A QUANTIFIED RELATIONSHIP MATRIX AIDED BY PROBABILISTIC DESIGN AND OPTIMIZATION

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Abstract

This paper describes how probabilistic analysis has been used in the conceptual design phase of an a/c fuel system. Probabilistic analysis has been used in combination with matrix methods such as the House of Quality and the Design Structure Matrix. The frameworks of the House of Quality and Design Structure Matrices are used to visualize dependencies between top level requirements and engineering design properties. A technique developed at Saab Aerospace that gives the matrix methods a more quantitative approach is also included. By adding probabilistic analysis 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 previously often has been the case, and thus promoting the selection of more optimal solutions. The quantitative approach also opens up for mathematically formal optimization which has been exploited by deriving Pareto fronts for visualization of conflicting objectives. One of those objectives being minimized variation.

1 Introduction

The objective of this paper is to describe how the use of matrix methods and probabilistic design may reduce system development time in the conceptual phase by introducing design automation early on. The objective is also to minimize the number of errors by helping the designer take combinatory effects into account and by increasing the understanding of how the flight conditions interact with the low-level design parameters and their variation.

The paper begins with an overview of the basics in fuel system design. This is necessary in order to understand the illustrative example that follows. This is followed by a description of early concept evaluation and how matrix methods in combination with probabilistic analysis and optimization have been implemented at Saab Aerospace in conceptual design of a/c fuel systems.

2 Background

The design application described in this paper is the conceptual design of an aircraft fuel system with multiple and conflicting objectives. This section describes fuel system fundamentals and basics for the matrix methods used in the later design application.

2.1 Aircraft fuel system fundamentals

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

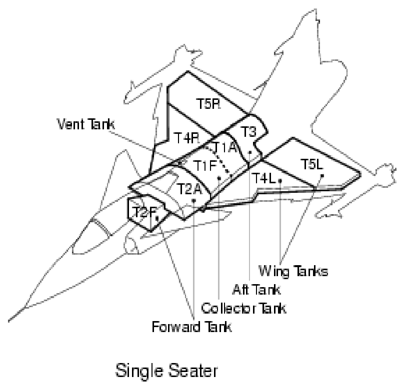


Figure 1. *The tank layout of Saab 39 Gripen*

The general fuel system layout consists of one or more boost pumps that feed fuel to the engine from a collector tank, usually a fuselage tank placed close to the CG.

There are several methods of ensuring engine feed pump submerge or fuel to the engine; most of these rely on a full engine feed tank. The engine feed tank is refilled by a fuel transfer system, pumping or siphoning fuel from the transfer tanks. Transfer tanks may be tanks located elsewhere in the fuselage, wing tanks, or drop tanks. There is also a vent system that ingests air during dive or defueling and expels air during climb or refueling, in order to maintain the desired tank pressure. The system may be pressurized to avoid pump cavitation or spontaneous fuel boiling at high altitude, or to provide a means of fuel transfer by siphoning. The fuel system's complexity varies from the small home built a/c with no system complexity, up to the modern fighter where the fuel system might be a critical element due to CG considerations and therefore very extensive with triple redundancy. If pressure refueling is required, a refueling system of some complexity must be added. The fuel may also sometimes serve as a heat sink, which adds a subsystem for cooling. Some of the fuel subsystems that may be identified in modern a/c are.

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

2.2 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, two of these are described namely the design structure matrix and the house of quality matrix.

2.2.1 The Design Structure Matrix

The Design Structure Matrix is an information exchange model, originally developed by [13] Steward, and has since then been developed further by for instance Eppinger et al [4]. 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 [3], design optimization [1], and conceptual design [11], 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 2, 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.

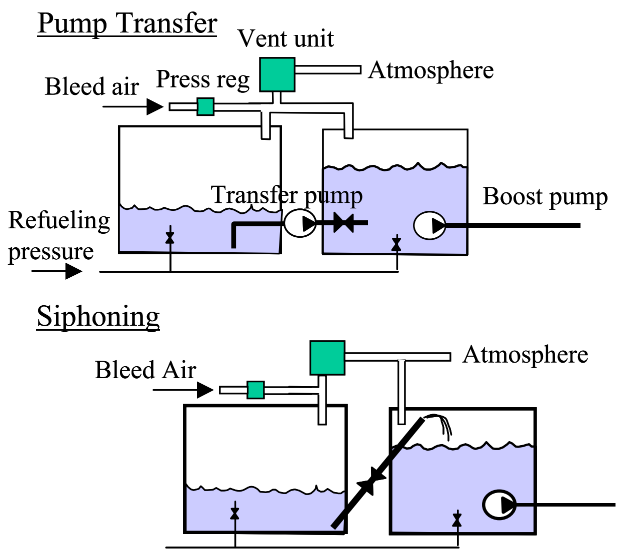


Figure 2: *Concept proposals. Pump concept at the top and siphon concept below.*

Subsystem dependencies of the pump and the siphon concepts are shown in Figure 3. For instance, it is possible to see 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. 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 3: *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. If the DSM is uncoupled or lower triangular, the design will most likely satisfy the first axiom of axiomatic design [14].

2.2.2 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 [2] Cohen or [7] Hauser and Clausing. However, it works just as well for showing dependencies between subsystems and top-level requirements, as shown by [1] Andersson.

The top-level requirements' impact on the pump concept is shown in Figure 4. 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 3. 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 4 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.

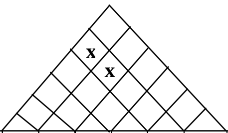
	Engine fuel consumption	Turn	Dive	Climb	Altitude	Refueling pressure
A. Pressurization system	x	x			x	
B. Engine feed	x				x	
C. Vent system			x	x		x
D. Refueling system						x
E. Transfer system		x			x	

Figure 4: *Top-level requirement impact on subsystems visualized using the House of Quality framework.*

3 Quantification

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.

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 existence 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 5: *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 5 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.

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, energy 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.

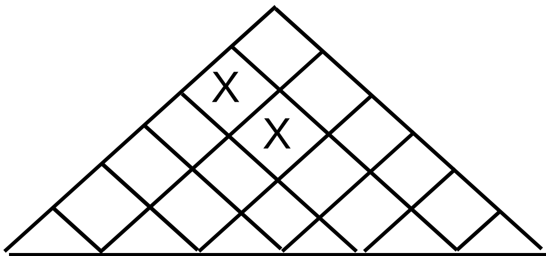
- Transfer system: Shall provide a transfer flow: mass flow of fuel [kg/s].
- Pressurization system: Shall minimize cavitation: 1=no cavitation, 0=100% vapor.
- Vent system: Shall ensure limit pressure by ingesting or expelling air at altitude change (mass flow of air [g/s]). There is also a rule of 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 6. 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 6. 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 6 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.

A refined trade study method will allow us to estimate the characteristics of an optimal system that meets the requirements. According to [12] Raymer trade studies answer design questions starting with: What if? Trade studies are as important as a good configuration layout or sizing analysis. Reference [12] 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 7 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?



			Eng cons kg/s 7,5	Turn Nz 1	Dive m/s 500	Climb m/s 110	Altitude m 3000	Refueling press kPa 350	A	B	C	D	E
A Pressure System	Targ-Press Sourc-press	25000 25000	cav transf 0,99 cav E-feed 1	cav transf 0,99			cav transf 0,99 cav E-feed 1		A				
B Engine feed	Pump power Pump eff d-suction zpump z-level	3000 0,5 0,05 1 0	Fuel press 262000				Fuel press 262000		X	B			
C Vent system	Tank volume d-ventpipe	2,3 0,04			Airflow g/s 140,3 v-air 91,6	Airflow g/s -30,9 v-air 20,1		overshoot pressure 175000 pa			C	X	
D Refueling system	d-ref inlet P-press	0,04 0						Ref Time 71 s			X	D	
E Transfer from tank#	Rho fuel d transf pipe Pump power Pump effic Z-target Z.source Target-depth Source-Depth	800 0,0254 400 0,5 0 1 0,2 0,2		Transf flow 3,0 kg/s			Transf flow 3,0 kg/s		X				E

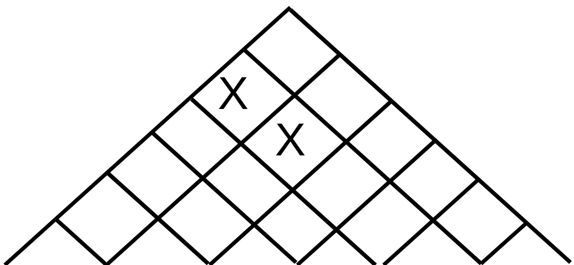
Figure 6: *The DSM and relationship matrix combined and with quantified elements for the pump concept*

	7,5	3	500	110	10000	350
25000 25000	cav transf 0,47 cav E-feed 1	cav transf 0,47			cav transf 0,47 cav E-feed 1	
3000 0,5 0,05 1 0	Fuel press 234000				Fuel press 234000	
2,3 0,04			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						Ref Time 71 s
800 0,0254 400 0,5 0 1 0,2 0,2		Transf flow 1,9 kg/s			Transf flow 1,9 kg/s	

Figure 7: *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 8, is better than the pump concept. In fact, the transfer flow looks very promising.

At a 2.7 g turn however, the transfer flow is zero due to the load factor, see Figure 9. 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	A	B	C	D
			7,5	1	500	110	3000	350	A	B	C	D
A Engine feed	w eff d zpump z-level	3000 0,5 0,05 1 0	Fuel press 237000 cav E-feed 1,00				Fuel press 237000 cav E-feed 1,00		A			
B Vent system	volume d-vp	2,3 0,04			Airflow g/s 140,3 v-air 91,6	Airflow g/s -30,9 v-air 20,1		overshoot pressure 175000 pa		B	X	
C Refueling system	d-refuel P-press	0,04 0						Ref Time 71 s		X	C	
D Transf/ press system	T-Press S-press d Z level Z outlet	25000 0 0,04 1 1,2	Transf flow 6,3 kg/s	Transf flow 6,3 kg/s								D

Figure 8: *The siphon concept at level flight at 3,000 m altitude.*

	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 0,5 0,05 1 0	Fuel press 251000 cav E-feed 1,00				Fuel press 251000 cav E-feed 1,00	
2,3 0,04			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						Ref Time 71 s
25000 0 0,04 1 1,2	Transf flow 0,0 kg/s	Transf flow 0,0 kg/s				

Figure 9: *The siphon concept at a 2.7 g turn at 3,000 m altitude.*

4 Dealing with uncertainties

Besides deterministic modeling of the system proposals, 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.

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 [9]

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.

4.1 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 10: 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.

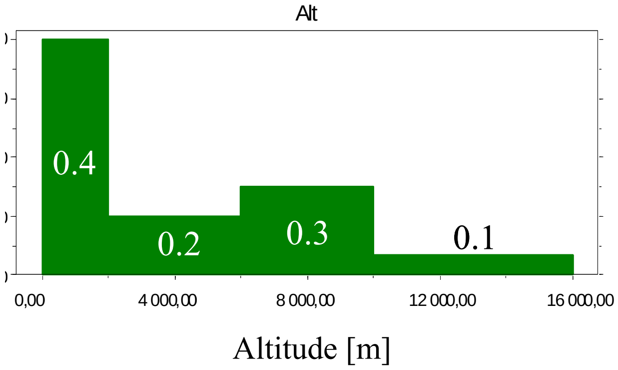


Figure 10: *Simplified but typical altitude distribution for a multi-role combat a/c, where 40% of the time will be spent below 2000 m, 20 % between 2000 and 6000 m etc.*

4.2 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 11.

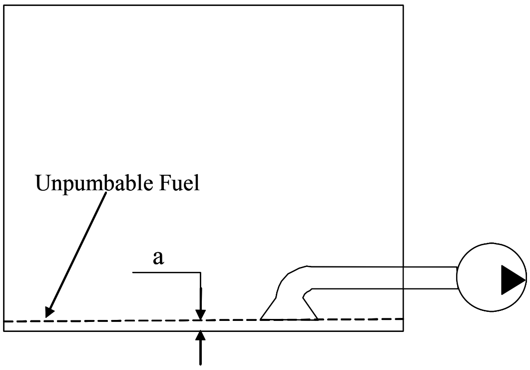


Figure 11. *The influence of residual unpumpable fuel on suction side pressure drop.*

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 12.

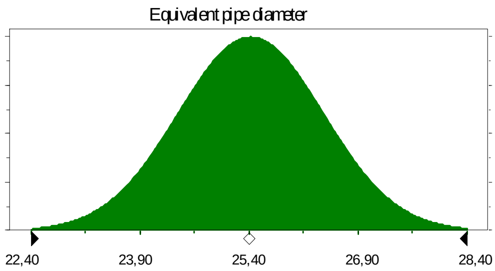


Figure 12: *Distribution of the equivalent pipe diameter expressed in mm.*

4.3 Fuel properties

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 $p_{startcav}$ is introduced, the actual equation and its origin is described in [5]. The factor $p_{startcav}$ is represented with the normal distribution shown in Figure 13, which is based on bench tests at Saab Aerospace.

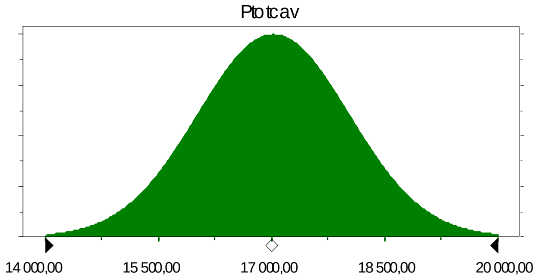


Figure 13. *Normal distribution of the $p_{startcav}$ parameter in expressed in Pa.*

4.4 Probabilistic 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 14.

4.5 Cavitation forecast

One of the most interesting system characteristics when evaluating an inline pump system is the degree of cavitation. 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 15. 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.

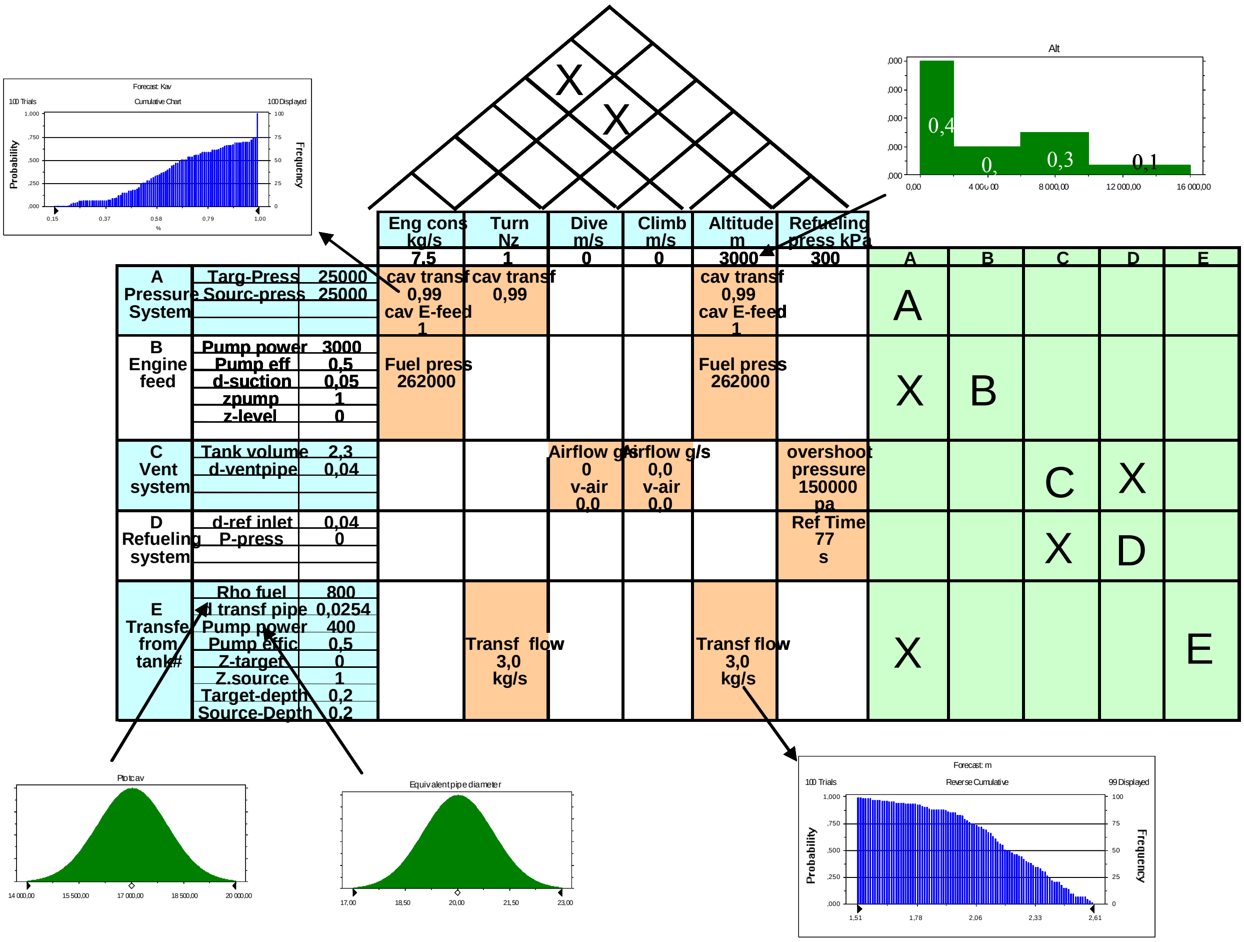


Figure 14. *Schematic of the system simulation where assumptions have replaced previously used single values and the simulation result is presented as cumulative charts*

Note that the historical approach is to simply not allow a lower pump reduction factor than 0.5. From the forecast in Figure 15, however, it is clear that the area below 0.5 is very small and may possibly be acceptable.

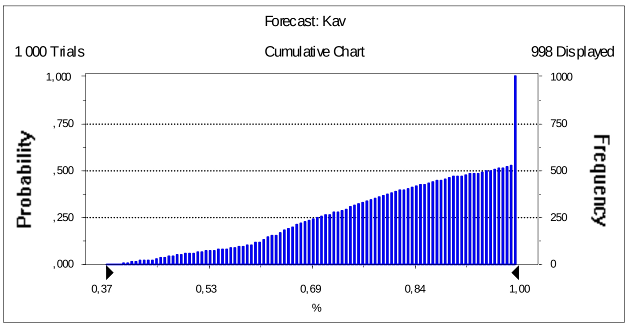


Figure 15. *Cavitation reduction factor, where 1 means no cavitation and 0 means 100% vapor.*

4.6 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 [8] JSSG states that “*When engine flow rate is large relative to the quantity of fuel on board, as is the case of afterburning 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 16 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.

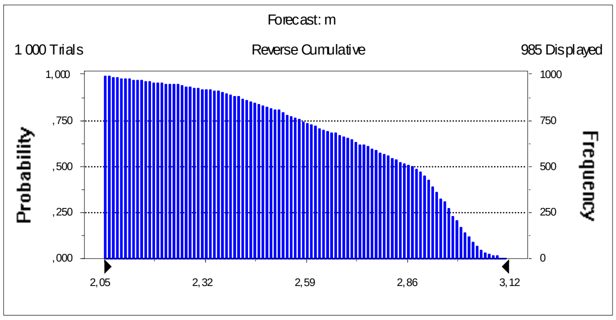


Figure 16. *Forecast of the transfer flow rate in kg/s.*

5 Optimizing variation

Variation is most often considered as a problem. As in this example: if the fuel transfer flow varies with flight conditions such as altitude and load factor and with variation in design parameters such as system pressure drop, this makes the system more vulnerable to change in context and makes the system performance less robust. Low variation is therefore desired but it is most often penalized with high cost or high system weight. Weight and low variation in transfer flow are conflicting objectives. One way of dealing with multi objective optimization is to visualize the problem with Pareto fronts.

5.1 Optimization framework

An optimization framework has been developed to enable optimization of the system based on the quantified relationship matrix. The fundamental principle for this framework can be seen as a combination of the model, the objective function, and the optimization algorithm as illustrated in Figure 17.

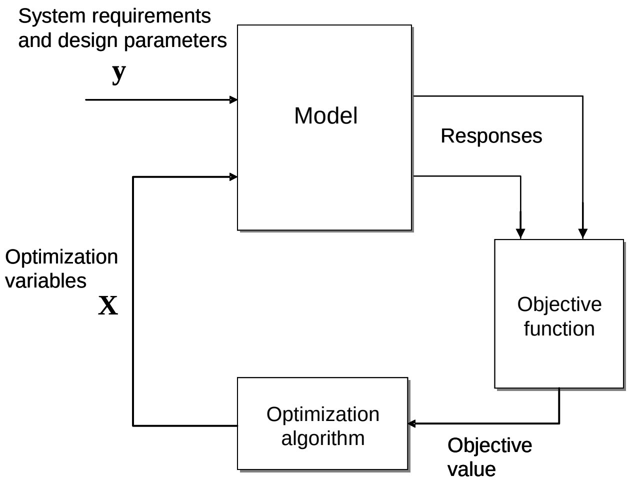


Figure 17. *Illustration of the optimization process.*

The risk analysis software Crystal Ball, used earlier, also contains an optimization toolbox OptQuest which is used here. OptQuest incorporates *metaheuristics* [6] to guide its search algorithm.

5.2 Optimization result

In this section, some illustrative results from the design application described above are presented. The example is primarily intended to constitute an illustration of the approach and implementation described rather than essential results of the specific design task.

In this example, the design objective is to minimize weight (f_1), and fuel flow variation (f_2). An objective function has therefore been created where the sub-objectives are weighted and form a weighted sum, that together with the penalty function is minimized, see equation (1).

The sub-objectives are normalized against a datum concept proposal (f_{i0}), which in this case is the solution that was considered the most promising before the optimization was begun. The sub objectives are system weight and fuel flow variation. The system weight includes weight of the plumbing, weight of the pump and weight of the tank structure.

Design variables (**x**) are, tank pressurization (the higher the pressure the higher the structural weight), pump size, and size of the plumbing.

Uncertain variables (**y**) include altitude, and $p_{startcav}$ which were simulated with distributions as shown in Figures 10 and 13. The load factor was also varied and the distribution is shown in Figure 18. The pump side pressure drop was not subjected to variation in this simulation in order to facilitate the optimization since the pipe size itself was used as an optimization variable.

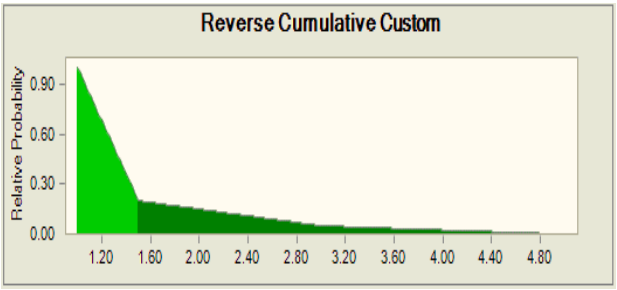


Figure 18. *Load factor distribution, where n_z varies from 1g to 4.8g*

Constraints (g_j) in optimization formulation include unacceptable high degree of pump cavitaion, and a fuel flow lower than a specified minimum value. These constraints are handled using penalty functions as described in equation (1) below.

$$
\begin{aligned}
&\min_{\mathbf{x}} \; \lambda_1 \frac{f_1(\mathbf{x},\mathbf{y})}{f_{10}} + \lambda_2 \frac{f_2(\mathbf{x},\mathbf{y})}{f_{20}} + \psi \\
&s.t. \\
&g_j(\mathbf{x},\mathbf{y}) \le 0 \quad j = 1,2 \qquad (1) \\
&\psi = \sum_j \max\left(0, g_j(\mathbf{x},\mathbf{y})\right)^2 \\
&\lambda_i > 0, \sum_i \lambda_i = 1, \; i = 1,2 \\
&\mathbf{x} = \left[x_1, x_2, \dots, x_n\right]
\end{aligned}
$$

5.2.1 Single objective optimization

An optimization run was made with the objective function set to minimum weight, i.e. $\lambda_1=1$ and $\lambda_2=0$. The reference value for weight is 24 kg when calculating the objective. It is possible to read from Figure 19 that the optimal objective value ended up at approximately 0.8 which correspond to a system weight of 20 kg

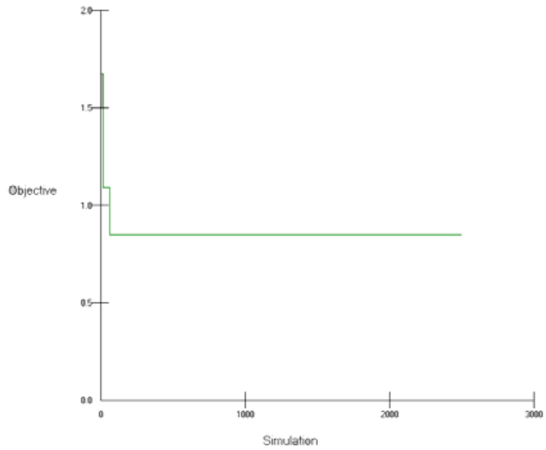


Figure 19. *The optimization result with objective to minimize system weight.*

An optimization was also performed with the objective set on minimum variation, $\lambda_1=0$ and $\lambda_2=1$. When the variance was minimized, the system weight grew to 36 kg. This confirms the notion that weight and flow variation are conflicting objectives

5.2.2 Pareto optimization

One way of handling a multi objective optimization problem with conflicting objectives is the use of Pareto fronts. A Pareto front contains only non dominated solutions. If the solution is not on the Pareto front it could be improved without degeneration in any of the objectives, it is therefore clear that the preferred choice is a design included in the set of pareto optimal solutions.

By varying the weights λ_1 and λ_2 in the objective function (1), a Pareto front was derived for this particular problem, as shown in Figure 20.

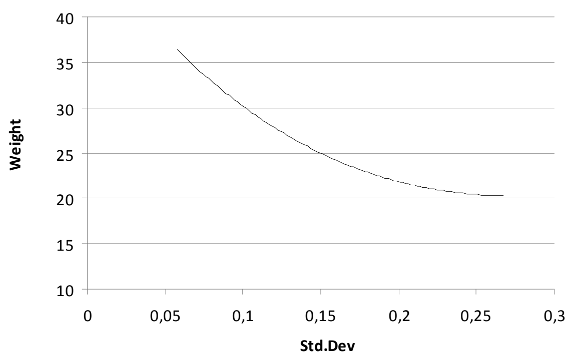


Figure 20: *A pareto front with system weight and fuel flow standard deviation as conflicting objectives*

It is possible to see that as the fuel flow becomes more stable the system weight increases. This is mainly due to the fact that a high tank pressure will suppress cavitation and therefore stabilize the fuel flow but at the same time increase the structure weight.

6 Discussion and conclusions

This paper describes system analysis performed in the conceptual phase, not to be confused with embodiment or detail design. When looking more closely at the conceptual phase, the aim is to determine the technical principal. According to Ulrich and Eppinger [15], the conceptual phase itself may be divided into two different activities: concept generation and concept selection. In the early stages of the conceptual phase, concept proposals are easily dismissed without deeper analysis. When the number of concepts decreases, the need for deeper analysis will increase.

The method described in this paper combines well known matrix methods with a simplified and stationary system model. The software is the easy-to-use spreadsheet program MS Excel in combination with the equally easy-to-use add-in program Crystal Ball. The combination of well known software and uncomplicated modeling makes the method particularly useful relatively early in the conceptual phase when concepts are still relatively numerous, see Figure 21. The efficiency of more advanced modeling is debatable this early in the design process due to the large degree of uncertainty. When the final selection is made, this approach may, however, need to be complemented with more refined analysis, such as dynamic modeling and in-depth cost assessment.

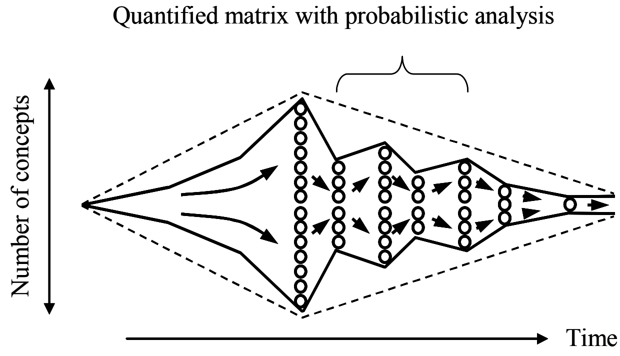


Figure 21. *Methods fitted into the concept generation and selection model of [15] Ulrich and Eppinger.*

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. The approach presented 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.

Also, by adding optimization it is possible to derive pareto frontiers in order to facilitate trade studies, where conflicting system characteristics are assessed against each other. In this paper this is illustrated by showing how a decreased fuel flow variation leads to an increased system weight.

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