozenburg and Eekels.*

A prescriptive process, on the other hand, typically stipulates a pattern of design activities for addressing the design problem rather than describing how the work is actually done. There are many prescriptive process suggestions for design to be found in the literature. The prescriptive models for design are regarded as more analytical or more algorithmic, providing a design methodology. The prescriptive process has more emphasis on the analytical work that forms the foundation for the concept generation. A more prescriptive process is the one described by [31] Pahl and Beitz and shown in Figure 3.
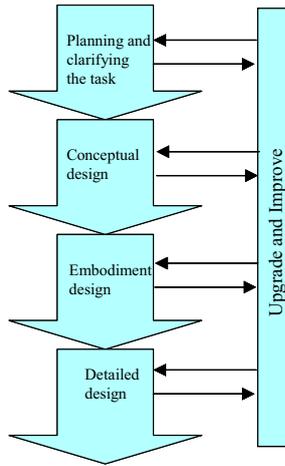
Figure 3: *Steps in the planning and design process according to [31] Pahl and Beitz.*

Another of the prescriptive processes described in the literature is the product development process suggested by [48] Ulrich and Eppinger shown in Figure 4. A significant difference between the two is that Ulrich and Eppinger have a separate testing and refinement phase where Pahl and Beitz instead encourage the designer to continuously test and refine throughout the entire process.
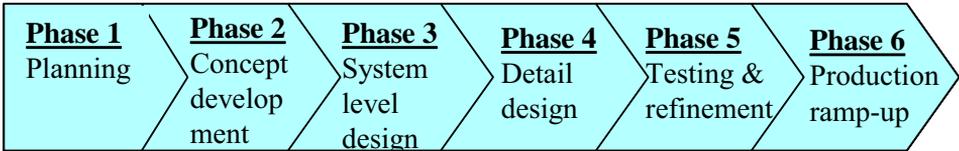
Figure 4: *The product and development process as suggested by [48] Ulrich and Eppinger.*

3.1.1 Concept design

Since part of this thesis targets conceptual design specifically, this phase in the design process will be described in more detail.

After completing the clarification phase, the conceptual design phase determines the principal solution. Conceptual design results in a specification of principle, according to [31] Pahl and Beitz. The conceptual phase may be divided into two principally different activities; concept generation and concept selection.

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 [7]. The morphological chart, described in a later section, exploits this and encourages the designer to identify novel combinations of components or sub-systems. Several authors propose different methods to be used to support concept generation. For example both Pahl and Beitz [31] and Ulrich and Eppinger [48] use a 'Black box' in order to break down an overall function into sub-functions. These sub-functions could be arranged in a functional structure as proposed, for example, by Pahl and Beitz [31] and Ullman [47]. Different solution principles for each sub-function could then be presented in a function-means tree as described by Andreassen in [3], or in a classification tree to use the nomenclature of Ulrich and Eppinger [48].

According to Ulrich and Eppinger [48], concept selection is an iterative process closely related to concept generation and testing. Concept selection may then again be separated into screening the inferior concepts and identifying the superior concepts. Concept screening and scoring methods help the team refine and improve the concepts, leading to one or more concepts upon which further testing and development activities will be focused. Concept generation and selection is shown schematically in Figure 5.
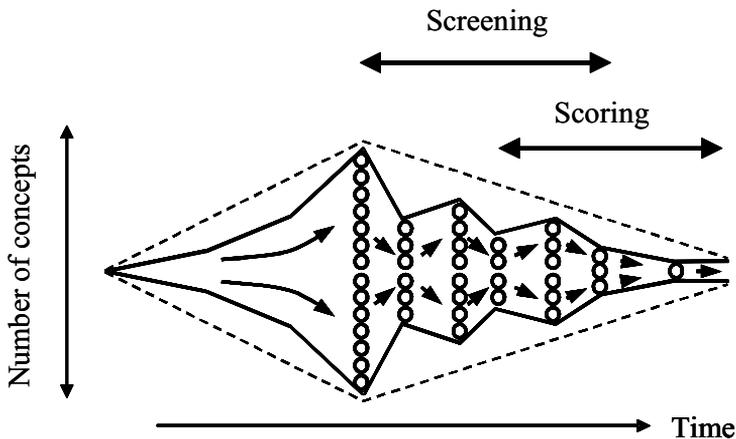
Figure 5: *Concept generation and selection according to [48]Ulrich and Eppinger.*

3.2 Matrix Methods in Engineering Design

A number of matrix based methods have been developed to support engineers in different stages of design. In this section, a small selection of these are described in more detail. Two notable matrix methods that are omitted are Kesselring's criteria-weight method described in [20] or [31] and Pugh's datum method [33], intended for concept

comparison and selection. These two methods are left out since they are not exploited in the research described in this thesis.

3.2.1 The Design Structure Matrix

The Design Structure Matrix is an information exchange model, originally developed by [41] Steward, and has since then been developed further by for instance Eppinger et al [8]. Complex systems and processes include several components/subsystems or activity steps which interact in a sometimes complex network of dependencies. The DSM is useful as a tool for mapping dependencies. The DSM may be applied in several engineering domains such as engineering management [8], design optimization [2], and conceptual design [32], to give just a few examples.

   In the illustrative example shown here, the purpose is to map subsystem dependencies so as not to overlook any combinatory effects. This is vital when evaluating complex systems. The example used is the comparison of the two fuel system proposals in Figure 6, one with pump transfer and one with fuel transfer by siphoning. The pump transfer concept includes a transfer pump that pumps fuel from the transfer tank and an engine feed pump that pumps fuel to the engine. Both tanks are pressurized in order to avoid pump cavitation. In the siphon concept, only the transfer tank is pressurized and the fuel is siphoned by differential pressure to the engine feed tank from where the fuel is pumped to the engine.
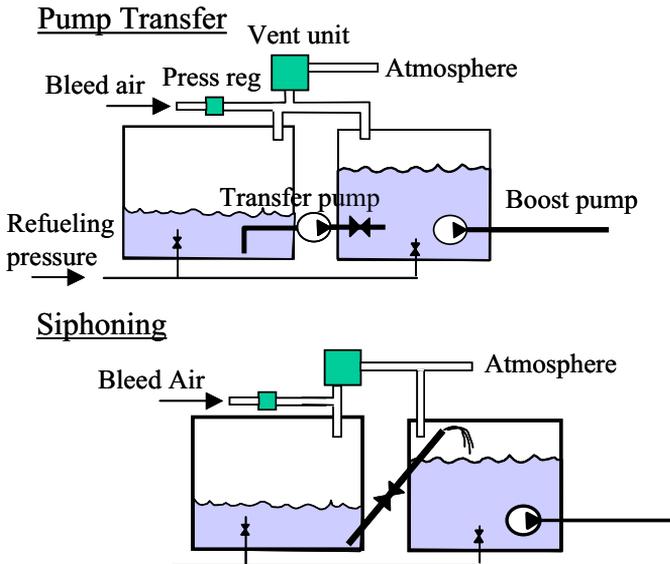
Figure 6: *Concept proposals. Pump concept at the top and siphon concept below.*

Subsystem dependencies of the pump and the siphon concepts are shown in Figure 7. For instance, it is possible to se how the engine feed in the pump concept relies on the pressurization system (to minimize cavitation). Another example is the interaction between the refueling and vent systems (shown in Figure 32 in a later chapter). Note that it is preferable to partition the matrix so that it becomes as lower triangular as possible in order to obtain as good a view of the information flow as possible.

Pump:

	A	B	C	D	E
A Pressurization	A				
B Engine feed	x	B			
C Vent system			C	x	
D Refueling			x	D	
E Fuel transfer	x				E

Siphon:

	A	B	C	D
A Engine feed	A			
B Vent system		B	x	
C Refueling		x	C	
D Fuel transfer	x			D

Figure 7: *Subsystem dependencies for the pump and the siphon concept visualized with the DSM.*

It might also be argued that if the matrix is kept diagonal or lower triangular this will yield some advantages: the system becomes more robust, it simplifies modification since changes only will affect subsystems that are 'down stream', which otherwise may lead to an endless loop of redesign without any clear optimum. This is in many ways similar to axiomatic design, which is discussed in a later section. If the DSM is uncoupled or lower triangular, the design will most likely satisfy the first axiom of axiomatic design.

3.2.2 The House of Quality

One way of visualizing the subsystem and requirements relationship is to use the framework of the relationship matrix from the House of Quality method. The House of Quality was originally developed as a quality tool for mapping customer expectations against product properties, as stated for instance by [6] Cohen or [18] Hauser and Clausing. However, it works just as well for showing dependencies between subsystems and top-level requirements, as shown by [2] Andersson.

The top-level requirements' impact on the pump concept is shown in Figure 8. Note

that the matrix has been transposed, with requirements at the top and subsystems to the left. The reason for this is explained in section 6.3.1. It can be seen, for example, that engine fuel consumption and altitude will impact the engine feed. The engine fuel consumption puts demands on fuel flow, and altitude (atmosphere pressure) will impact the sensitivity to cavitation. The characteristic House of Quality roof in Figure 8 shows the dependencies between the top requirements. In this case the fuel consumption and the maximum turn rate will decrease as altitude increase. The matrix, used in this manner, is henceforth referred to as the relationship matrix.

	Engine fuel consumption	Turn	Dive	Climb	Altitude	Refueling pressure
A. Pressurization system	x	x			x	
B. Engine feed	x				x	
C. Vent system			x	x		x
D. Refueling system						x
E. Transfer system		x			x	

Figure 8: *Top-level requirement impact on subsystems visualized using the House of Quality framework.*

3.2.3 Axiomatic design

Axiomatic design, a design methodology described in [44], consists of much academic theory and a great deal of mathematics. Eventually it boils down to a vector of functional requirements {FR} and vector of design parameters {DP}. These two vectors are related to each other by a matrix [A], called the design matrix, which describes the design, as shown in Figure 9.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$

Figure 9: *The framework of axiomatic design.*

Axiomatic design fundamentals are the two axioms (i.e. given without proof). The first axiom, the independence axiom, tells us that the DPs must preferably remain uncoupled. If a coupling is impossible to avoid, the design matrix should be made lower triangular by partitioning the matrix, which in practice means that there is no backward influence if the DPs are redesigned or if the FRs are changed, provided the activities are made in the correct order. A coupled matrix that can not be partitioned in such a way is called a full matrix and should always be avoided, see Figure 10.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad \begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & X \\ X & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$

Figure 10: *An uncoupled design on the left, a decoupled design in the middle and a coupled design on the right.*

The second axiom tells us that if the first axiom is satisfied, the information (complexity) should be kept to a minimum.

The axiomatic design methodology encourages the designer to break down costumer expectations into requirement and find out how they impact the design parameters, and also to keep the design uncoupled and as simple as possible. This is sound and will most certainly produce a design with fewer fundamental shortcomings. However, the author, even though he tries to adopt axiomatic thinking in his own daily engineering work in the aerospace industry, has two minor objections.

First, a coupled design may sometimes be preferred to an uncoupled design because it saves weight. Low weight and functionality are always conflicting objectives in a/c design. The first axiom is therefore not always applicable in the sense that coupled designs by default are undesirable, even though it is most often a sound principle

Second. Suh [44] seems to confuse what in the field of control theory is known as reference value (set point) and actual value. There are several examples of designs that do not satisfy all requirements but nevertheless are successful. Perhaps functional performance (actual value) is a more appropriate denotation than functional requirements (reference value), which are then to be compared to the requirements in a later evalua-

tion in order to obtain a design loop and eventually end up at an optimum.

3.2.4 The Morphological matrix

The morphological chart is a method that supports synthesis 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 sub-functions 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 11.

The Saab Gripen fuel system

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	SAPOM	OBIGGS	Stored OBIGGS	Stored nitrogen	Etc

Figure 11: *Morphological matrix showing the fuel subsystem combination of the Saab Gripen.*

Morphology is a way of thinking introduced by the astrophysicist Fritz Zwicky (1898-1974). One of the ideas of morphology is to search systematically for a solution to a problem by trying out all possible combinations in a matrix. Zwicky termed the matrix a 'morphologic box'; other names used 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 [50], [51] and [52].

   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 11 already gives the designer no less than 2,880 possible concept combinations. Other approaches in the literature that address some of these deficiencies include a web based morphological matrix that supports collaborative engineering design [19], and computerized morphological analysis applied to scenario development and strategy analysis by the Swedish Defence Research Agency [36]. Further, Weiss and Gilboa [49] present a framework where the performance of solution principles is ranked from 5 to 0 and "optimal" concepts are generated by selecting the solution principles that yield the highest ranking. This is a very crude quantification of the properties of the solution principles and the optimization is not formalized mathematically.

3.2.5 Summary of matrix methods

A classification of matrix based methods for product design in general can be found in Malmqvist [26]. However, his thesis focuses on the use of matrix methods in the conceptual design phase in particular. There are a number of matrix based methods that may support different activities in conceptual design such as synthesis, analysis or evaluation. An attempt to classify some of these methods and what design activity they support is shown in Figure 12.
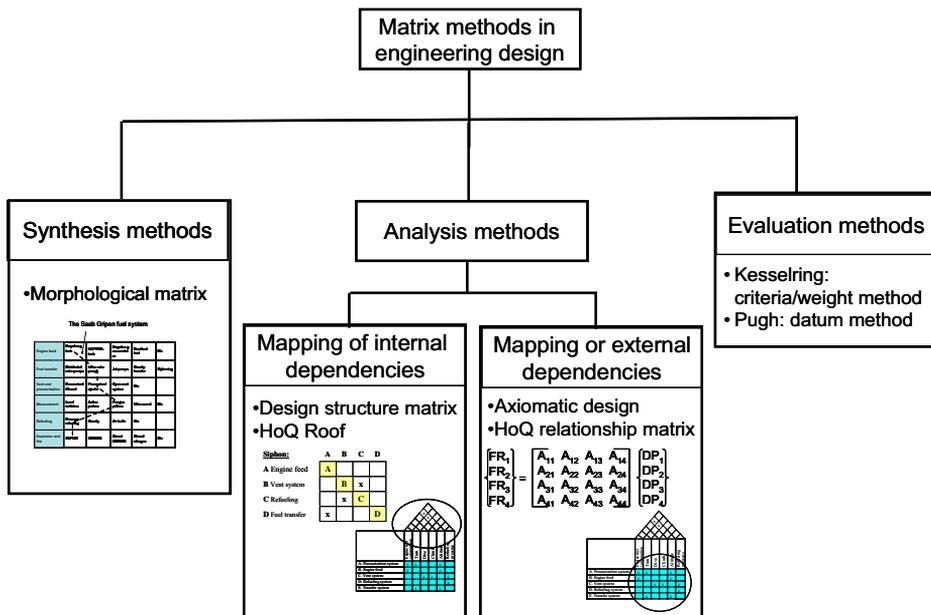

Figure 12: *Classification of some matrix methods in engineering design in relation to different activities in the conceptual design phase.*

Upon closer study and comparison of some of the methods themselves, it is possible to recognize close resemblance between for instance the DSM and Hose of Quality (HoQ) methods and axiomatic design. A design with an uncoupled DSM will for instance most likely satisfy the first axiom of axiomatic design. Axiomatic design and the relationship matrix of HoQ are both exploiting the same technique of mapping similar information flow.

3.3 Computational design

In this section some aspects of computational design are described. Computational design is a fast growing field whose development is obviously closely coupled to the rapid improvement in the computational capability of computers. There is no clear definition of the term computational design, and it is interpreted differently in different engineering domains due its broad implication. However, computational design methods are characterized by operating on computer models in different ways in order to extract information. Described here are modeling and simulation, optimization, and probabilistic design, which all doubtlessly qualify as computational design activities.

3.3.1 Modeling and simulation

How a model may be defined in a broader sense is described by [35] as; "*A model is a representation of a system that replicates part of its form, fit, function, or a mix of the three, in order to predict how the system might perform or survive under various conditions*".

Another explanation is given by [10] who begins by defining an experiment as extracting information about a system by exercising its inputs. A model may then be defined as something that answers questions about the system without performing experiments on the real system. Models may be mental, verbal, physical or mathematical. A simulation is then defined as an experiment performed on a model. However, this thesis is limited to exploitation of mathematical models, typically those implemented in a computer environment. In fact, part of this thesis targets computer modeling of large fluid systems specifically [II], which could generally be described by a mix of differential and algebraic equations.

3.3.2 Optimization

As the computational capabilities of computers increase, the scope for simulation and numerical optimization is enlarged. A great part of the design process will always be intuitive. However, analytical techniques, simulation models, and numerical optimization could be of great value and permit vast improvements in design according to [2] Andersson.

Optimization methods can be divided into derivative and non-derivative methods. Non-gradient methods are more robust in locating the global optimum and are applicable to the typical engineering problem that most often lacks an easily obtained derivative to be used in the optimization. The disadvantage, however, is that it is not possible

to prove that the actual optimum has been found. However, as gradient methods might get stuck on a local optimum this is partially true for them as well. Another disadvantage with non-gradient methods is that they require more function calls and are thus more expensive from a computational point of view. There are a large number of non-gradient methods, for example the complex method described below, genetic algorithms, and the similar evolutionary algorithms developed in the 1970s.

Optimization is commonly used to support and speed up aircraft design. Traditionally, optimization has been widely used in disciplines such as structural engineering and aerodynamics, and recently also in the growing field of multidisciplinary design optimization [30], [43], [30]. The methods used range from analytical techniques to heuristic and stochastic search methods such as genetic algorithms, simulated annealing, and a great many more [16], [17]. Approximation techniques such as response surface methods [42] and Kriging [40] are also frequently used. In this thesis, the focus is on using optimization based on simulation models.

The Complex algorithm

The Complex method was first presented in [5] Box in the mid 1960s. The method begins by randomly generating k feasible points in the solution space. The geometrical figure with k vertices/points in R^n is called a complex. The number of points in the complex has to be greater than the number of optimization parameters. Box recommended that the complex consist of twice as many points as optimization parameters. The value of the objective function is calculated for each point and the basic idea of the algorithm is to replace the worst point by a new and better point. The new point is calculated as the reflection of the worst point through the centroid of the remaining points in the complex. The reflection distance is varied so that the complex expands to search in new regions, and contracts if the new point repeats as the worst. In the next iteration, a new point has become the worst, which in turn is reflected through the centroid of the new complex. This procedure is continued until the whole complex has converged to the optimum, as shown in Figure 13. For a more detailed description, see [23] Krus et al.
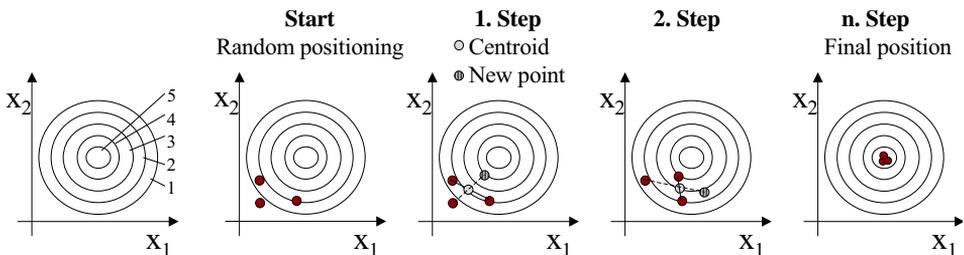
Figure 13: *The progress of the Complex method for a two dimensional example, with the optimum located in the center of the circles.*

3.3.3 Probabilistic design

Probabilistic design is a non-deterministic technique that helps the design team to handle and also model uncertainties. "*Probabilistic analysis allows for examination of systems with imprecise or incomplete information*", according to Mavris and DeLaurentis [26]. All design parameters are subject to variation and if significant variation is taken into account it is more probable that the design will be successful. The uncertainties are dealt with by introducing distributions instead of fixed numbers when describing these properties. The parameter distributions are typically used as input to a Monte Carlo simulation. A Monte Carlo Algorithm is a method which solves a problem by generating suitable random numbers and observing that fraction of the numbers that obey some property or properties. The method is useful for obtaining numerical solutions to problems which are too complicated to solve analytically. By running a specified number of Monte Carlo trails, it is possible to obtain variation forecasts of system characteristics that are of special interest when evaluating the design.

4

Aircraft System Design

AIRCRAFT CONCEPTUAL DESIGN is most often associated with a/c sizing such as determining main geometrical dimensions, weights, engines and amount of fuel carried. These are doubtless vital issues that have to be addressed. However, the subsystems and components that make up the aircraft are equally important but unfortunately most often forgotten. It is important *"to extend the view of aircraft system design beyond the preliminary aircraft design level"* as stated by Scholtz in [38]. The importance of including aircraft systems already in the conceptual phase of the a/c itself is motivated by the fact that in medium-range civil transport, systems account for about a third of the aircraft empty mass as well as a third of the development and production costs. The ratio is even higher for military aircraft.

In this chapter, early introduction of system design is illuminated by giving an illustrative example from paper [I], consisting of a conceptual study for a long-range version of JAS 39 Gripen. This project has also formed a large part of the industrial and empirical foundation for the research presented later in this thesis. The conceptual design methods described in chapter 6 were largely invented and tested while designing fuel system proposals for the a/c modification concepts described in this chapter.

4.1 Conceptual study of a long-range Gripen

Several concept proposals were investigated with extended a/c range as one of the primary aims. The objective of the study is to increase Gripen's competitiveness and flexibility in the long-range segment of the fighter market. The investigated concepts included enlargement of the existing fuel tanks, addition of new fuel tanks (external and internal), new engines with better fuel economy, and combinations of these. However, modifications that were restricted to the addition of new fuel tanks showed the greatest

promise and only these were pursued to a higher level of detail. Some of these modifications are described below.

4.1.1 Conformal tank - ventral position

This concept proposal, intended for subsonic missions such as ground attack or ferry flight, includes a ventral conformal fuel tank, see Figure 14, which is detachable but lacks in-flight separation capability. The main objective is to free the wing pylons for tactical loads rather than drop tanks.

The fuel tank forward limit is the nose gear door, the rearward limit is the engine access door, and the cross section is governed by the kinematics of the main landing gear doors and ground clearance. This concept proposal was nicknamed "the bath tub".

This proposal is economically attractive, but suffers from major drawbacks in the form of reduction in static directional stability and an increase in drag that gives a relatively small net gain considering the large amount of fuel added.
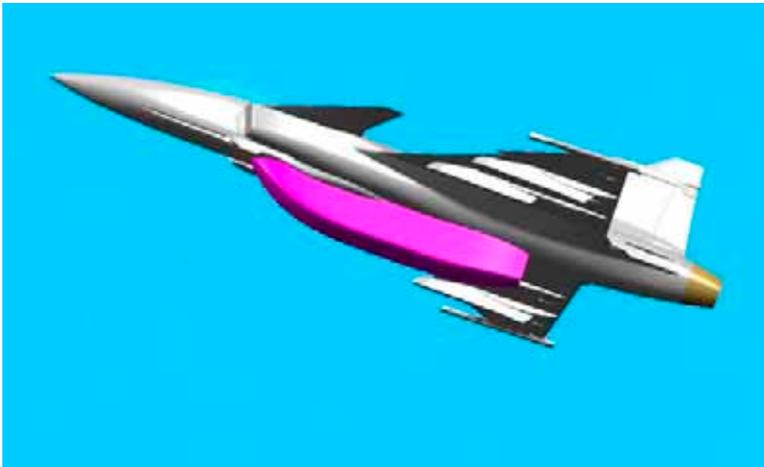
Figure 14: *The bath tub concept.*

4.1.2 Conformal tank – dorsal position

Two versions of dorsal conformal tanks were studied, one without speed requirements and one with supersonic capability. The low speed version, shown in Figure 15, has roughly double the fuel capability of the supersonic version. Wave drag was the limiting factor for size in the supersonic alternative; directional stability and pitch moment were problems which both alternatives shared.

However, it turned out that the version with the larger tank was just as capable of reaching supersonic speed as the specially designed alternative. The greatest benefit from this proposal, apart from increased weapon load capability if drop tanks are not needed, is its inherent potential for low supersonic drag increase, assuming the cross

section area distribution is properly designed to minimize the wave drag increment.

Potential problem areas that were envisioned were high angle of attack directional stability, exacerbated transonic pitch-up causing greater load factor transients, and canopy jettison. Fuel tank venting might also prove problematic since the new tank will be a 'high point'. This may cause unprogrammed fuel transfer and fuel drainage through the vent system while performing zooming climbs and steep dives.
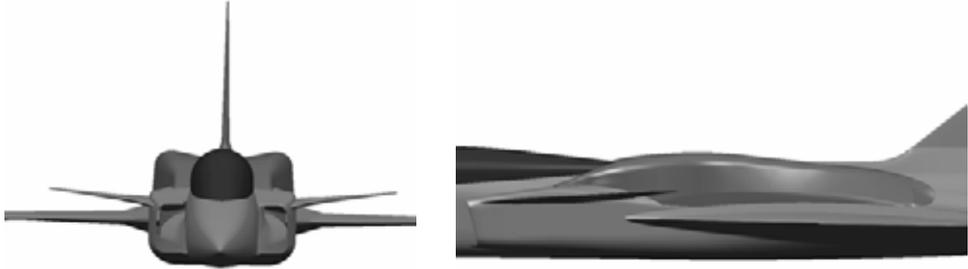
Figure 15: *The dorsal conformal tank concept, low speed proposal.*

4.1.3   New internal tanks - extended fuselage

The initial idea was to fit a double-seat forward fuselage to a single seat a/c. The aft seat is then replaced with a fuel tank, see Figure 16.

Figure 16: *The forward fuselage section of the two-seater mounted on a single seat a/c, and with the aft seat replaced with a fuel tank.*

However, a forward fuselage stretch like this would in itself cause problems with a center of gravity (CG) position placed too far forward. The proposed cure for this is to

also stretch the aft body by adding fuselage sections aft of the CG, see Figure 17. This not only puts the CG back in place, but more fuel tank volume is also added.
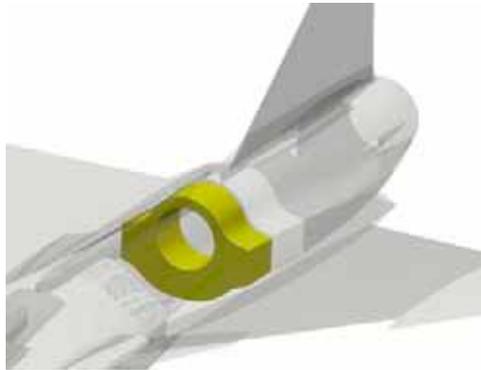
Figure 17: *A new fuselage section is added aft of the CG, thus getting the CG back in place and also adding more fuel.*

Possible problem areas are that the forebody modification will interfere with the ram air intake ducting of the environmental control system. It would also lead to a longer gun release recession which may prove problematic. As for the aft body stretch, this will lower the ground and tail clearance on take off and landing. An extended fuselage will also increase fuselage bending moment and thereby increase weight. Weight increase also means a need for beefed-up main gear, which unfortunately will not fit within the dimensions of the current housing.

4.1.4 New internal tanks - relocated main gear

The concepts mentioned all resulted in major modifications to the external shape of the aircraft. Being concerned not to change too much in a winning concept, which, to its credit, the basic Gripen concept really is, other ways of solving the range problem had to be considered. There are two huge "cavities" in the fuselage where the main gear currently is housed when retracted, which are eminently suitable for housing fuel tanks. The volume is large and well placed, very close to the a/c CG. The problem is then where to relocate the main gear, and could the layout of the main gear remain the same? The answer is no; since more fuel will now be carried inside and the payload requirement is unchanged, basically an increase in maximum take-off weight (MTOW) is necessary. An increase in MTOW would require the use of larger brakes with more energy absorption capability. In order to house a larger brake, rims with larger diameter are necessary. This will increase the overall dimensions of the wheels and tires. Since both gear and housing need to be relocated to the wing, it is obvious that the layout and kinematics of the gear must also change.
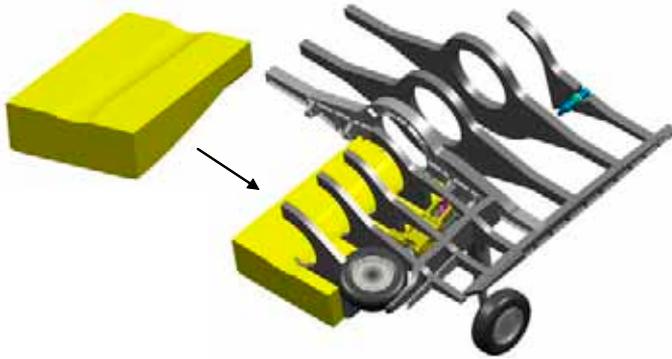
Figure 18: *The landing gear bay converted into a fuel tank, and a new landing gear with the mounting integrated into the wing structure.*

Two different main landing gear and landing gear integration concepts were evaluated. The first proposal, see Figure 18, integrated the main gear into a new blended wing structure and a new wing joint moved further out. The second proposal adapts to the existing design and geometry of the present wing and attaches the new main gear to the outside of the wing box, see Figure 19.

Figure 19: *The present (left) and proposed new (right) landing gear.*

Both alternatives include a new fairing that covers part of the wheel and main strut when the gear is retracted. As a spin-off, both proposals enable ventral twin storage which is an improvement compared to the present single store carriage, by enhancing weapon carriage capability and of course flexibility, see Figure 20.

The concept with the gear attached outside of the wing box was eventually selected as overall most promising and recommended for further development.
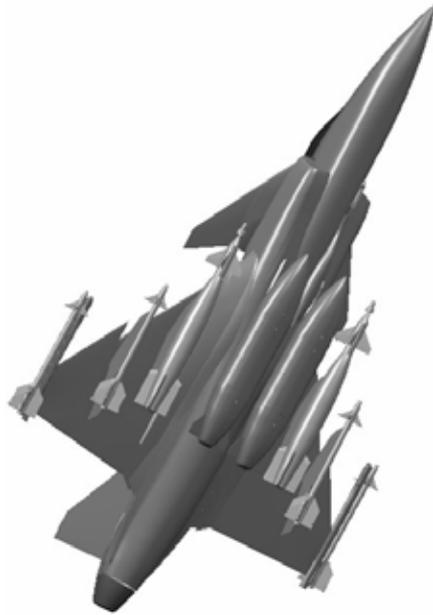
Figure 20: *Ventral twin stores.*

4.2 Systems Analysis

First, a number of concepts were generated at a/c level, of which some were easily dis-
missed without deeper analysis. As the number of concepts decreased, the analysis was
taken deeper into the a/c hierarchy, see Figure 21. System and subsystem design were
investigated and evaluated. The concept proposals were then assessed against each
other, weighing together top-level and system-level considerations.
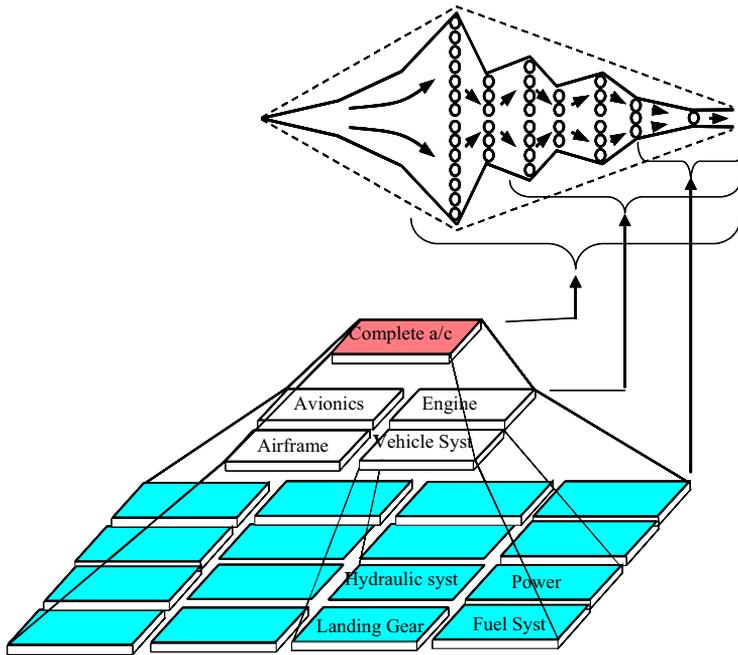
Figure 21*: Concept generation and selection related to the a/c hierarchical decomposition.*

The analysis on each hierarchical level was taken to a degree where the design team was confident that the concept would be realizable. In some cases (for instance the tank pressurization system), this led to deep analysis often associated to the embodiment or the detail design phase. The difference is that in the conceptual phase, the calculations aim to increase confidence in the concept, unlike the later phases where the aim is to determine dimensions.

Most often in a/c design, seemingly good ideas are dismissed for reason of simple practicalities. Surprisingly often, this practicality applies to landing gear design in general. This is even more common when it comes to modification of existing a/c. A similar conclusion is drawn in [34], which states that the landing gear is the internal component most likely to cause trouble in a/c conceptual design. This was taken into account early on and eventually led a proposal that amongst other things included larger gear and brakes.

However, the next practicality, that almost overthrew the proposal, was engine bleed for tank pressurization. Larger tank volume requires more air for pressurization if maximum dive speed is kept the same. A great deal of effort was put into analysis of the existing pressurization system in the hope of finding a way to increase pressurization performance. When it was clear that this was not the way forward, the main effort was redirected into conceptual design of a new pressurization system. Lesson learned: The devil is in the details.

5
Aircraft Fuel System Fundamentals

T̲HE COMPLEXITY OF a fuel system varies from the small, home-built a/c with no system complexity, up to the modern fighter were the fuel system may be critical for center of gravity (CG) reasons and therefore, very extensive, with triple redundancy. Most combat a/c fuel systems consist of several tanks for reasons of space, slosh, CG management or safety. The general layout may consist of one or more boost pumps that feed the engine/engines from a collector tank, usually a fuselage tank placed close to the CG. The collector tank is replenished by a fuel transfer system, which pumps fuel from the source tanks. Source tanks may be other fuselage, wing or drop tanks. The system may be pressurized to avoid cavitation in pumps, spontaneous fuel boiling at high altitude or to aid or provide the means for fuel transfer. The a/c fuel system may consist of several sub systems that. The ones discussed here are:

- Engine Feed System

- Fuel Transfer System

- Pressurization and Vent System

- Refueling System, Ground and Air to Air

Other systems that might be identified, and that are described in [11] Gavel, are:

- Measurement and Management System

- Fire Prevention and Explosion Suppression System

- Cooling System where the fuel serves as a heat sink to other systems

5.1 Jet fuel

5.1.1 The history of jet fuels

Early aero turbine engines were fuelled with gasoline or illuminating oil, i.e. kerosene. Difficulties in combustor design also led to experiments with diesel fuel, gas oil and hydrogen, but kerosene proved to be optimal. The development of fuels was (is) an iterative process including advances in engine design, improvements in fuel quality followed by further advances in engine design. Early US military jet a/c used aviation gasoline, which was widely available at the time. However, the lead content was hostile to turbine blading which led to the development of the kerosene-based JP-1 (Jet Propellant). Due to the rigid specification limits of JP-1, the crude oil would only yield a small portion of jet fuel, about 3%, all according to [15] Goodger. So with the increasing number of jet a/c it became obvious that a new specification was needed. Moves were made to a wide cut fuel, JP-3 in 1947. Wide cut fuel consist of both gasoline and kerosene fractions and therefore gives a relatively better outcome from the crude oil. Significant problems with volatility led to a new specification in 1951, JP-4, still a wide cut fuel but with a vapor pressure not as high as JP3. A civil version of wide cut fuel, Jet-B, appeared in 1958. Wide cut fuels are very volatile compared to kerosene, so in order to avoid vapor build up within ships (a/c carriers), a fuel for naval use with high flash point and low VP was specified in 1952, the JP-5 high flash kerosene. The penalty paid was a higher freezing point. As flying altitudes increased, the demands for lower volatility increased. The freezing point of JP-5, however, was considered to be too high. This eventually led to the specification of aviation kerosene, Jet-A1 (civil) in 1958 and JP-8 (military) in 1968.

5.1.2 Fuel production and specification

The most common source of jet fuel is crude oil, which consists of many thousands of different hydrocarbons. The crude oil is divided into fractions by distillation to provide the required boiling temperature range, see Figure 22.
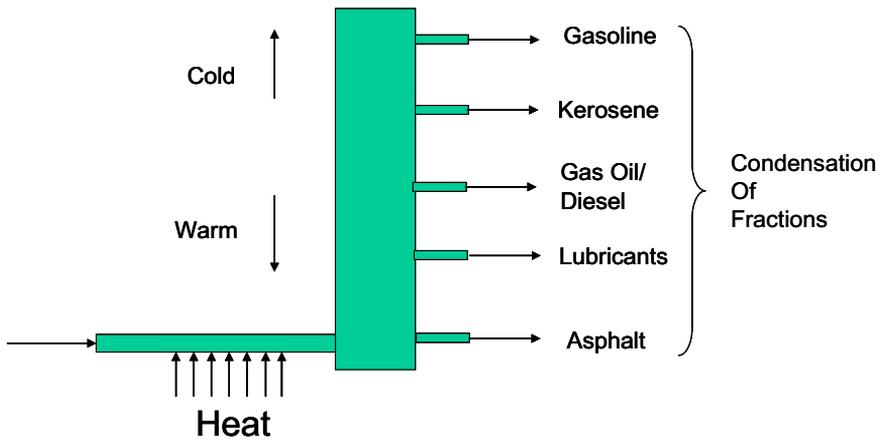
Figure 22: *Fractioning of crude oil.*

The condensation/boiling temperatures for different jet fuels at atmosphere pressure are shown in Figure 23.
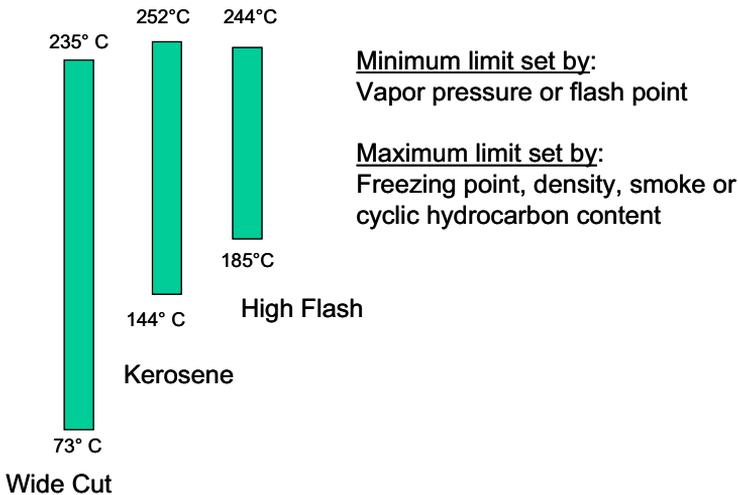
Figure 23: *Boiling ranges for different fuel types.*

The specification of an aviation fuel is a statement of the requirements of the hardware, engine, fuel system etc. The specification limits are a compromise between the requirements of the fuel supplier, the a/c operator, and the a/c and engine manufacturers. Many countries have a national activity in the field of aviation fuel. This has led to a number of specifications, where some specify more or less the same fuel. A selection is listed in the table below. In addition to the specified requirements, there are a number of

additives that may be prescribed by the a/c manufacturer.

Fuel type:	NATO	US (mil)	US (civil)	UK	SWE
Kerosene	F-35		Jet A Jet A-1	Avtur	
	F-34	JP-8			MC75
Wide Cut			Jet B	Avtag	
	F-40	JP-4			MC77
High Flash	F-43			Avcat	
	F-44	JP-5			
High Thermal Stability		JPTS JP-7			
High Density		JP-10			

5.2 Fuel tanks

According to [4] Raymer, there are three main types of fuel tank: discrete, bladder and integral tanks. The discrete tank is a separate fuel container similar to the fuel tank of a car. Discrete tanks are usually used only for small general aviation or home built a/c. The bladder tank is a shaped rubber bladder placed in a fuselage cavity. The rubber is thick and may cause a fuel loss of about 10%. The bladder may also be made self-sealing, which makes it even thicker. Bladder tanks are often difficult to use in cavities with a complex structural arrangement such as wing tanks. Integral tanks are cavities within the airframe structure that are sealed to form fuel tanks. Bladder tanks have historically been considered less prone to leakage, which explains the willingness to pay the weight penalty. As the technique for integral tank manufacture has improved, the leakage problem is now less troublesome and integral tanks are the predominant type in modern a/c design. There are, however, modern applications of bladder tanks, for instance cargo bay installation in tanker a/c intended for air-to-air refueling. The fuel tank layout of the JAS 39 Gripen is shown in Figure 24. Note the lack of fuel in the engine region.
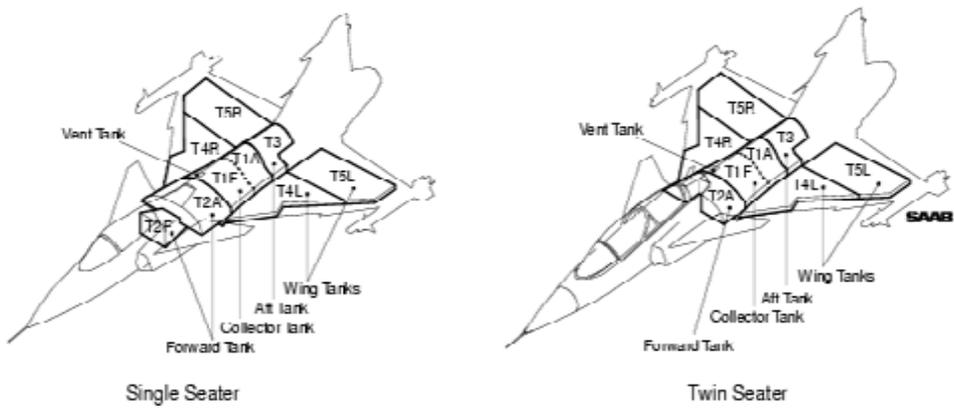
Figure 24: *Location of fuel tanks in JAS 39 Gripen*.

5.3 The engine feed system

The engine feed is by far the most important task of the fuel system. The objective of the engine feed (which is considered part of the airframe and is not to be confused with the engine's own internal fuel system) is to boost the pressure in order to avoid cavitation in the engine system. The engine and airframe interface is often defined as shown in Figure 25, where the engine feed system is considered to consist of the engine feed tank, the boost pump, and the engine feed pipe.
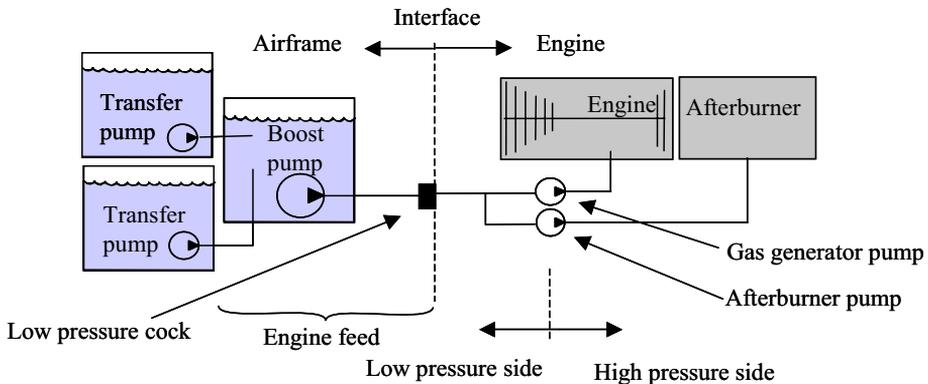
Figure 25: *Fuselage and engine fuel system*.

The availability of fuel to the engine(s) should be required for all conditions in the air vehicle operational envelope and known extreme conditions, according to [5]. Even

though there are a number of ways to deal with this, it is most often ensured by a double-ended boost pump installed in a negative g compartment as shown Figure 26.

Level flight   Negative g
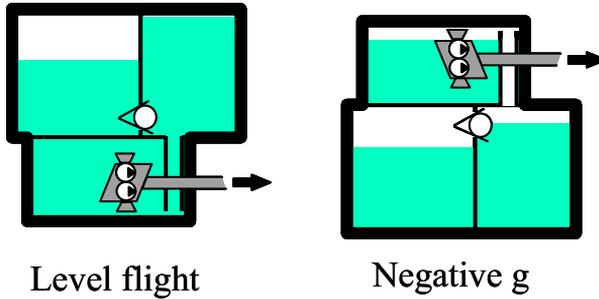
Figure 26: *Negative g tank with double ended boost pump.*

5.4 The fuel transfer system

The simplest way of transferring fuel is by gravity. This method is used in general aviation and commercial a/c depending on the tank configuration. An example of an a/c with gravity transfer is Saab 2000, shown in Figure 27, where the dihedral aids the transfer of fuel from the outboard to the inboard tank.
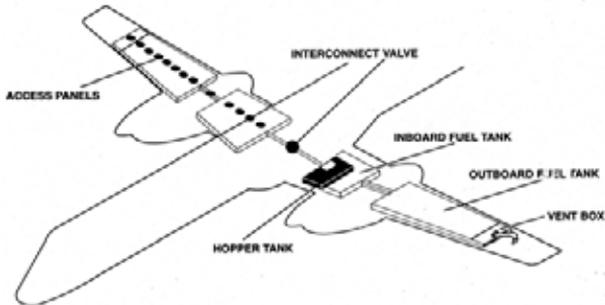
Figure 27: *Dihedral gravity transfer of fuel from outboard to inboard wing tank.*

A more complex method is siphoning, shown in Figure 28, where the source tank is pressurized, thus pushing the fuel to the collector tank. Generally, it is engine bleed air, direct or conditioned by the environmental control system, which supplies the air via a pressure regulator.
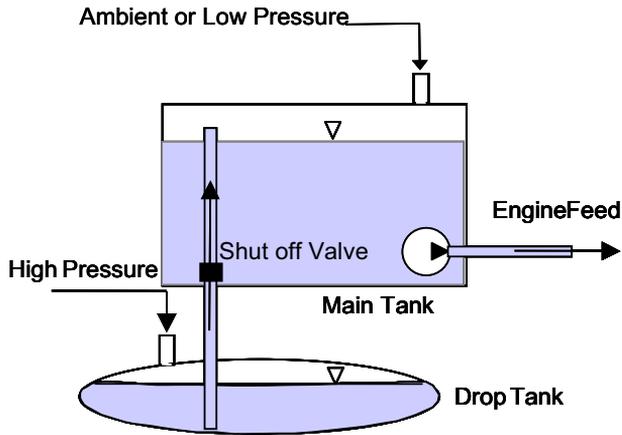
Figure 28: *Siphoning of fuel from drop tank to main tank.*

Pump transfer may be of two principally different types, inline or distributed, see Figure 29. The inline pump is often a centrally placed pump, and transfers fuel from several tanks. This is lightweight and compact but is susceptible to cavitation in suction lines due to pressure drop. Distributed pumps are located in the transfer tank, thus minimizing suction head and cavitation. The fuel transfer system is described in more detail in [13] and also in appended paper [VII].
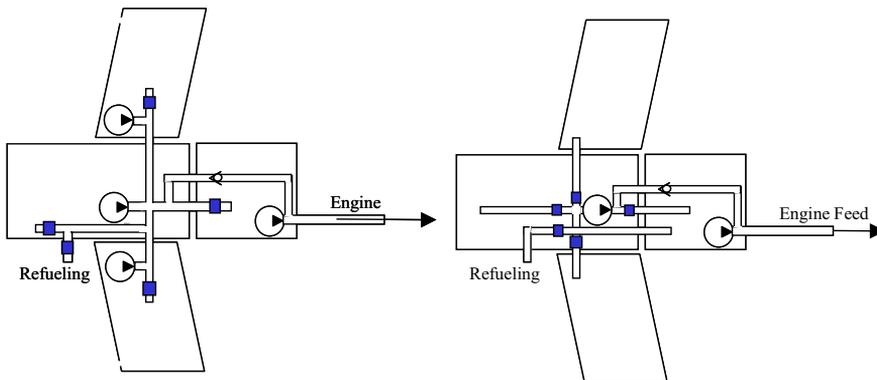
Figure 29: *Pump transfer, distributed at the left and centralized at the right.*

5.5 Vent and pressurization system

The primary function of the vent system (or pressurization system) is to maintain the tank pressure within permitted levels during maneuvering and refueling, ingest gas dur-

ing dive or defueling, expel air during climb or refueling, and ensure limit pressure in case of refueling overshoot. Figure 30 shows the starboard side of an open or unpressurized system in an airliner where the tanks are connected to ambient pressure through a series of pipes and vent tanks.
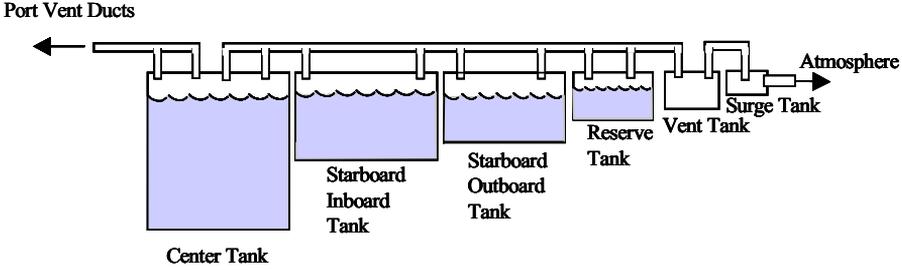
Figure 30: *The starboard side of an airliner open vent system.*

At high altitude, it may be desired to pressurize the tanks to avoid fuel boiling, either spontaneous boiling in the tanks caused by low atmosphere pressure, or boiling in pipes caused by suction from pumps. The pressure source is often engine bleed air. Alternatives to engine bleed are pressurization by ram air or inert gas. Pressure may also be applied with the sole purpose of providing the means for siphoning. The vent and pressurization systems may be of three principally different types: open, semi-open or closed. The semi-open and closed types of system are pressurized, as shown in Figure 31.
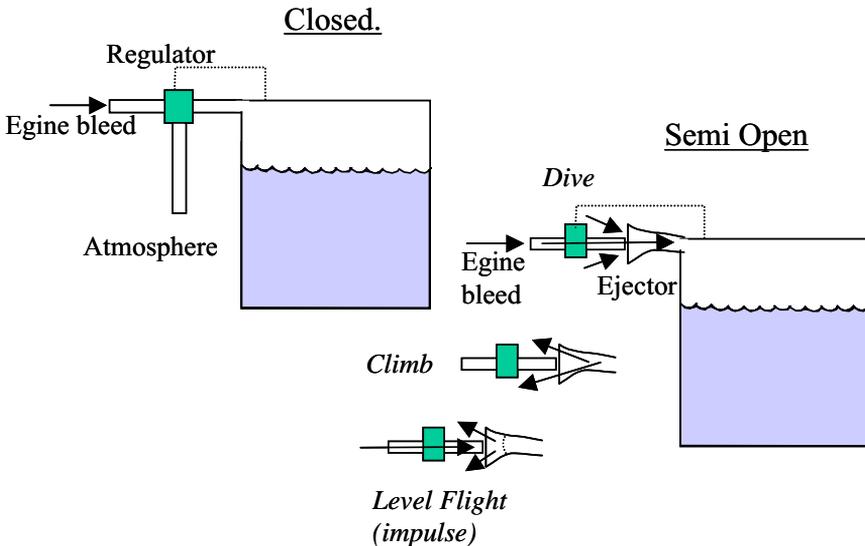
Figure 31: *Example of tank pressurization.*

In the semi-open system, the tank pressure at steady state is accomplished by primary flow impulse in the ejector. This is similar to blowing steadily into a bottle, thus creating pressure inside it. In a dive, the primary flow will induce a secondary flow that minimizes the maximum bleed air out take which compensates for the wastefulness at steady state flight. In a climb, the semi-open system works as an open system.

5.6 Refueling system

5.6.1 Ground refueling

According to McKinley [28], aircraft with small fuel tanks like general aviation a/c have gravity refueling with manual shut-off. As tanks become larger, 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 for high refueling flow rates. However, the risk of too high tank pressures in case of overshoot, see Figure 32, and pressure surge at shut-off increases with higher refueling rates. The vent system must ensure limit pressure in case of refueling overshoot, according to Gartenberg [11]. The overboard pipe is preferably routed to a wing or fin tip for good separation in case of in-flight drainage. It is also very important to find a location with stable aerodynamic conditions. In fin and wing tips space is scarce, which has a limiting impact on the diameter.
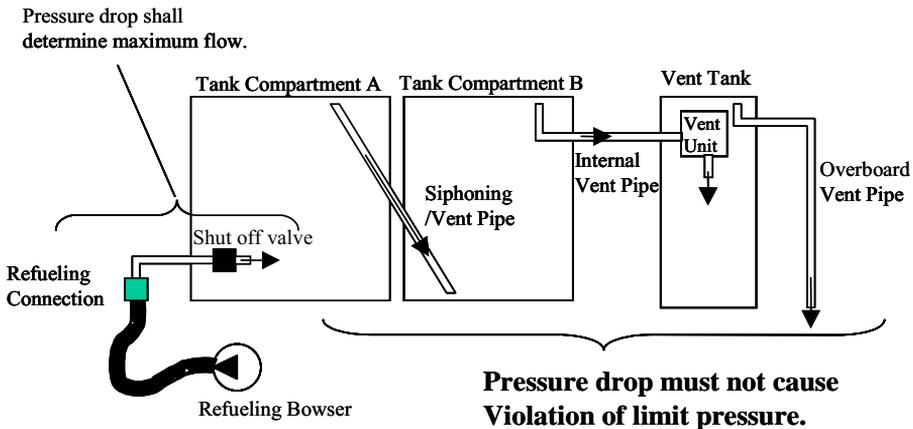
Figure 32: *Typical refueling system.*

5.6.2 Air to Air Refueling (AAR)

There are two different types of system in use for Air to Air Refueling (AAR) as follows:

- Probe and drouge system

- Boom system

The probe and drouge system, shown in Figure 33, is today the most widespread method for AAR. The drouge is a meshwork cone whose drag keeps the end of the hose in a stable position. The reception coupling is usually equipped with a pressure regulator with surge suppression capability. The receiver aircraft is equipped with the probe system whose main function is to enable engagement with the drouge and act as a flow path into the fuel system. The US Air Force is alone in using the boom system. In this system, a rigid boom, with control surfaces, is extended from the tanker and inserted into a receptacle coupling on the receiver aircraft. This system can provide much greater flow rates than the probe and drouge system, which is beneficial when refueling large bombers such as the B-52, the B-1 and the B-2 etc. The boom can be equipped with a boom drouge adapter kit (BDA) that consists of a short hose and a drouge. With the BDA-kit installed, a/c with probe and drouge type receivers can be refueled.
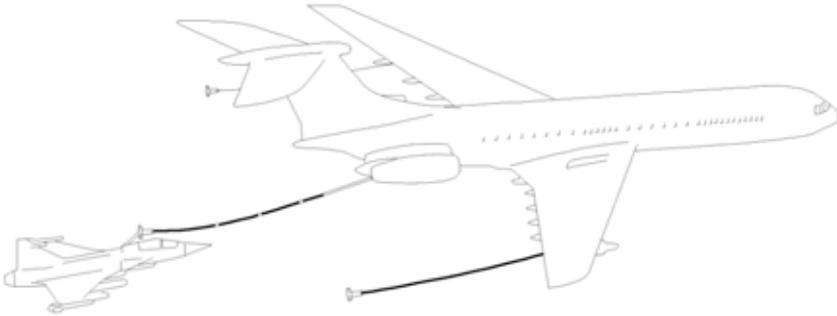
Figure 33: *Probe and drouge Air-to-Air Refueling of JAS 39 Gripen.*

6

Aircraft Fuel System Design

T̲HE FOLLOWING SECTION will describe how the methods and techniques discussed in the theory section have been implemented and further developed in actual a/c projects at Saab Aerospace. The reader is first given a description of a strategy for development of large system models. The system model is regarded as a system in its own right and the strategy is complete and covers all design phases. Apart from providing the reader with a modeling strategy, it also gives a good overview of all stages in design.

This is followed by design methods intended for the conceptual phase of the fuel systems itself. These methods are described in chronological order from a process perspective. First, synthesis with a morphological matrix is described, and then analysis with the house of quality matrix, and finally concept selection based on optimization.

6.1 Strategy for modeling of large a/c fluid systems

In [34] Roozenburg and Eekels it is stated that: "*Simulating is imitating the behavior of a system by means of another system*".

Since the simulation model may be regarded as a system in its own right, the processes used for designing the system itself should work equally well for designing the simulation model. Most often, company or organization decrees stipulate what design process to use. The main objective of this work is not the choice of process, but rather to identify the activities within the process. Nevertheless, in order to do so a process will be suggested.

In [22] Keski-Seppälä, the engineering process from [31] Pahl and Beitz is suggested as the core of the Computational Fluid Dynamic (CFD) simulation design process. This implies that this process should work well also for modeling of fluid systems. One of the attractive features that apply well when designing a model is the continuous verification and validation.

If the activities in building a large fluid system model are fitted into the planning and design process of Pahl and Beitz, it might look like Figure 34 below. The strategy proposal discussed here is described in detail in paper [II].
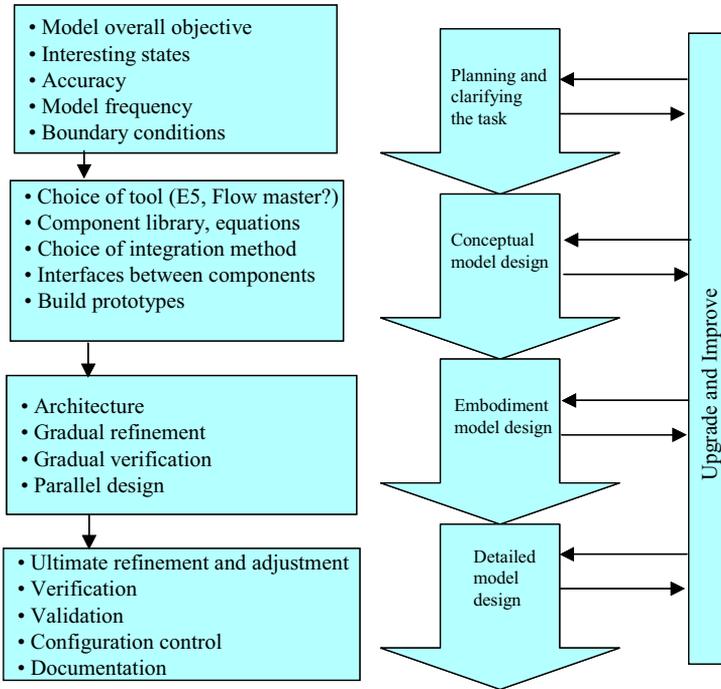
Figure 34: *The activities of building a large fluid system model fitted into the planning and design process of [31]Pahl and Beitz.*

6.1.1 Planning and clarifying the task

As stated in [31] Pahl and Beitz: "*Notwithstanding the method, a successful planning process takes into account the market, the company and the economy. The purpose of this clarification of the task is to collect information about the requirements that have to be fulfilled. This activity leads to a requirements list*". In the case of model building, the overall design process may be regarded as the customer. Questions that have to be addressed include:

- Which are the states that need to be accurate? (It is not possible to model everything with high accuracy!)

- How accurate must the predictions be?

- How fast are the events that are to be simulated?

- What are the interfaces to other systems/models?

These questions need to be answered while simultaneously considering the economic framework and other company specific constraints. In order to obtain the answers, the objective of the model has to be determined. A problem here is that sometimes the objective is to predict behavior that is otherwise difficult to foresee. In this case, it is impossible to say what accuracy is desired due to the nature of the problem. According to [25] Law: "*When a simulation study is initiated there may not be a clear idea of the problems to be solved. Thus, as the study proceeds and the nature of the problem become clearer, this information should be conveyed to the manager, who may reformulate the study's objective*". Nevertheless, even if it is not entirely clear what phenomena are going to be studied, matters regarding model performance have to be addressed during the planning phase.

6.1.2   Conceptual model design

In this phase the concept is chosen that best satisfies the desired properties specified earlier. The main concept drivers are most often accuracy and upper frequency limit. There are four main contributors to simulation inaccuracy as follows:

- <u>Numerical error</u>, Inaccuracy due to the chosen integration method and the length of the time step.

- <u>Parameter error</u>, Wrong parameter input.

- <u>Model error</u>, Simplifications in the model may, deliberately or accidentally, have a large impact on the simulation result.

- <u>Error in validation data</u>, Measurement errors in the test data used for validation are not unusual.

Simulation models become complex and unstructured without the correct tools. Today there are several simulation tools on the market with a graphical interface, which gives a good overview of the model. These are most often of the drag-and-click type that makes the modeling tool easy to use thus minimizing the number of mistakes. Examples of tools currently available are the component-based Flowmaster, Easy 5, HOPSAN and AMESIM, and the equation-based Simulink, Systembuild, and many others. Component libraries may be of two principally different types: signal port or power port. These are illustrated in Figure 35 below.
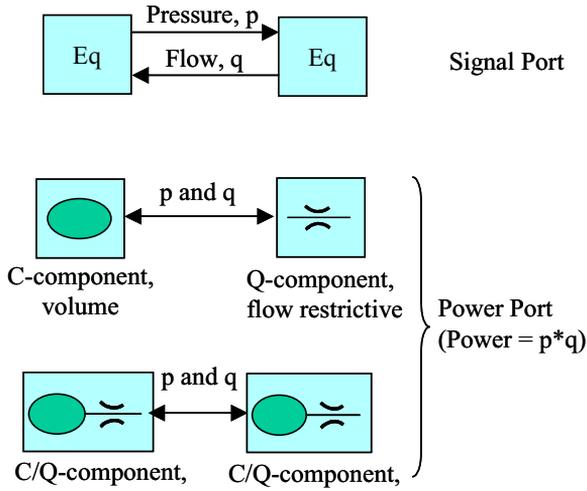
Figure 35: *Signal flow and power port modeling.*

When the detailed design of a library is studied more deeply, every single component may be found to be a set of equations that has to be solved. When choosing a library, it is important to know to what level of accuracy and bandwidth the equations are valid. An example of different ways of describing a hydraulic pipe (hereafter referred to as a line) is shown in Figure 36.
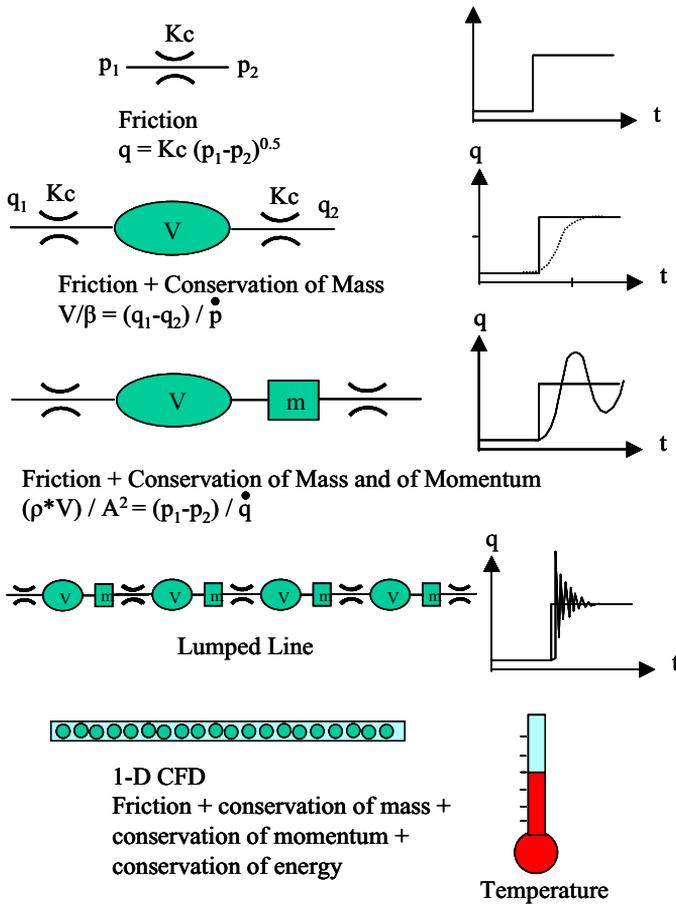
Figure 36: *Different ways of describing a line.*

6.1.3 Embodiment model design

The conceptual phase is followed by the embodiment design phase. "*Unlike the conceptual phase, embodiment design involves a large number of corrective steps in which analysis and synthesis constantly alternate and complement each other*", as stated in [31] Pahl and Beitz.

The overall tactics in the embodiment of a large fluid system model is to first build a simplified model of the total system containing all the functionality and that is divided into sub-models. By simplified is meant for example that a constant pressure source might represent a pump, an orifice might initially replace a complex piping system etc. The sub-models may then be developed separately and in parallel by different teams. As the sub-models increase in complexity, tests are made against the top-level model, which is, if successful, upgraded with the new sub-model version.

6.1.4 Detail model design

In reference [31], Pahl and Beitz say that: "*In the detail design phase, arrangements, forms, dimensions and surface properties of all the individual properties are finally laid down. The outcome is a specification of production*". If this were translated into model design, the outcome would be a specification of simulation.

From the embodiment phase comes a system model that is executable and complete with regard to functionality. The sub-models and components, however, do not necessarily have the ultimate degrees of complexity needed for a valid simulation result.

In the detail design phase, the model is given its ultimate complexity in order to produce valid simulation results. Even though evaluation against available test data must be performed throughout the whole model design process, detail design and verification/validation are more intimately related, see Figure 37, and are therefore (in this text) regarded as one. Verification consists of ensuring that the model is in compliance with the specification defining it and validation of ensuring that the specification is correct and complete, as defined in [24] Landberg.
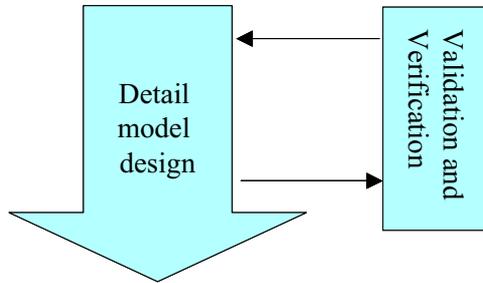
Figure 37: *The intimate relation between detail design and verification and validation.*

Is there such a thing as an ultimately adjusted and verified system model for an a/c fluid system? Probably not! As the model takes form, new problems that need to be solved, but were not included in the specification, will most likely turn up. At best it is possible to conclude that the model is valid in parts of the system envelope. Nevertheless, there must be a point where the model is considered operational. Furthermore, history has shown at Saab that the best way to verify a model is to use the model on real problems. Note also that a model used to design a new system will generally be less detailed than one used to fine-tune an existing system since less data will be available as stated by [25] Law. The detail design phase also includes configuration management and documentation. Simulation results may become useless if the status of the model is not entirely clear. Problems usually occur some time after the simulation has been performed, when reviewing earlier design decisions.

6.2 Quantification of the morphological matrix

This section describes an elaboration of the morphological matrix that has been used for fuel system design [III] and [45]. The elaborated morph matrix is a conventional morphological matrix that has built-in mathematical models of the solution elements.

Pahl and Beitz [31] state 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 and power consumption. Furthermore, it is the author's opinion that quantified models should be used as early as possible in the design process.

The quantified matrix gives the engineer immediate access to approximated properties of the complete system. Every potential sub-solution is described either with physical or statistical equations, or a combination thereof. Useful measures of merits are thereby quantified for each solution alternative. By aggregating the properties for the chosen sub-solutions, a quantified value of the complete product can be obtained.

The design application described below is the synthesis of an aircraft fuel system with multiple and perhaps conflicting objectives. The internal ranking of the objectives is vaguely defined at this early stage of design. Parametrical models and a morphological matrix have been developed for the fuel system, which will be described in this section. The optimization framework and some illustrative results are also presented here.

6.2.1 Interactive and quantified morphological matrix

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 any change in top-level requirements or design parameter and is therefore regarded as interactive in this sense.

Morphological Matrix

Funktion	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	Siphoning	Gravity	2
Wing Tank Transfer	Distributed pump	Inline pump	Jet pump	Siphoning	Gravity	2
Drop Tank Transfer	Distributed pump	Inline pump	Jet pump	Siphoning	Gravity	2
Σ Transfer						=
Vent & Pressurization	Closed system	Ejector system	Non Pressurized			2
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	Power Airflow power Level	Dive		MTBF
NGT		0	7	+ 7 =	14	0	+ 1590 = 1590				2 128
Inline pump	51204		3	7			711		23 077		
Inline pump	51204		3	9			711		23 077		
Inline pump	58182		3	14			750		23 077		
			9	+ 30 =	39	2172 =	2172		7 692 =		7 692
Ejector system	0				6			70	172		2 370
Both					9						2 342
Pressurized					32						14 286
None					0		0				1 000 000
None					0		0				1 000 000
Σ				kg	100	W	3763	241		h	657

Figure 38: *The morph matrix is shown above and the quantified system properties are shown below.*

Let us first take a look at the morph chart shown in Figure 38. The upper matrix shows a morphological matrix for a/c fuel systems, similar to the one shown in Figure 11. The column to the left shows a proposed system combination for a small or mid-size combat a/c. The model outcome is displayed in the lower chart. The quantified properties are weight, electrical power and compressed air consumption, and Mean Time Between Failure (MTBF).

The top level requirements are shown in Figure 39, which needs to be filled with data for altitude, descent rate, engine consumption, load factor, and the density of the fuel used.

Altitude	z	**15000**	m
Engine feed mass flow rate at alt=Z	mf.efz	**1**	kg/s
Engine feed mass flow rate at alt=0	mf.efg	**6**	kg/s
Transfer mass flow rate	mf.tp	**3**	kg/s
Fuel density	rho.fuel	**800**	kg/m3
Load factor	g	**3**	g
Dive rate	d	**300**	m/s
Ground level temperature		**15**	°c

Figure 39: *Top-level requirements.*

In the spreadsheet model, there are underlying sheets for each subsystem with design parameters that have to be chosen. These might be pipe diameters, pressurization level, pump characteristics, tank volumes etc. The quantified system characteristics are then derived by physical models, rules of thumb, statistics or combinations thereof. The outcome is approximate and only valid for ranking of the concept proposal. The model is not valid for promising future performance. The actual equations, their origin and the implementation in MS Excel are thoroughly described in Svahn [45] and also [III].

However, the matrix has also proved useful for a first assessment of fuel system characteristics in the conceptual phase of the a/c itself. This is usually done today using statistically based equations as described by for instance Raymer [34], Berry [4] or Torenbeek [46] to give just a few examples.

6.2.2 Optimization

In order to automate the solution selection process as described earlier, an optimization framework has been developed to enable optimization of the system based on the morphological matrix. The fundamental principle for this framework can be seen as the combination of the model, the objective function, and the optimization algorithm as illustrated in Figure 40.
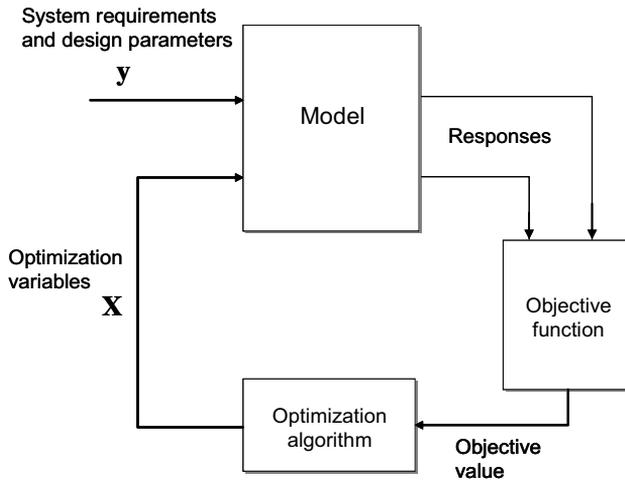
Figure 40. *Illustration of the optimization process.*

The risk analysis software Crystal Ball with the optimization toolbox OptQuest is used here. OptQuest incorporates *metaheuristics* [14] to guide its search algorithm. It is capable of handling continuous as well as discrete parameter problems.

6.2.3 Optimization result

In this section, some illustrative results from the design application described above are presented. Four cases have been selected, and the purpose of the presented results is primarily to illustrate the presented approach and implementation, rather than essential results of the specific design task.

In this example, the design objective is to minimize weight, power and compressed air consumption and also to maximize MTBF of the system. An objective function has therefore been created where the sub-objectives are weighted and form a sum that together with the penalty function is minimized. The sub-objectives are normalized against a datum concept proposal, which in this case is the concept that is considered the most promising before optimization is begun.

Design variables are the discrete solution selections, and also tank pressure levels which are continuous. Constraints on incompatible solutions are handled with penalty functions. For instance, siphon transfer may not be combined with a non-pressurized system. The case investigated here is a mid-sized combat a/c where the objective function and also the top requirements are altered.

Datum concept

Conventional conceptual design has been in progress in parallel with the work of formulating the optimization problem. This is inevitable, and it is the author's opinion that

optimization will never replace conventional conceptual design, just make it more rational. The concept considered to be the most promising one at this point is used as the datum concept used as reference. The datum concept is illustrated in Figure 38.

Minimum weight

An optimization was made with the objective function set as minimum weight. It showed that the datum concept was optimal also in this case, but the weight was reduced by about 0.5 kg by lowering the tank pressurization level. The similarity to the datum concept is hardly surprising since much focus is on weight. In figure 41 below, the graph shows the optimization convergence.
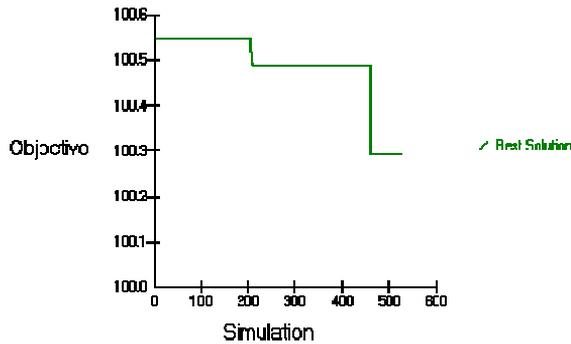
Figure 41. *Convergence of the optimization with the objective of minimizing system weight.*

Minimum power

The objective function was altered to minimum electrical power consumption. The model suggested air pressure siphoning for fuel transfer instead of electrical pump transfer, which seems logical. The power consumption decreased from 3.7 kW to just under 1 kW as shown if Figure 42. However, the concept is penalized by increased weight, which grew from 100 kg to 183 kg and by an increase in compressed air outtake from 241 g/s to 281 g/s.
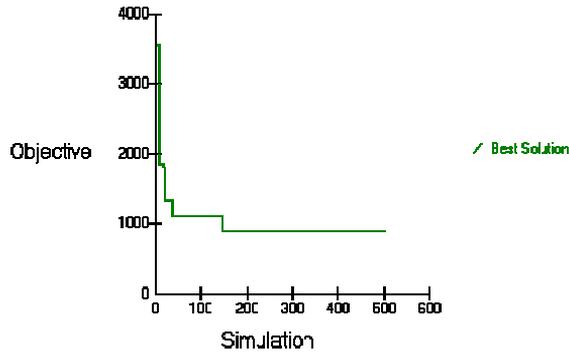
Figure 42. Convergence of *the optimization with the objective of minimizing electrical power consumption.*

Multi-objective

In order to enable multi-objective optimization the sub-objectives are normalized with the datum concept, thus enabling a single objective function to handle a multi-objective problem. In other words, a single objective problem is obtained by using a weighted objective method. All sub-objectives are chosen to contribute equally much to the objective function. The suggested concept is siphon transfer from the fuselage and wings combined with pump transfer from the drop tank. Pressure levels are 24 kPa in the fuselage and wings and 44 kPa in the drop tank. This is not the orthodox type system combination. One common way to solve this design problem is the other way around with pumps internally and siphoning from external tanks. This is probably because the drop tanks are just drop tanks and it is considered wasteful to equip them with expensive components such as pumps. Perhaps the tanks are not dropped that often so this might be an appealing alternative after all? In Figure 43, the result from this optimization is visualized.
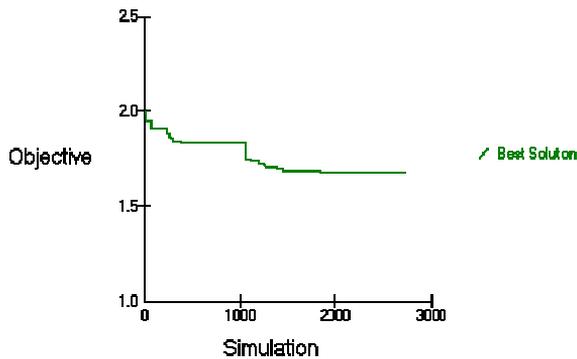

Figure 43. Convergence of *the optimization considering a multi-objective function.*

Top level requirement trade study

What if the top level requirements are too strict? The drop tanks are dropped before combat and turning during ferry is less that the specified 3 g. Let's try 1.5 g. In this case, the model suggests siphoning from the drop tank as well, which seems logical since a modest air pressure alone will then overcome the fuel head without being penalized by the structure weight driven by high pressure or the electrical consumption of a pump. The objective function improvement compared to the 3 g simulation is shown in figure 44, the main improvement coming from lower electrical consumption.
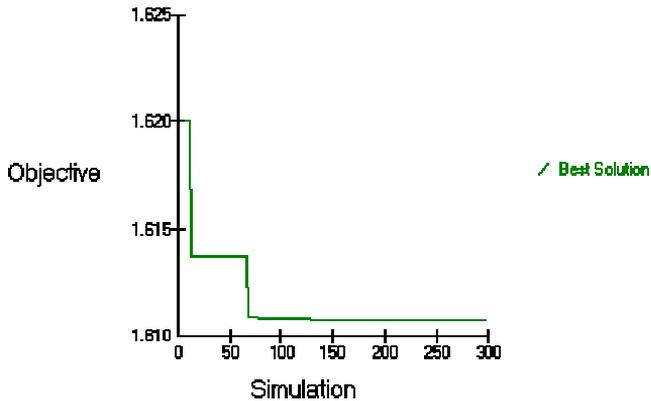

Figure 44. *The optimization result with a multi objective but with lower load factor requirement.*

6.3 Quantification of the relationship matrix

The objective in this section is to describe how the use of the relationship matrix and the DSM may reduce system development time in the conceptual phase by early introduction of computational design tools. A further objective is to minimize the number of mistakes by helping the designer take combinatory effects into account, and by increasing understanding of how the flight conditions impact the low-level design parameters. This is true also for the quantified morph matrix with the difference that the morph matrix is used for exploring the design space while the methods in this section are explicitly motivated by extracting information and gaining knowledge about the design.

The same design proposals used earlier in the text to illustrate the matrix methods, Figure 6, will serve as an example here as well.

6.3.1 Combining the DSM and the relationship matrix

In order to obtain a more compact view of the problem it is possible to combine the DSM with the relationship matrix as shown below. The DSM shows the direction of a two-way relationship, compared to the relationship matrix roof that just shows the exis-

tence of a relationship. By transposing the relationship matrix, as described earlier, it is possible to display the subsystems' relationships with the DSM rather than the roof.
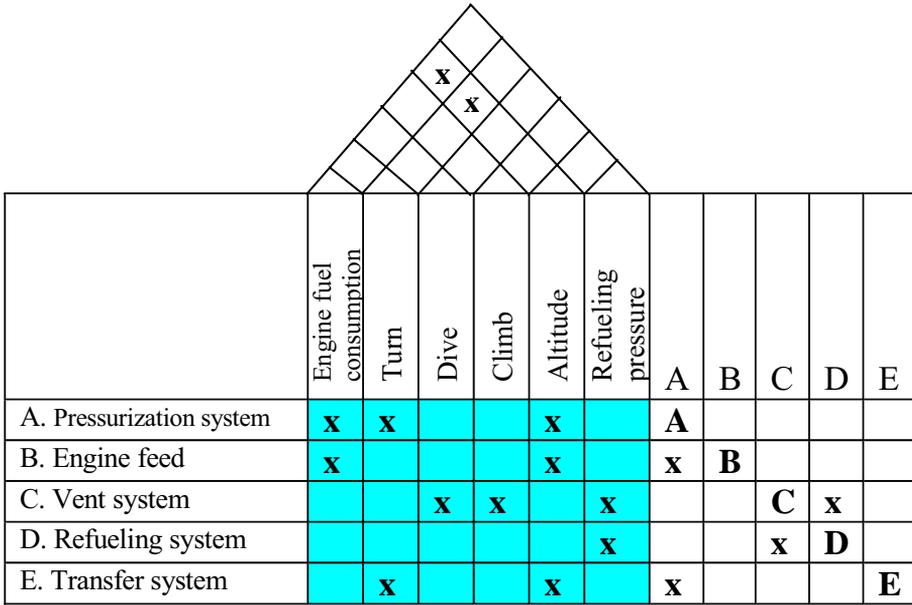
	Engine fuel consumption	Turn	Dive	Climb	Altitude	Refueling pressure	A	B	C	D	E
A. Pressurization system	x	x			x		A				
B. Engine feed	x				x		x	B			
C. Vent system			x	x		x			C	x	
D. Refueling system						x			x	D	
E. Transfer system		x			x		x				E

Figure 45: *The DSM and relationship matrix combined in the same framework, visualizing dependencies for the pump concept.*

In the relationship matrix part of the matrix in Figure 45 it is possible to read that the top requirements that affect the transfer subsystem are turn and altitude. The fuel head will increase with load factor when pumping the fuel which lowers the flow, and increasing altitude will increase the pump cavitation. In the DSM part it can be seen that the transfer system's performance is influenced by the tank pressurization system that suppresses cavitation in the transfer pump. The characteristic House of Quality roof displays the dependencies between the top requirements. In this case, the fuel consumption and the maximum turn rate will decrease as altitude increases.

6.3.2 Quantification of the elements

When the relationships between subsystems and requirements have been established, the characteristics and performance of the concept must be determined. Fuel flow, degree of cavitation, engine fuel consumption, fuel and air pressures are some of the properties that are useful as measures of merit in a trade study and which therefore need to be quantified. The idea is that the property describing a subsystem's main task is quantified and inserted as the coupling element in the relationship matrix.

- <u>Transfer system</u>: Shall provide a transfer flow: mass flow of fuel [kg/s].

- Pressurization system: Shall minimize cavitation: 1=no cavitation, 0=100% vapor.

- Vent system: Shall ensure limit pressure by ingesting or expelling air at altitude change (mass flow of air [g/s]). There is also a rule of thumb that air velocities in air ducts should be kept below 70 m/s (air velocity [m/s]). The vent system shall also ensure limit pressure at refueling overshoot (overshoot pressure [Pa]).

- Engine feed system: Shall provide engine feed pressure: [Pa]

- Refueling: Shall minimize refueling (turn-around) time: [s]

The design parameters, used for the calculation of the coupling element, are shown in the left subsystem column of Figure 46. This enables visualization of how the top-level requirements and subsystem dependencies impact the subsystem details such as pipe diameters, pump size etc.

Let us analyze the transfer system in Figure 46. The transfer system is influenced by turn rate (g-force), altitude, and the pressurization system, as displayed by the coupling elements. The flight case shown at the top of Figure 46 is level flight (1g) at 3000 m. So, if the engineering parameters are as shown to the left, tank pressure 25 kPa, pump power 400 w etc, the transfer flow will be 3 kg/s, practically without any cavitation (0.99). The degree of cavitation is displayed in the coupling elements of the pressurization system, since it is the pressurization system's main task to suppress cavitation in the engine feed and transfer systems.
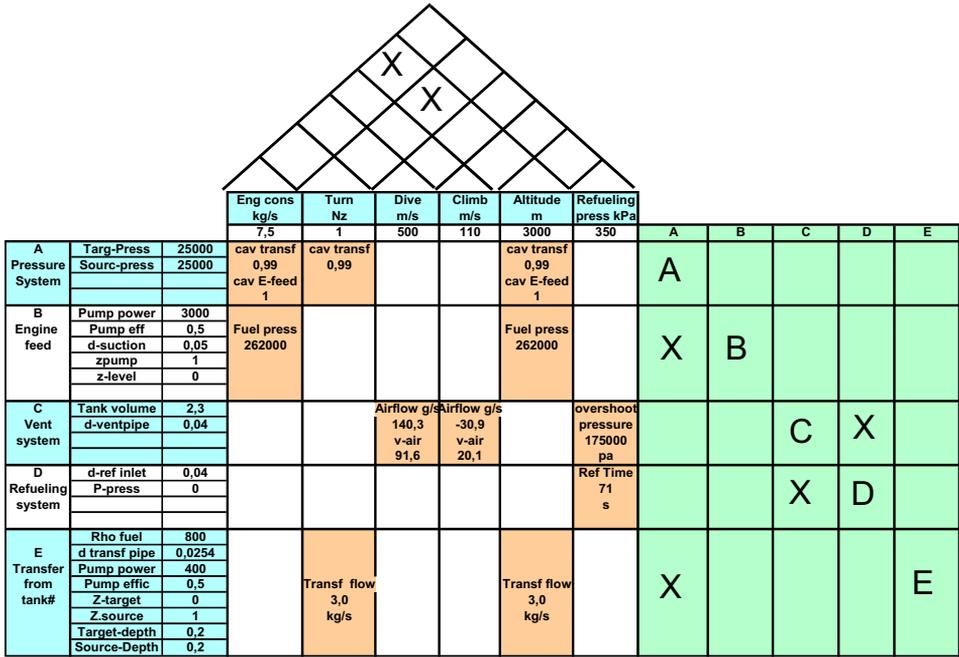
Figure 46: *The DSM and relationship matrix combined and with quantified elements for the pump concept.*

A refined trade study method will allow us to estimate the characteristics of an optimal system that meets the requirements. According to [34] Raymer trade studies answer design questions starting with: What if? Trade studies are as important as a good configuration layout or sizing analysis. Reference [34] also states that only through trade studies will the optimum design emerge.

Here, a spreadsheet program (MS Excel) with a built-in modeling-/solver tool has been used. (If a more sophisticated analysis is desired, it is possible to link the framework to a more advanced modeling tool). Behind every quantified element in the coupled part of the matrix is an equation, thus facilitating a direct first trade study. An example of this is Figure 47 where the system impact of a 3 g turn at 10,000 m is shown. The impact is increased transfer pump cavitation due to altitude and decreased transfer flow, from 3.0 kg/s to 1.9 kg/s, due to the load factor and the cavitation. If the matrix is automated, as in this case, practically no additional work is necessary to answer the following question: What if the tank pressure is increased to 35 kPa?

	7,5	3	500	110	10000	350
25000	cav transf 0,47	cav transf 0,47			cav transf 0,47	
25000	cav E-feed 1				cav E-feed 1	
3000	Fuel press 234000				Fuel press 234000	
0,5						
0,05						
1						
0						
2,3			Airflow g/s 140,3	Airflow g/s -30,9		overshoot pressure 175000 pa
0,04			v-air 91,6	v-air 20,1		
0,04						Ref Time 71 s
0						
800						
0,0254						
400						
0,5		Transf flow 1,9 kg/s			Transf flow 1,9 kg/s	
0						
1						
0,2						
0,2						

Figure 47: *The pump concept stressed by a 3 g turn at 10,000 m altitude.*

An important part of design is to terminate the inferior concepts and identify the superior one. One of the tools used in concept elimination may very well be the quantified relationship matrix previously used in the trade study. Or the matrix may very well be derived solely for this purpose. The example below shows how the "siphon" concept proves to be sensitive to load factor. The performance at 1g and 3,000 m altitude, shown in Figure 48, is better than the pump concept. In fact, the transfer flow looks very promising.
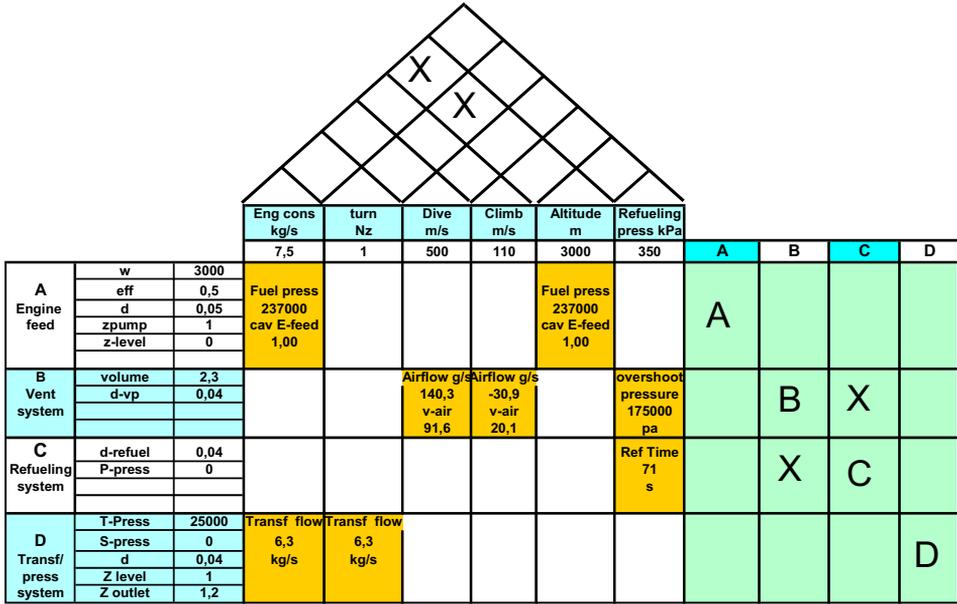
			Eng cons kg/s	turn Nz	Dive m/s	Climb m/s	Altitude m	Refueling press kPa	A	B	C	D
			7,5	1	500	110	3000	350	**A**	**B**	**C**	**D**
A Engine feed	w	3000	Fuel press 237000 cav E-feed 1,00				Fuel press 237000 cav E-feed 1,00		**A**			
	eff	0,5										
	d	0,05										
	zpump	1										
	z-level	0										
B Vent system	volume	2,3			Airflow g/s 140,3 v-air 91,6	Airflow g/s -30,9 v-air 20,1		overshoot pressure 175000 pa		**B**	**X**	
	d-vp	0,04										
C Refueling system	d-refuel	0,04						Ref Time 71 s		**X**	**C**	
	P-press	0										
D Transf/ press system	T-Press	25000	Transf flow 6,3 kg/s	Transf flow 6,3 kg/s								**D**
	S-press	0										
	d	0,04										
	Z level	1										
	Z outlet	1,2										

Figure 48: *The siphon concept at level flight at 3,000 m altitude.*

At a 2.7 g turn however, the transfer flow is zero due to the load factor, see Figure 49. The conclusion is that this concept can be eliminated if the a/c is supposed to perform sustained turns at load factors > 2.7 g.

	Eng cons kg/s	turn Nz	Dive m/s	Climb m/s	Altitude m	Refueling press kPa
	7,5	2,7	500	110	3000	350
3000	Fuel press 251000 cav E-feed 1,00				Fuel press 251000 cav E-feed 1,00	
0,5						
0,05						
1						
0						
2,3			Airflow g/s 140,3 v-air 91,6	Airflow g/s -30,9 v-air 20,1		overshoot pressure 175000 pa
0,04						
0,04						Ref Time 71 s
0						
25000	Transf flow 0,0 kg/s	Transf flow 0,0 kg/s				
0						
0,04						
1						
1,2						

Figure 49*: The siphon concept at a 2.7 g turn at 3,000 m altitude.*

6.3.3 Dealing with uncertainties

Besides deterministic modeling of the system proposal, it is also of interest to be able to analyze uncertainties in parameters, and to be able to combine probabilistic analysis with the relationship matrix. One of the major difficulties when designing an a/c fuel system is to predict pump cavitation. The main factors that will influence the degree of cavitation are tank pressure (ambient + pressurization), suction side pressure drop, and the properties of the fuel used (vapor pressure and air solubility). All these factors are subject to variation and if this variation is taken into account already in the early stages of design, it is more probable that a successful concept will be chosen. The uncertainties have been dealt with by introducing distributions instead of fixed numbers when describing these properties.

Tank pressure

The predominant cause of variation in tank pressure is the ambient pressure i.e. variation in altitude. When designing a multi-role combat a/c, different tactical mission profiles are weighted together to define an altitude distribution. A simplified but typical altitude distribution is shown in Figure 50: the altitude is expressed in meters. It can be seen that 40% of the time will be spent below 2,000 m, 20% between 2,000 and 6,000 m, etc.
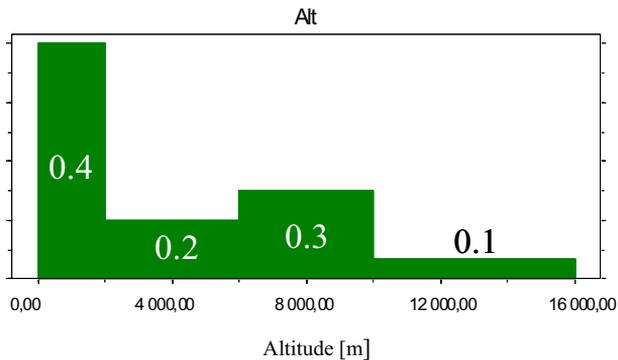

Figure 50: *Simplified but typical altitude distribution for a multi-role combat a/c, where 40% of the time will be spent below 2000 m, 20 % between 2000 and 6000 m etc.*

Suction side pressure drop

The suction side pressure drop is determined by the geometry of the suction pipe, diameter, length, bends, surface roughness, suction head etc. These properties do not vary enough to justify the use of distributions. However, the desire to minimize the unpumpable fuel will make distance 'a' influence the inlet pressure drop, see Figure 51.
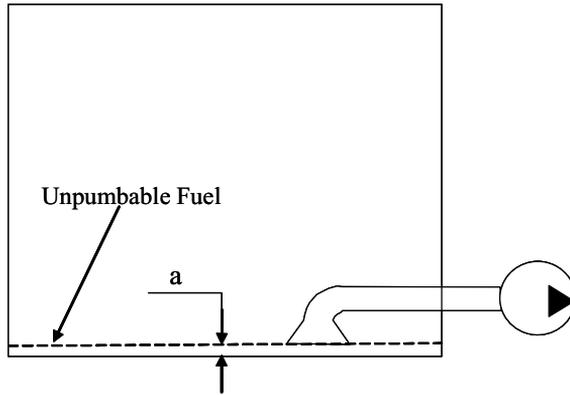
Figure 51. *The influence of residual unpumpable fuel on suction side pressure drop.*

If distance 'a' is too large, the amount of residual fuel will be unacceptable, and if it is too small, the pipe inlet will act as a restriction and increase pressure loss. Distance 'a' will vary since it is preferred from a stress (and ultimately weight) perspective to use floating suspension of the pipes. Here, distance 'a' is modeled as an equivalent pipe diameter. Distance 'a' and the diameter of the bell mouth determine the inlet area. The equivalent pipe diameter is then calculated as the diameter of a pipe with the same area as the inlet area. The equivalent pipe diameter is assumed to have a normal distribution, as shown in Figure 52.
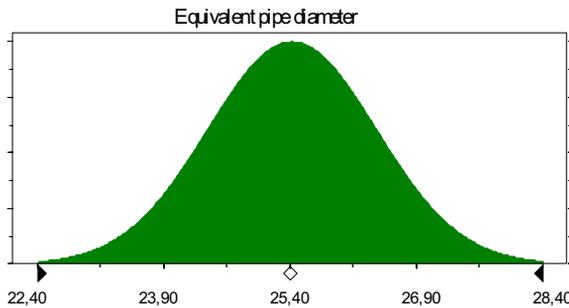

Figure 52: *Distribution of the equivalent pipe diameter expressed in mm.*

Fuel properties

As stated earlier, the most common source of jet fuel is crude oil, which consists of many thousands of different hydrocarbons. When producing jet fuel, the crude oil is divided into fractions by distillation to provide the required boiling temperature range. The actual physics behind vaporization and gas formation is very complex; instead an empirically derived equation using a factor p_{totcav} is introduced, the actual equation and

its origin is described in paper [VI]. The factor p_{totcav} is represented with the normal distribution shown in Figure 53, which is based on bench tests at Saab Aerospace.

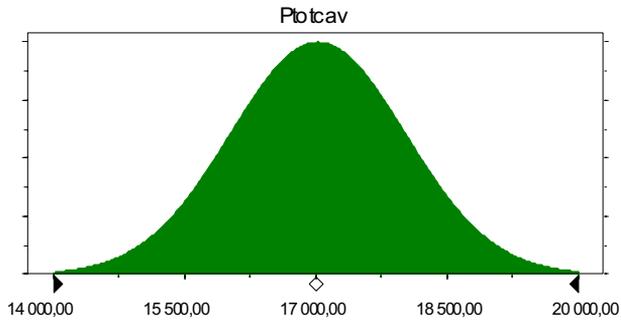Figure 53. *Normal distribution of the p_{totcav} parameter in expressed in Pa.*

System simulation

As stated earlier, the system is modeled in the spreadsheet program MS Excel. By using the add-in program Crystal Ball it is possible to describe a range of values for each uncertain cell in the spreadsheet. The parameter distributions are used as input to a Monte Carlo simulation.

By running a specified number of Monte Carlo trails, it is possible to obtain variation forecasts of system characteristics that are of special interest when evaluating the concept proposal. A schematic of the simulation inputs and outputs is shown in Figure 54.
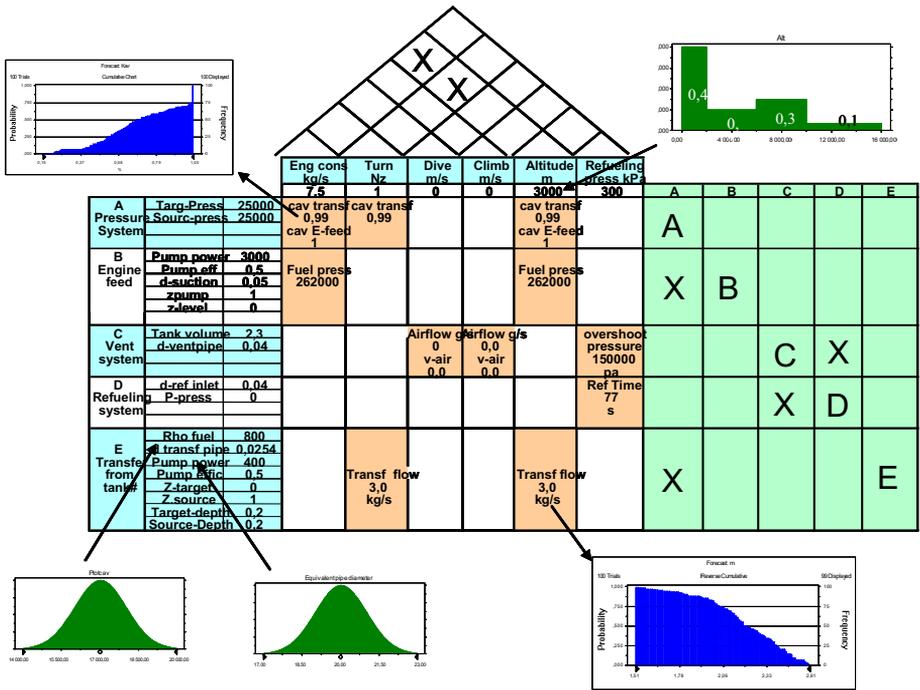
Figure 54. *Schematic of the system simulation where assumptions have replaced previously used single values and the simulation result is presented as cumulative charts*

Cavitation forecast

One of the most interesting system characteristics when evaluating an inline pump system is the degree of cavitation. As stated earlier, some degree of cavitation is to be considered normal in an a/c fuel system. It is, however, important to keep it at an acceptable level.

The cavitation forecast is shown in Figure 55. This is a most valuable input to the concept selection process. The cavitation forecast will serve as input to the feasibility assessment of the concept. Together with the pump manufacturer, the a/c designer can asses whether the concept is likely to be successful.

Note that the historical approach is to simply not allow a lower pump reduction factor than 0.5. From the forecast in Figure 55, however, it is clear that the area below 0.5 is very small and may possibly be acceptable.
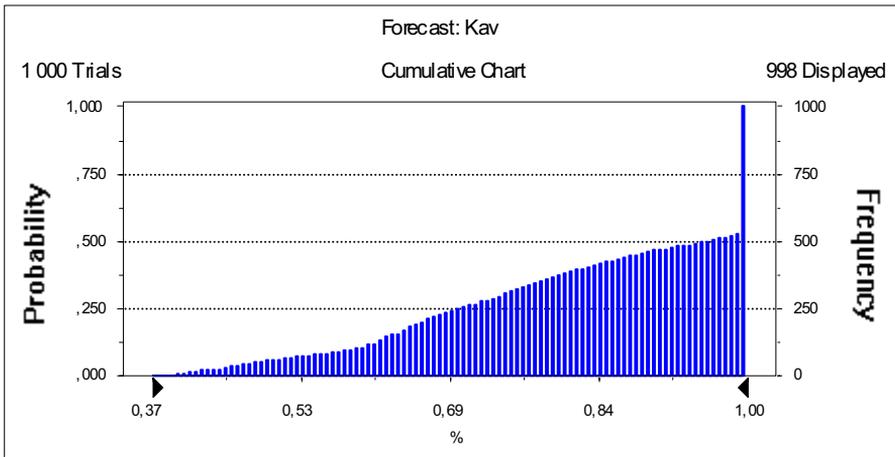
Figure 55. *Cavitation reduction factor, where 1 means no cavitation and 0 means 100% vapor.*

Flow forecast

The usual approach when designing an a/c, of course, is that the fuel transfer flow to the engine feed tank must be equal to or greater than the engine fuel consumption. When designing a combat a/c with afterburner operation, however, it is not entirely clear what the requirement regarding fuel transfer flow is. Reference [20] JSSG states that "*When engine flow rate is large relative to the quantity of fuel on board, as is the case of after-burning fighter air vehicles, the transfer rate need not match maximum engine capability. When the transfer rate is not equal to engine flow, an acceptable compromise rate should be identified and the operation conditions defined.*"

The flow forecast in Figure 56 will not alone answer the question of whether the flow rate is acceptable. It is, however, a valuable input to the concept evaluation process and will in combination with detailed studies of specific mission profiles, help to assess whether the concept performance is sufficient.
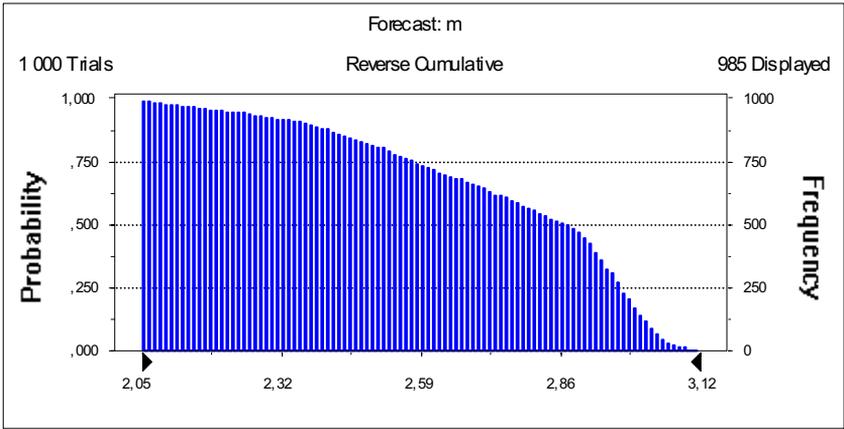
Figure 56. *Forecast of the transfer flow rate in kg/s.*

6.4 Optimization as a tool in fuel system design

This section, which is a condensation of paper [VII], shows how optimization has been successfully used at Saab Aerospace as a tool that supports concept selection. The design case used for demonstration purposes is concept selection for a fuel transfer system for a drop tank. A drop tank is fitted to a combat a/c to extend the operating range, see Figure 57. The a/c has an existing inline pump system for fuel transfer from the wings and fuselage tanks. It would of course be an advantage if the existing system could also be utilized for the drop tank.
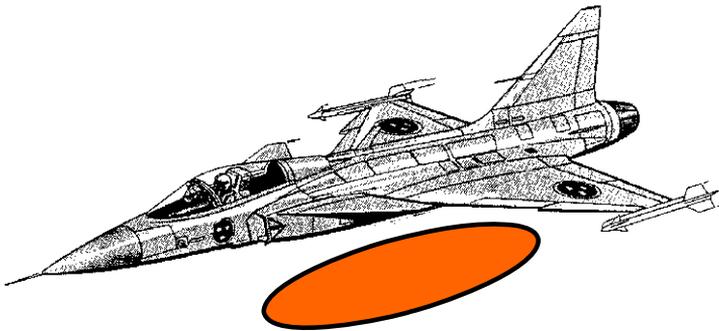

Figure 57: *Illustration of the design case.*

6.4.1 The concepts

Three concepts are considered in this study: a hook-up to the existing inline system, siphoning, and the existing inline system with pressure aid. The unassisted pump (ambient pressure in the source tank) is lightweight and relatively low-cost, but will most likely suffer from cavitation as altitude increases. The siphoning proposal is the opposite: heavy weight and high-cost but also high performance. The combination where the pump is aided by tank pressure, to minimize cavitation, is somewhere in-between with regard to weight and performance. The concepts have to be assessed against the mission profile(s). Is the drop tank intended for ferry flight, ground attack or interception missions? Schematics of the design proposals are shown in Figure 58. Note that the relationship matrix, as described earlier, is useful to map dependencies between the requirements and the design parameters.
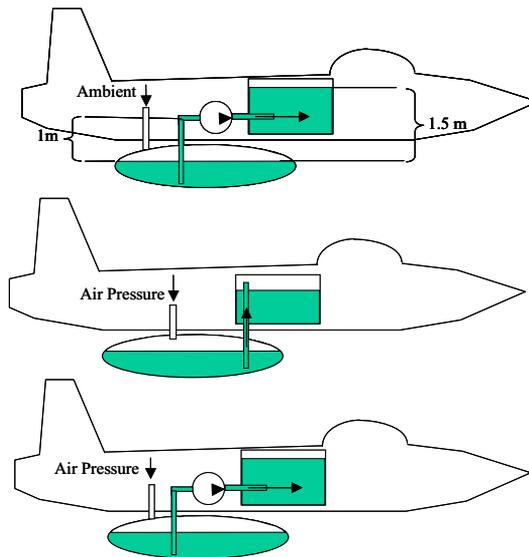

Figure 58: *The transfer concepts: unassisted pump at the top, siphoning in the middle, and a pressure aided pump at the bottom.*

The top requirements that will influence the system design are:

- Flight Altitude. As altitude increases, the formation of gases on the suction side of pumps will lower the fuel flow and eventually damage the pump.
- Turn Rate. If the load factor (n_z, the z component of the load vector n, also known as g-force) increases, the fuel head will increase and the flow will decrease.
- Engine fuel consumption. The higher the engine consumption the higher the demand on the transfer flow.
- Thermal Operation. The temperature will influence the gas formation; this is

however ignored in this study. This is a valid assumption if operating in ISA (international standard atmosphere) with a kerosene-based fuel like JP-8. If operating in a hot climate or using a wide cut fuel the temperature will begin to have a significant impact on system performance.

6.4.2 The model

The system was modeled in Easy5, which is commercial software intended for system modeling using the power port technique. However, a library developed at Saab was used, where the components are able to handle both fuel and air. The library also considers a two-dimensional load vector. The design parameters in this study were the pressurization level and the pump size, i.e. the maximum power of the pump. The flight data used as input were altitude, turn rate at a specified operation point (or rather ambient pressure and load factor), and type of fuel. The optimization loop starts by randomly generating a set of initial values for the design parameters. The system is then simulated and performance variables such as fuel flow, degree of cavitation, and system weight are calculated. The performance of the system, together with the weight, is then used as input to the optimization algorithm. The optimization algorithm returns a new set of design parameters to the system model, which is again simulated. This is looped until an interruption criterion is satisfied and the system is considered to be optimal. The model's architecture is shown in Figure 59.
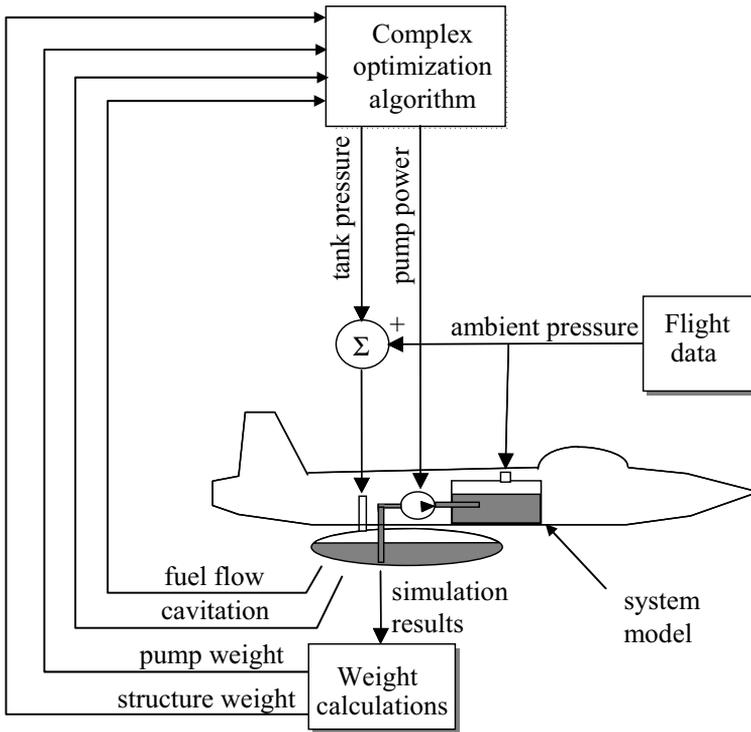
Figure 59: *Schematic of the system model.*

Both the genetic algorithm and the complex method were tested: the complex method, however, gave the best result in this case.

6.4.3 Optimization result

The optimization result is interpreted as follows: pumps under 100 W and tank pressure below 5 kPa are considered impractical. As expected, the optimal system concept varied with the top-level requirements. For a flow rate of 2.5 kg/s, the preferred concept as a function of altitude and turn rate is shown in Figure 60.
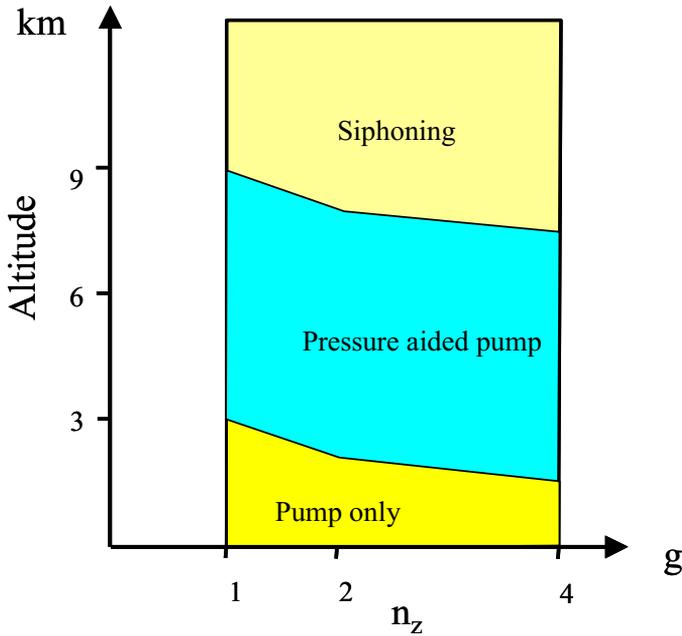
Figure 60: *Preferred concept as a function of turn rate and altitude.*

It can be seen that as altitude increases, the required tank pressure also increases. Eventually, the pressure becomes so high that there is no need for a pump. This occurs at a pressure of approximately 50 kPa. The impact of the load factor (the slope between the different areas) was not as significant as first anticipated. Nevertheless, it cannot be ruled out as a factor. A spin-off effect from the optimization is weight as a function of the requirements. Note that pipes, couplings, and shut-off valves etc are in this case considered to have the same weight for all concepts and are therefore not included in the objective function. The additional weight as a function of altitude and turn rate is shown in Figure 61.

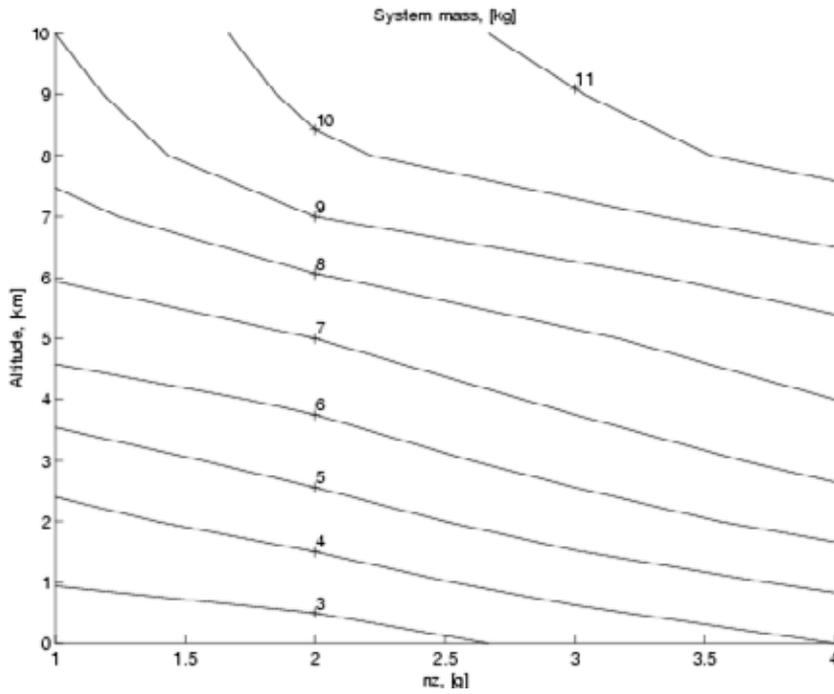Figure 61: *System weight as a function of turn rate and altitude.*

If system weight is critical, which it was not in this case, the result in Figure 61 could be used in a trade study where system weight is assessed against the top require-ments.

7
Discussion and Conclusions

THE METHODS AND techniques described in this thesis could be related to a greater whole by fitting them into the overall design process as described by [31] Pahl and Beitz. The interactive and automated morphological matrix is useful in the conceptual phase for generating concepts and making a first screening. The quantified relationship matrix and the optimization for concept selection, are also useful in the conceptual phase when screening and selecting concept proposals for further development. The modeling strategy, on the other hand, is intended for very large models, hardly something worth building at the conceptual phase when uncertainties are significant, and is therefore more appropriate in the detail design phase or perhaps the embodiment phase, see Figure 62.
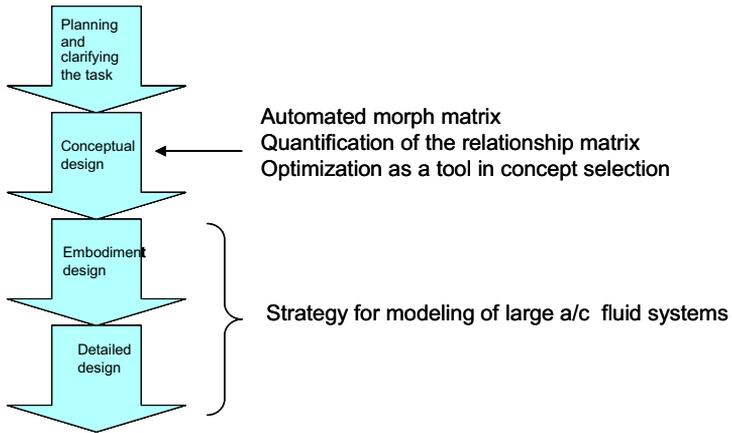
Figure 62: *The methods described in this thesis fitted into the over all design process of [31] Pahl and Beitz.*

The automated morphological matrix is intended for concept generation but may also be useful in early screening. The matrix is partly based on rough approximations and statistics and should therefore be used with care when screening. The automated morph matrix relates to the conceptual phase as shown in Figure 63.

The quantified relationship matrix, which is a simple and stationary system model made in a spreadsheet program, has proven useful in early evaluation when concepts are numerous. Making a more detailed model is not meaningful at this stage. The model error would become large despite a high degree of detail, due to the large number of assumptions and uncertainties resulting from the lack of information.

The optimization for concept selection, as used here, requires function calls from a more advanced and dynamic model. The optimization is therefore more suitable for concept evaluation later in the conceptual phase when the number of concepts has been reduced, see Figure 63.
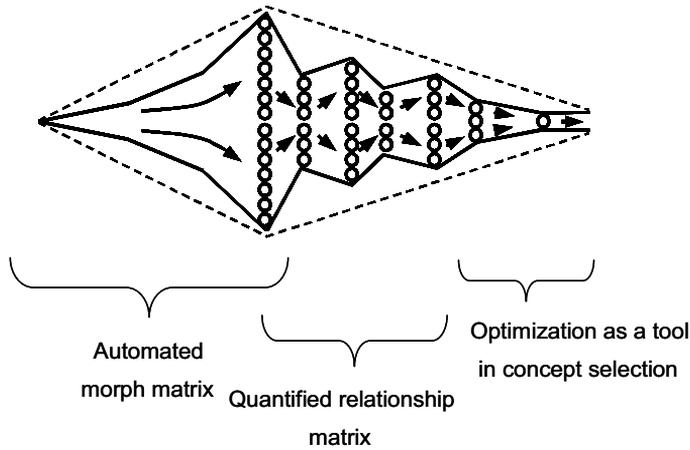
Figure 63: *Methods fitted into the concept generation and selection model of [48] Ulrich and Eppinger.*

In the reminder of this chapter the different methods will be discussed separately and at the end there is a section with concluding remarks.

7.1 Modeling strategy

In paper [II] a number of model design issues and activities at the engineering level are identified. If these are properly dealt with and fitted into an overall process or methodology, it might be concluded that:

- The time from design onset to operable model will decrease

- The probability of building the right model will increase (one that yields a simulation outcome that meets the stakeholders' expectations)

- There will be fewer (time-consuming) mistakes than with an ad hoc approach.

Condensing the experience gained during the modeling of JAS 39 Gripen fuel system yields the following list:

- Clearly define model accuracy and model frequency

- Minimize model complexity as far as possible

- Avoid stiff equations

- Perform frequent test simulations throughout the entire model development.

7.2 Quantifying the morphological matrix

The mathematical framework presented in papers [III] and [IV] 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 can 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 optimization 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 when using optimization 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.

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.

7.3 Quantifying the relationship matrix

Quantification of the elements in the coupling matrix between subsystems/components and top requirements, as described in paper [V] and handling uncertainties with probabilistic design methods, as described in paper [VI], has the following advantages.

- It will increase understanding of the top-level requirements' impact on low-level design parameters such as pipe diameter, pump size etc

- It is an easy way to introduce computational design tools already in early stages of conceptual design

- The subsystem interactions can be taken into account when evaluating the complete system

- Trade study and sizing in early stages are facilitated, which is important since it is vital that the concepts have about the same degree of optimality when assessed against each other.

- It may be helpful in the early termination of concepts by identifying design proposals that do not meet the requirements

- By combining the design structure matrix and a relationship matrix, it is also possible to visualize the coupling between both the top requirements and other systems or subsystems

- By using probabilistic analysis in the conceptual phase it is possible to explore the entire range of system behavior early on, rather than just focusing on one or more worst case scenarios as has previously often been the case. The worst case scenarios tell us what is possible but not what is probable. This does not replace the worst case scenarios. It is, however, a most useful tool when evaluating concepts by putting the – often unlikely – worst case in a broader perspective and thus promoting more optimal solutions.

7.4 Optimization in conceptual fuel system design

It would not be wise to choose a concept on the basis of the optimization result alone, as described in paper [VI]. There are always aspects that are difficult to quantify in an objective function, for example system simplicity from a robustness perspective. However, the benefit of quantifying the problem when formulating the objective function must not be underestimated. This is valid both for the formulation of the objective function and for the modeling of the system itself. Also, Figures 34 and 35, which are an outcome of the optimization, have a pedagogic value when explaining the problem to higher-level decision makers, which is often a part of the concept selection process. To summarize, it might be concluded that:

- The use of optimization will facilitate the concept selection process and increase the probability of choosing the best concept depending on the top-level requirements

- The use of optimization will increase understanding of how top-level requirements impact low-level practicalities such as fuel system design

- Quantifying the problem will enhance understanding of the problem so that the likelihood of choosing the best concept is greater.

As discussed earlier in this thesis, lack of experience in a/c specific supply systems is a growing problem in a/c system design. Therefore, methods such as the ones presented in this thesis are very valuable in concept design. The main drawback when using optimization, as here, is that an inexperienced engineer, perhaps due to a badly formulated objective function, may draw the wrong conclusions. It might however, be argued that:

- The process of gaining experience is enhanced and thus accelerated using the technique presented in this thesis.

7.5 Concluding remarks

Answers to the research questions formulated in chapter 2 are described implicitly in the earlier sections of this chapter. However, a condensed version with explicit answers is presented below:

- There are several ways to support conceptual design of a/c fuel systems. Shown in this thesis are conceptual design supported by an interactive morphological matrix, a quantified relationship matrix, and with optimization based concept selection.

- Optimization can be used in the conceptual phase either by screening concept combinations derived with a morphological matrix, eliminating inferior ones, or by using optimization as a tool in active selection.

- By mapping dependencies between top level requirement and design parameters in a quantified relationship matrix, the designer obtains a good understanding of how top level requirements influence low level design parameters. This is also true for the usage of optimization in general since the formulation of the objective function forces the designer to reflect on the measures of merit.

- By applying the modeling strategy described in [II] the development time for a large fluid system model will be reduced compared to an ad hoc approach or industry practice.

7.6 Future work

First of all, it would be interesting to expand the work presented in this thesis into other engineering domains. However, a/c fluid systems have some unique characteristics that perhaps make this domain more suitable. There is no strong geometrical dependence which is the case for mechanical systems with complex kinematics to name one example. Also, an a/c designer is in general considered to be less inclined to take risks and therefore more willing to use computationally heavy and/or time consuming design methods. Nevertheless, the methods described in this thesis are all built on a foundation of well proven methods that are general, so an expansion into other domains might be rewarding.

If remaining in the area of a/c fuel system design, conceivable areas of improvements include:

The modeling strategy has been developed by compiling experience from the design effort in earlier models. The next natural step is to use the strategy in an actual project, develop a large model, and draw conclusions from this work. However, already at this stage it is possible to see that it would be rewarding if more work were put into the validation part of the strategy and answers sought to difficult questions such as how to perform validation in practice and how to determine when, for what purpose, and on what grounds the model is considered to be valid.

The interactive morphological matrix is developed and considered valid for mid-size combat a/c, it would be interesting to expand the model for other types of a/c, for instance commercial transport or small UAVs. Furthermore, when the morphological matrix is combined with optimization, the objectives will most often conflict, and it is not clear which objective is the most important one. Techniques for multi-objective optimization could therefore be applicable where a group of concepts are selected which are all optimal depending on the relative importance of the objectives. This is a matter for

future work and would be an interesting continuation of this thesis. It would also be interesting to combine the morphological matrix with probabilistic design; some work has in fact already been done in this area.

The quantification of the relationship matrix opens up for the use of optimization, if this were studied in more detail, it would most probably prove to be fruitful.

A suggestion for future work, regarding optimization as a tool in concept selection, is to expand the objective function; possible additions to the measure of merit are number of components, component price and possibly power consumption and failure rate**.**

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