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Understanding mission objectives and priorities with QFD

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Abstract. Translating the customer's perception of quality and performance into technical terms and requirements for a product is important for guiding design, verification, and process development. Capturing the unspoken priorities and communicating them through the organization can efficiently guide the product or service development towards solutions that meet the customers' needs. The methods used at Kongsberg Defence Systems today do not sufficiently capture and communicate the voice of the customer and their fundamental needs. The research uncovered that key decision makers in the organization had significant variance in their understanding of customer priorities, and a partial misalignment with the priorities provided by customer representatives. The implementation of Quality Function Deployment (QFD) for the Joint Strike Missile provided an effective communication tool for customer needs, and illuminated the relative importance of system attributes and how they relate to the customer's priorities. This paper argues that the Quality Function Deployment is a valuable tool communicating mission objectives, to enable innovation, and to guide verification and validation efforts at a later stage. For complex products, however, QFD shows weaknesses that must be addressed to support efficient decision making.

Introduction

The Joint Strike Missile (JSM) has been in development at Kongsberg Defence Systems (KDS) since 2004 and is one of the most advanced military development programs ever conducted in Norway. Its objective is to equip future Royal Norwegian Air Force (RoNAF) F-35 combat aircraft with a weapon that allows for high precision engagement of highly defended sea-, littoral-, and land targets at very long range. In many ways the missile operates as a small autonomous aircraft that has been designed to strike vessels equipped with advanced self-defence systems at a distance, as well as land-based targets. The JSM is made from advanced composites, and is designed to have a minimal radar signature. Along with its ability to fly along the ground and hide in the terrain, this ensures that the missile will go undetected until very close to the target. The final development is expected to be concluded by the end of 2017, and the integration of the missile on the F -35 is expected to be completed as part of a specific iteration of upgrades on the F-35, known as "Block 4", during 2022-2024.

As an AS9100 certified organization, KDS is committed to continuously improving, with emphasis on meeting customer needs and regulatory requirements. With support from KDS, this research investigates the application of Quality Function Deployment (QFD) to improve KDS's requirements engineering capacity and ensuring that customer needs and priorities are thoroughly reflected in the development of its products.

The following research was conducted on the JSM system as a proof of concept of the potential contributions from QFD, leaving out the support equipment and focusing on the core product. Even though the development has been going on for quite some time, there are still JSM specific benefits to expect from the QFD analysis; for instance, a better understanding of which characteristics should be given the most attention during system and subsystem verification and validation.

The following section will set the scene for the research process and present the main questions investigated in this paper. This is followed by an explanation of the work conducted to gather the required data, the observations that have been made, and finally an overall discussion of the findings.

Background

The main external stakeholders for the JSM are the RoNAF and aircraft manufacturer Lockheed Martin (LMCO). The customer, RoNAF, through their long-term strategic planning, has identified a need for a weapon for high precision engagement of highly defended sea-, littoral-, and land targets at very long range, with an advanced set of capabilities to counter tomorrow's threats. The needs identification for what would become JSM began while the government was evaluating new fighter aircraft to replace the aging F-16. Feasibility studies were conducted involving KDS, the Norwegian and Australian Air Force, and US and UK defense consultants and experts. A specification was formed, an image, of what the next generation missile's operational capabilities should be, formally known as the Operational Requirement Document (ORD). This continued to evolve when RoNAF contracted LMCO to build a model of the missile concept into their simulator, Partner Manned Training System, for concept validation purposes. Soon thereafter KDS was under contract to develop the JSM based on the ORD. The JSM capabilities and characteristics were developed form the experience of the Royal Norwegian Navy's sibling, the Naval Strike Missile (NSM). However, while many of its features and characteristics are similar, only a fraction of NSM could be brought forward into JSM, resulting in significant development effort and reconsideration of every aspect.

Neither documentation from the development of the ORD, the ORD itself, nor the contract, indicates any prioritization among needs, requirements or the project management triangle of cost, schedule and quality. The Air System project manager stated in an interview (Sørsdal, 2015) that the prioritization among characteristics was done through the work culminating in the ORD, meaning that primarily RoNAF, already was very specific about the solution at the time. An additional internal top level requirements document was created as well, named the KDS Requirements document. This acted as a placeholder for the stretch goals that were identified during the feasibility study, but not specified by RoNAF in the ORD. These are formulated as shall-requirements and included in the official requirement documents list, but because KDS has not financially committed itself and established a formal ownership to these requirements, they are in practice just *should* goals. However, this document does not indicate any prioritization either.

The JSM program is organized in two separate, but closely related projects; *Air System*, and *JSM Development*. These two projects have independent project management and resources, but are both under the same program manager. In the System of Systems (SoS) that incorporates the JSM program, the JSM Development project is set to focus on the missile itself, the storage container, and maintenance equipment. The Air System project works with the customer and LMCO as the primary and formal interface, writing detailed JSM and SoS concepts, detailed missile specifications for the JSM development project, and developing the mutual interface specification with LMCO. In addition they develop planning software to be integrated in the aircraft's ground based tactical and strategic planning system. The organizational relationships and specification flow is illustrated in Figure 1.

Two additional channels have also been formed in later years. The Air System project has established the *Operational Forum*, a series of meetings for early validation of system concepts, and JSM Development project has had similar *Technical Focus Group* meetings with the customer to establish what is "good enough" on those very important, but hard-to-quantify performance characteristics of specific subsystems.

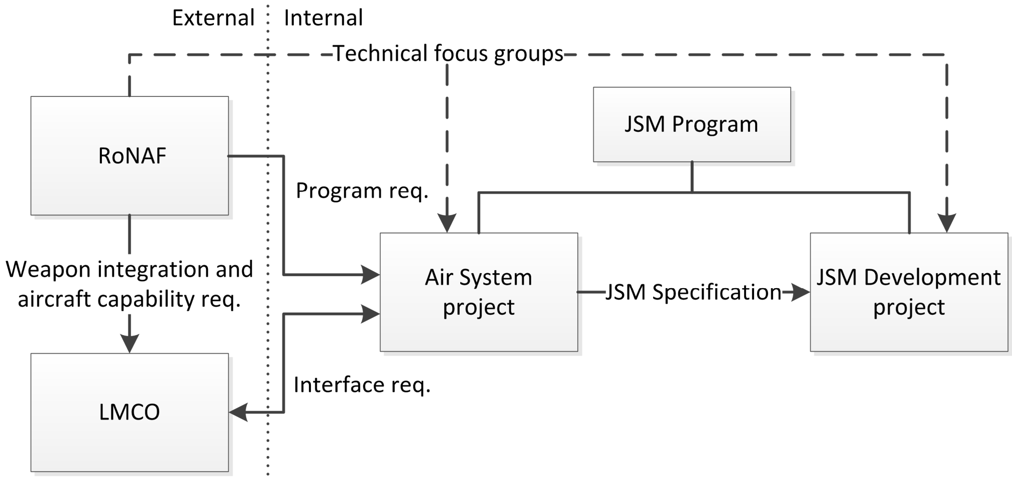


Figure 1. Organizational entities and requirement flow

Because of the magnitude of new development and reconsiderations that have been made without an established set of priorities, the development teams have had difficulties with prioritizing effectively, and decisions seem to take longer than necessary. These experiences show that it would be beneficial to obtain a deeper understanding of the needs and priorities behind the system requirements than those found in the ORD and KDS Requirements document. Quality Function Deployment is a potential Systems Engineering method for establishing these priorities, and is included in the INCOSE Systems Engineering Handbook (Haskins, 2011) as a recommended tool for supporting the requirement analysis process. When established in the beginning of the project lifecycle, it can benefit throughout the Systems Engineering development lifecycle to also support trade studies. Also for the current state of the JSM project, it would be beneficial to know the importance of the different needs and system characteristics for the purpose of focusing efforts during qualification and verification, as well as prioritizing early validation activities with the customer.

The authors' assertion is that the Quality Function Deployment method can assist in communicating the goals and priorities of the system and subsystems between the customer and engineering disciplines. It can increase the decisiveness and confidence in priorities, especially when facing trade-off decisions, increase the effectiveness of the organization and product value.

To investigate this claim the author has created a proof of concept by applying QFD on the JSM project. The following questions are posed to uncover if the information conveyed by the QFD products were relevant to the development team and management:

1. Is the Quality Function Deployment process a good tool for understanding the customer perceived qualities and priorities?
2. How well does the Quality Function Deployment communicate the importance of technical characteristics to the development team?
3. How can the products of the Quality Function Deployment process be useful when a trade-off decision must be made?

Research method

The process used for implementing QFD is largely based on the book by Ficalora, J.P. and Cohen, L. (2009); *Quality function deployment and Six Sigma: a QFD handbook*. This book has a complete list of steps needed to be performed in a QFD analysis and tips on how to perform them, including building the House of Quality.

This research into the application of QFD as a method in KDS was conducted in two major phases;

1. Establish customer needs and priorities
2. Establish the House of Quality

Phase 1 investigates the state of priority understanding in the organization; namely, is there currently an uncertainty about the customer priorities for the product? A questionnaire was distributed to measure this understanding by letting the requirement engineering team and project management attempt to set priorities according to what they believe the customer priorities are. Additionally, a group of key decision-makers at the technical level also provided their perceived customer priorities for comparison. The data gathered was analyzed to evaluate the statistical dispersion in believed customer priorities across the internal (KDS) organization. These results should indicate the degree of uncertainty about the customer priorities and if this would explain contradicting behavior.

After a statistical mean of the priorities according to the program itself was computed, it was compared to a set of priorities given by a group of representatives from the customer organization. The comparison should validate or invalidate the internal perception and show if it is possible to gain any benefits from establishing a formal mode of communication for product priorities with the customer.

Feedback is gathered to get a qualitative impression about the method used to collect priority weights. This should indicate if the users believe in the data collected, and if the data gathering method was easy and understandable enough to use.

To build the House of Quality (HoQ) matrices in phase 2, a walkthrough session with a focus group was scheduled to establish the relationships between customer needs and system quality characteristics, and the positive and negative correlations between each system quality characteristic. The focus group was monitored for their level of interaction and need for explanation of the method and tools. Ideally, the group should focus on establishing the content and commenting the results. Feedback on ease of use and value of the results were gathered from the meeting and short interviews with select participants afterwards.

Phase 1: Establish Customer Priorities

Understanding customer needs. A complete set of needs from a Voice of the Customer elicitation process can be substantial and usually result in output that fall in to several categories; customer needs, substitute quality characteristics, functions, reliability and target values. QFD first focus on the customer needs. Literature commonly points to this as the most important step in QFD (Ficalora and Cohen, 2009). Getting the needs right lays the groundwork for the understanding of quality through the whole QFD process. The elicitation of priority weights are based also on the perception of these formulations. To keep the analysis focused and useful, the needs follow a set of rules (Veral, 2009):

1. The need shall be something the product can do better or worse, as seen from a customer standpoint. Can the perceived performance or quality be rated on a scale from one to ten?
2. The answer should not be binary - pass or fail – there is limited value in continuing the analysis on a need without room for trade-offs. This includes the situations where there is a hard goal you must reach, and improving on top of that does not make sense.
3. The need shall be formulated so that it is fairly intuitive how an improvement in a product characteristic can contribute to the satisfaction of that particular need. Included here is the notion that it should be obvious if more, less or a target value is desired.
4. Ideally the need should not be specific to the product concept. If such formulations are found, ask what benefit it will give the customer. The *Five Whys* technique can be useful to help focus on the real needs, instead of how the customer (or contractor) envisions the solution (Bijan, Yu, Stracener & Woods, 2012).

For this proof of concept the author could not interact directly with the customer for the development of needs. Instead, the author analyzed the ORD and grouped the non-functional requirements in an affinity diagram according to the general theme of the characteristic they were describing. This proved to be useful and enabled the author to create a rough sketch of the customer needs. Through interviews with requirement engineers who have been in contact with the customer in the past, it was possible to formulate more precise need statements for the different themes that were discovered, and structure the needs in a new affinity diagram. Further refinement was performed to ensure the quality of the needs hierarchy according to Kirkwood's list of desirable properties of value hierarchies (Kirkwood, 1997). For instance the needs should be mutually exclusive within each tier, otherwise the partial redundancy can result in needs receiving more weight that intended when "double counted". The resulting three level needs hierarchy is given in Figure 2. The needs cover all aspects of the missile while following the rules stated above. The next step involved creating a questionnaire to capture the priorities of these needs.

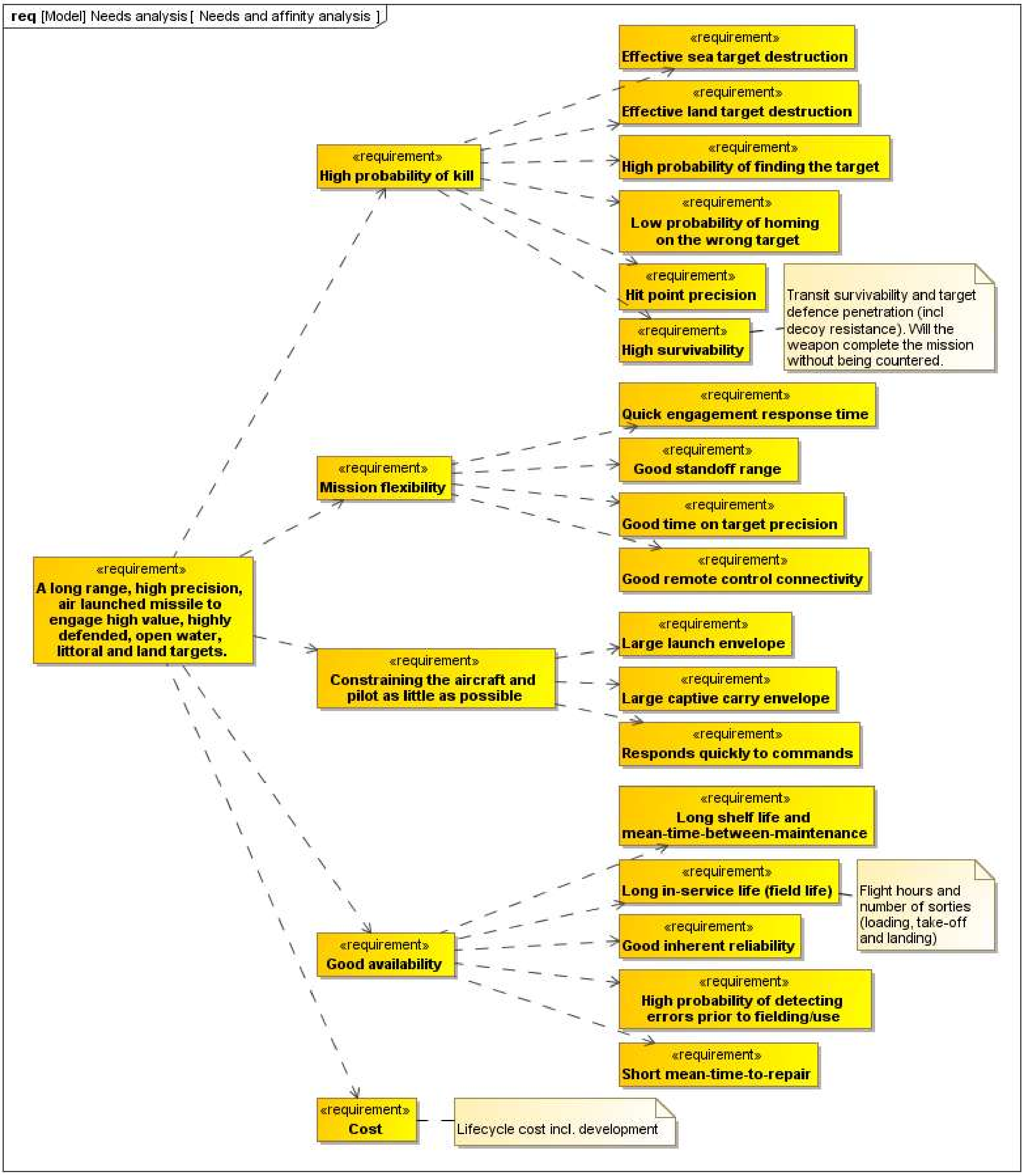


Figure 2. Customer needs hierarchy

Measuring customer priorities. The prioritization among needs was done with the help of the Analytical Hierarchy Process (AHP) (Saaty, 2000). This method is well known in decision making theory, but also used in QFD to elicitate priorities. It is a highly developed method which originates back to Thomas L. Saaty's book on the subject, *The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation* (1980). It is a thorough way of eliciting priorities as it forces the person filling out the questionnaire to think about how each element compares against each other, rather than e.g. simpler methods where each element is scored individually, like the five-point scale (R. Likert, 1932). Relative prioritization is also less prone to central tendency bias, in which almost everything is rated important as customer often tend to do. For the data to help developers prioritize, it is important that the customers can clearly differentiate the importance of different needs.

With AHP, comparing every need against each other scales according to the formula$(n * (n-1))/2$, generating many entries. The number of judgements required for the leaf nodes in Figure 2 would require as many as 171 judgements. Arranging the needs in a hierarchy reduces the number of questions that need to be answered, as only the needs within each group need to be compared against each other. For the Figure 2 hierarchy this reduced the number of judgements to 44. Another benefit seen in this research is that the judgements here are made in general between items that are closely related to each other and therefore easier to evaluate. The abstract nature of the top-level needs also makes them easier to evaluate in the context of other top-level needs. However, some reported that it felt unnatural to prioritize between a few of the needs because both were critical to the higher level objective. This shows an important reason of having the option to set equal importance.

Figure 3 shows the first section from the questionnaire as constructed in an Microsoft Excel™ spreadsheet. This first section is for comparing the top level needs against each other. The questionnaire was answered by selecting the appropriate value given by Saaty's relative importance scale from a drop down in each of the 44 yellow cells. The values represent the level of preference for the customer need on the left, over the customer need above. An explanation of the values were given as seen in Figure 4, with some additional text for each tier to help differentiate the levels, e.g. for "Very strongly preferred" it says "One element is favored very strongly over another; its dominance is demonstrated in practice".

Top level objectives Consistency rating = 0,07

	High probability of kill	Mission flexibility	Constraining aircraft/pilot as little as possible	Good availability	Cost
High probability of kill	1	7	3	3	5
Mission flexibility	1/7	1	1/3	1	3
Constraining aircraft/pilot as little as possible	1/3	3	1	3	3
Good availability	1/3	1	1/3	1	1
Cost	1/5	1/3	1/3	1	1

Figure 3. Questionnaire judgments for top-level objectives

Select the appropriate rating in each of the yellow cells according to the following scale:	Preffer row over column	Preffer column over row
Extremly preferred	9	1/9
Very strongly preferred	7	1/7
Strongly preferred	5	1/5
Moderatly preferred	3	1/3
Equally important	1	1

Figure 4. Saaty's relative importance scale

By having the questionnaire in a spreadsheet, the author was able to run the calculations in real time and display the results as soon as the questions were answered, allowing the participants to reconsider their responses. It also enabled calculation of Saaty's consistency rating as seen at the top of Figure 3. This rating provides a feedback loop to the participant on whether the answers are fairly consistent or not. If answering that B is more important than A, C is more important than B, and A is more important than C, you have an impossible circle of priorities where the participants would receive a warning of inconsistency which in turn should encourage them to review their answers. However, in case they are confident in their answers they are free to leave them as is and the weight calculations will be best effort.

Interviews with five of the participants after they handed in the questionnaire revealed that they used an average of 30 minutes to fill in the form. They also observed that the form was fairly simple to use and understand, although one noted that it was only ok after being given some time to look it over. The author notes that 3 of the questionnaire participants needed additional assistance to understand the correct use of Saaty's relative importance scale in regards to the direction of preference. The common perception was that the results seemed to represent their priorities well, but one participant felt insecure about some of the answers because of a bad consistency rating. None of the participants felt that the survey was too comprehensive and that they could have managed even if there were more detail.

The internal perception. The questionnaire was answered by 31 participants. These were split into 3 groups for further analysis; Customer (3 participants), Requirement engineering and management (13 participants), and Technical Engineering (15 participants). Common for all participants is that they have decision authority or significant influence on the product outcome. While the two first groups are fairly obvious, the Technical Engineering group consists entirely of senior engineers, many of whom are team leaders in their specific area, and also have a seat in an interdisciplinary forum tasked with solving trade-off situations and interdisciplinary problems.

To better understand how well the organization agreed on the customers' priorities, the author created a statistical plot of the priority weights gathered internally. Each customer need is placed along the x-axis, and priority weight along the y-axis, as seen in Figure 6. The *box and whisker plot*, made popular by John W. Tukey (1977), was selected as the best representation of how the participants' inputs are distributed along the y-axis. The horizontal line through the box is showing the median, the rectangle represents the interquartile range (50% of the votes), and the upper and lower whiskers reach out to the highest and lowest priority weight submitted. The median and interquartile range, in comparison to mean and standard deviation, is not as sensitive to extreme values and better represents the central tendency when the data is skewed as found in this case.

As shown in Figure 6, the internal participants exhibit a significant variance on certain customer needs. In particular the "Low probability of homing on the wrong target", "High survivability", and "Cost" are topics of greatest internal disagreement according to the statistics. However, during a meeting where this figure was presented, a discussion took place to understand the reasons for this. For instance if a missile homes on the wrong target or doesn't survive the enemy's defence systems its usefulness in the scenario is reduced, but if the price per missile is lower, then maybe the customer would use more of them to ensure effectiveness. It was apparent that this was a theme easily identified by the audience and that the statistics revealed an inherent uncertainty. Some even speculated that there could be a moral question of value for a missile that would only hit its intended target and not kill or damage anyone or anything else.

Another observation is that some participants of the survey believe that certain needs are much more important than what the rest of the participants think. Take for instance "Good remote control connectivity". The top 25% of votes stretch out to almost 6 times the priority of the majority. The same goes for "Effective sea target destruction" and "Cost" which also have been given very high priorities by a few. These cases are very interesting, and should be taken seriously, so that the people with such strong perceptions for these criteria are given the opportunity to discuss their view with the rest of the team. It might be that the person with a non-majority opinion has understood something the others have not, or that s/he needs to realize the importance of other customer needs when making future decisions.

Another important discussion that came up during the internal review session was about the thresholds of the individual needs. It is clear that at a certain point the needs are fulfilled, and making the product better will not provide a significant contribution. Also in terms of trade-off analysis you cannot deliver zero "Standoff range" and "Hit point precision" because "Cost" had a higher priority. The air force already has "dumb bombs" and this is not what they are asking for. At this point it was agreed that whatever the customers' priorities were, it may be difficult to act on a priority with a single priority

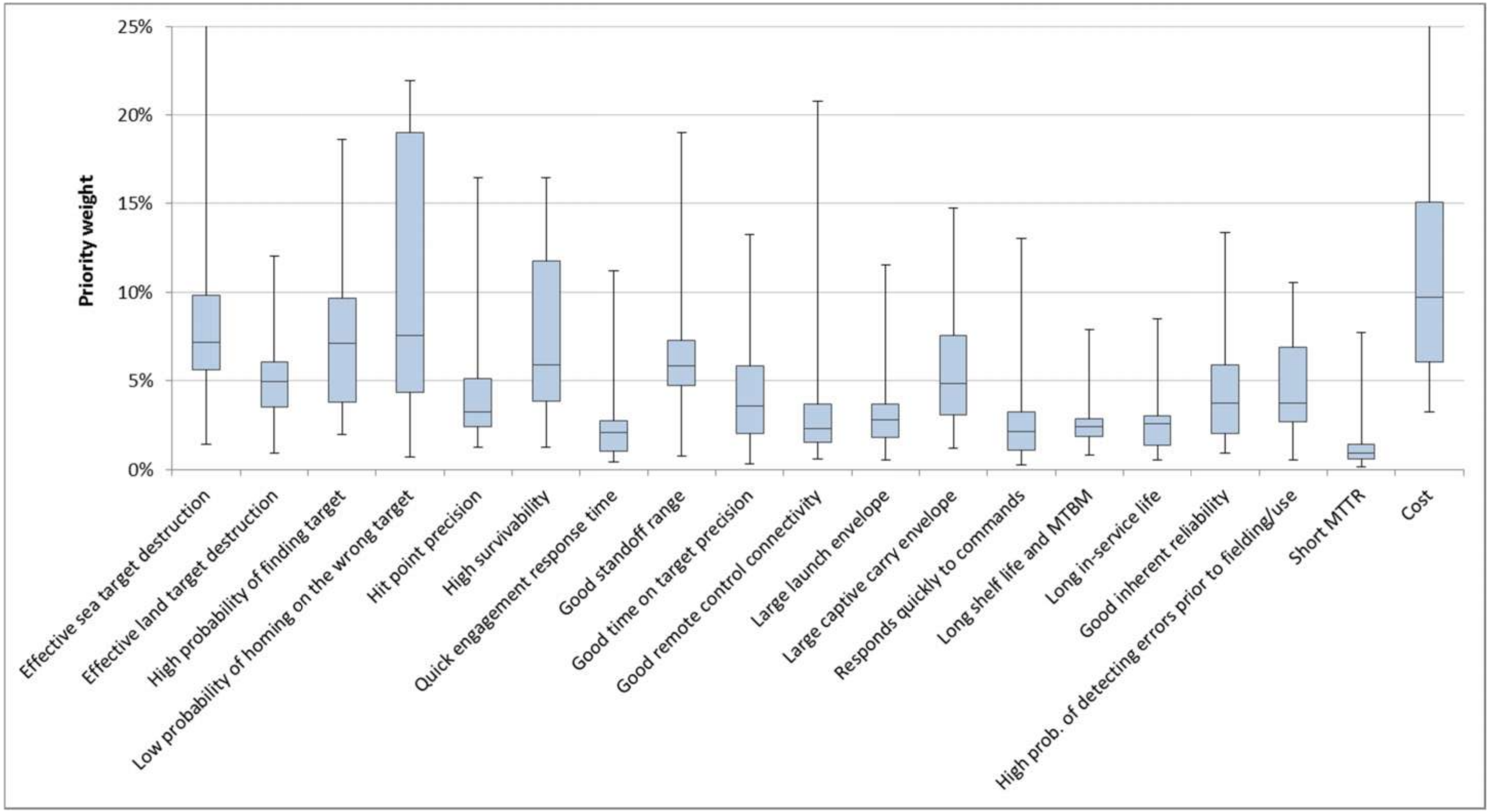


Figure 6. Internal priority consensus

representation. Additional possibilities for characterization of the need should be investigated to support efficient decision-making.

In summary, the graphical representation of the data was well received, but some would like to see each priority against the average, possibly represented as a straight line going through the chart. This would provide a quick reference for whether the customer need was prioritized up or down.

Comparing respondent results. The radar-chart in Figure 7 shows the difference in mean priority weight between the requirements engineering team's perceived customer priorities, and the customers own answers to the questionnaire. The mean of the votes was chosen for this representation since the chart does not display additional information regarding the dispersion. The statistical mean is better in this situation because it retains more information by letting every vote count equally. The customer needs are sorted according to the difference between the groups' ratings around the radar-chart, resulting in sectors where the southern sector are points of good agreement, and the northern sectors indicate misaligned perceptions of priority.

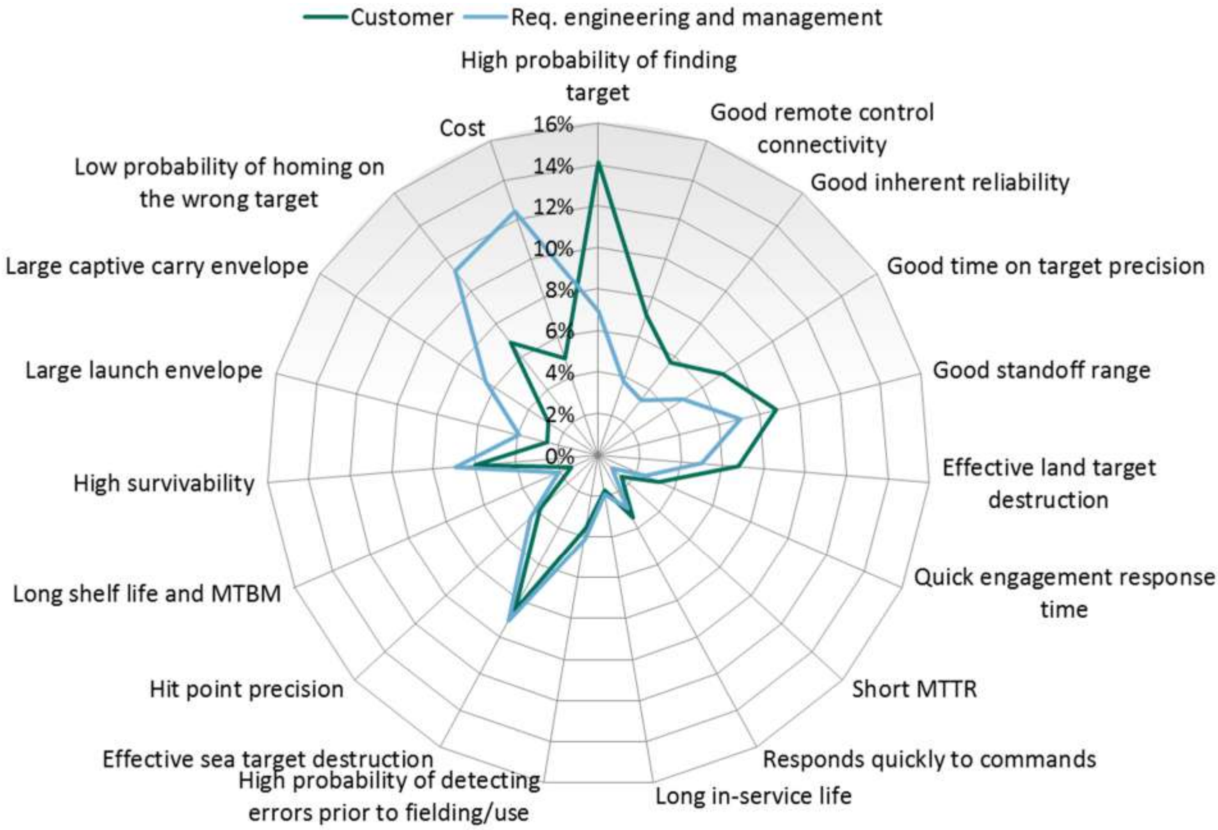


Figure 7. Mean priority weight by respondent group

During a meeting summarizing the results one of the participants expressed the idea that this should have been used in the customer organization to synchronize their views internally, and not just between the two organizations. Naturally different parts of RoNAF have different needs, as well as other stakeholders, but the requirement engineering team has experienced this different focus coming from different sources representing the same customer group. The data collected from the customers during this research confirms this.

A process emerged from this meeting where the needs and priority elicitation process used in this research could be applied advantageously to counter the customer disunity and help them establish a common understanding:

1. Sit down with the customer representatives and agree on the needs hierarchy, being clear about the definition of each need.

2. Let each representative fill out the AHP based questionnaire individually. It is important to help the individuals in the defence organization portray their own views, which otherwise may be held back in the presence of higher ranking officers.
3. Sit down again and discuss the findings, why do some believe one element is more important than others and so on, until all can agree on a common way forward.

Having such a well-established set of priorities would be a good communication tool for our requirement engineers. Also, the discussions taking place in the process outlined above are likely to provide interesting information in general requirement elicitation and the next step in the quality function deployment process; establishing the Substitute Quality Characteristics (SQCs) and their relationship to the fundamental customer needs.

A similar group comparison was done between requirement engineering and the technical engineering representatives with no major deviations from each other, showing that even though there are differences of opinion between individuals, the requirement and technical engineering groups as a whole are somewhat synchronized with each other.

Phase 2: Establish the House of Quality

The HoQ stands at the center of the QFD process and provides structure for the large amounts of information gathered. It originates back to Dr. Yoji Akao, chairman of the QFD Research Committee of the Japan Society for Quality Control. Through his article on QFD (Akao & Kogure, 1983), he was the first to bring the concept to the western readers. The HoQ is used to map the customer needs defined in phase 1 into concrete and measurable product and process parameters. These parameters are called Substitute Quality Characteristics (SQCs) as they replace the desired qualities stated in customers' voice (the needs), with technical quality characteristics the engineers can relate to and measure. The importance of each SQC is derived from the customer needs through the mapping presented in the center of the HoQ (see Figure 8). The HoQ also provides a means for mapping the SQCs effect on each other in a canted matrix at the top, commonly referred to as "the roof" of the HoQ because of its shape.

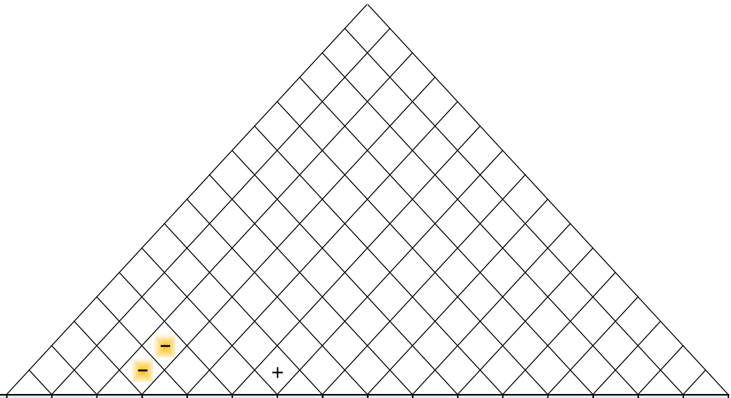
A top-down process was used to establish the initial set of SQCs. A series of interviews was arranged with representatives from both requirement engineering and technical engineering; 8 in total. These interviews began with the needs hierarchy in Figure 2, starting with one or two needs that had a close relation to the engineer's area of expertise. The meetings consisted of drawing mind maps on sheets of paper and talking through what characteristics are contributing or opposing to the objective. After each meeting the mind maps would be translated into the HoQ matrix with an indication of the relationship. For finding the target goals for the product the author reviewed the list against the JSM requirement specification for related requirements, as well as adding a few characteristics to the list that were missing from the interviews. Note that a lot of the SQCs were reflected in the JSM requirement specification, but not all, emphasizing the importance of having a top-down approach. The list of SQCs and measures of merit was reviewed by two requirement engineers for completeness and for assistance with finding set target goals for the product characteristics that were missing in the requirement specification.

A challenge with establishing the quality characteristics for this system is that a significant portion of the system's performance is determined by the level of complexity and degree of development of certain software implemented features. An example is satisfaction of the customer need for missile survivability in a hostile environment. A part of ensuring survivability is fulfilled through stealth technology and passive sensors, which are measurable and certainly verifiable. But a large part of the survivability concept is based on the missile being “smart” in how it flies and how it chooses to expose itself to potential threats. Doing this in the best possible manner requires years of research and analysis and cannot be quantified easily. The technical focus groups mentioned earlier have been established for the purpose of determining what is *good enough* in these cases. For the purpose of the QFD, these quality characteristics have been identified with “complexity” as the measure of merit. Even though a clear goal can’t be defined, the priority derived through the QFD is still valid.

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship		Performance and quality characteristics (How's) / Voice of the Customer (What's)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						Direction of Improvement	▼	▼	▲	▲	▲	▲	▼	▲	▲	▲	▲	▲	▲	▲		
							Power-on to ready-to-fire duration	On-board missile plan generation tim	Normal cruise speed	Nominal range at sea level	Additional range per feet of altitude	Variable missile speed	Time on Target estimate deviation	Route connectivity planning	Antenna efficiency	Link 16 antenna sector elevation	Link 16 antenna sector azimuth	Link 16 sensitivity	Link 16 output power	Maximum launch altitude		
1		8 %	0,085		High probability of kill	Effective sea target destruction																
2		7 %	0,068			Effective land target destruction																
3		14 %	0,141			High probability of finding target																
4		7 %	0,069			Low probability of homing on the wrong target																
5		4 %	0,039			Hit point precision																
6		6 %	0,060			High survivability																
7		3 %	0,032	9	Mission flexibility	Quick engagement response time	○	○	●													
8		9 %	0,089	9		Good standoff range				●	●									○		
9		7 %	0,071	9		Good time on target precision						●	●									
10		7 %	0,071	9		Good Link 16 remote control connectivity								●	●	●	●	●	●			
11		3 %	0,025		Constraining the aircraft and pilot as little as possible	Large launch envelope																
12		3 %	0,029			Large captive carry envelope																
13		3 %	0,034			Responds quickly to commands																
14		1 %	0,014		Good availability	Long shelf life and MTBM																
15		2 %	0,017			Long in-service life																
16		6 %	0,056			Good inherent reliability																
17		4 %	0,036			High probability of detecting errors prior to fielding/use																
18		2 %	0,015			Short MTTR																
19		5 %	0,049			Cost																

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Target	< x sec	< x sec/y NM	x Mach	> x NM	Glide ratio > x	x to y Mach	< [SSS-JSM-X46] seconds	?	>x%	0±x°	0±x° rearward	x dB	x W	x ft		
Max Relationship	3	3	9	9	9	9	9	9	9	9	9	9	9	3		
Technical Importance Rating	9,5	9,5	28,6	79,7	79,7	64,2	64,2	63,7	63,7	63,7	63,7	63,7	63,7	26,6	0,0	0,0
Relative Weight	1 %	1 %	4 %	11 %	11 %	9 %	9 %	9 %	9 %	9 %	9 %	9 %	9 %	4 %	0 %	0 %
Weight Chart																
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Figure 8. House of Quality – first attempt

A traditional HoQ was prepared in Microsoft Excel™ to facilitate the calculation of SQC importance as shown in Figure 8. This version has all the customer needs on the left side with their respective priorities, and a small set of SQCs on the top. The bottom rows indicate the measures of merit and resulting priority per SQC. The relationship matrix and correlation matrix (also known as "the roof"), is partially filled out.

After attaining 63 different quality characteristics describing the JSM it became increasingly difficult to manage the data in the HoQ. The main issues with the analysis tool were as follows:

1. Scaling the matrix to accommodate the increasing amount of information became very time consuming.
2. The HoQ presents too much information at once when the number of elements reaches a certain threshold. This makes it difficult to present and find the information of interest.
3. While the list of customer needs were relatively short and stable at the point of filling out the House of Quality, the list of Quality Characteristics and Measures of Merit were the main data. Because of this, it was very impractical that the main working area was represented vertically. If a dedicated SW tool existed (instead of using a commercial spreadsheet), this could be solved by displaying the data in canted cells.

Because of the issues described above, the implementation of the HoQ was iterated and evolved. The new version provided a separate sheet for entry of customer need and priority weights (Figure 9), a separate sheet for entry of SQCs and relationships (Figure 10), and a third sheet for correlation between SQCs (Figure 11). The Figures 9 to 11 only show a subset of the customer needs and SQCs for the purpose of this document, but the full version can be downloaded from the following URL: http://tinyurl.com/JSM-HoQ

Note that in Figure 10, the main relationship matrix shows the customer needs on the top, and the SQCs listed down on the left. This is different from the traditional HoQ and how it is portrayed in all literature on the subject. Having the data entry, and the majority of information displayed horizontally fixed problem 3. Presenting the data this way also enabled scrolling down the list of SQCs and use list features of the spreadsheet to filter depending on requirement weight (e.g. top 10 important characteristics), or filter all the elements with a relationship to a certain customer need. The row with customer needs is also "frozen", meaning that while scrolling down the list of SQCs the customer needs stay fixed in place so the items further down the list also can be easily correlated with the needs. These mechanics in addition to separating the information and data entry onto separate spreadsheets increased the readability tremendously when the number of data elements passed a certain threshold, taking care of problem number 2 for our system in particular.

Splitting the HOQ also made it possible to design the spreadsheets to dynamically extend to the required size when entering more information. Entering customer needs on sheet number one added the required columns, markup and formulas on sheet two. Adding additional SQCs on sheet two added both rows and columns for correlation in sheet three. This fixed problem 1, and made the system of spreadsheets easy to reuse for other systems or for further breakdown of the SQCs' in system design matrices. This represented an auxiliary contribution from the research as it was not part of the original scope.

The new version of the HoQ matrices was used in a workshop with representatives from both senior technical engineering and requirement engineering. The purpose of the workshop was to establish and review the relationships between customer needs and quality characteristics, and discuss the value of the HoQ. The participants quickly understood how the matrix worked without much more assistance than pointing out what was listed where, and a symbol legend in the corner of the spreadsheet. The participants started commenting on their opposing view to the author's initial effort to document the relationships, and also explained to each other why certain elements were important in regards to certain customer needs. Many relationships were added, or adjusted for strength during the meeting.

Row number	Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Weight / Importance	Relative Weight
1	Flexibility - Quick engagement response time	0,0318	10,19 %
2	Flexibility - Good standoff range	0,0885	28,41 %
3	Flexibility - Good time on target precision	0,0714	22,89 %
4	Flexibility - Good Link 16 remote control connectivity	0,0707	22,69 %
5	Cost	0,0493	15,82 %

Figure 9. Sheet 1 - Customer needs and priorities

							Column Number	1	2	3	4	5
							Strongest Relationship In Column	●	●	●	●	○
							Relative Weight	10,19 %	28,41 %	22,89 %	22,69 %	15,82 %
Row Number	Strongest Relationship In Row	Requirement Weight	Relative Weight	Difficulty (0=Easy, 10=Extremly Difficult)	Minimize (▼), Maximize (▲), or Target (◇)	Target or Limit value	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "System Requirments" or "Hows")	Flexibility - Quick engagement response tim	Flexibility - Good standoff range	Flexibility - Good time on target precision	Flexibility - Good Link 16 remote control conn	Cost
1	●	322	11,17 %		▼	< x sec [SSS-JSM-X46]	Flight time precision relative to estimation	○	○	●		
2	○	116	4,01 %		▼	< x m [SSS-JSM-X5/X60]	Sea Skim altitude less than				○	○
3	●	220	7,64 %		▲	Complexity	Route planner connectivity planning				●	▽
4	●	325	11,28 %		▼	< x nm deviation	Route planner range estimator precision	○	●	▽		▽
5	●	204	7,09 %		▲	> x %	Link 16 antenna efficiency				●	
6	●	204	7,09 %		▲	< x dBm [SSS-JSM-1358]	Link 16 tranceiver sensitivity				●	
7	●	204	7,09 %		▲	>= xW [SSS-JSM-1357]	Link 16 output power				●	
8	○	133	4,61 %		▲	>= x ft [SSS-JSM-546]	Maximum launch altitude		○			○
9	●	256	8,87 %		▲	>= x nm [SSS-JSM-1370/X45]	Minimum weapon range at sea altitude		●			
10	●	256	8,87 %		▲	>= x nm [SSS-JSM-X44]	Minimum weapon range from max launch altitude		●			
11	●	347	12,06 %		▲	>= x Mach	Air speed	●	●			
12	●	237	8,21 %		▲	max-min Mach	Velocity envelope (throttling capability)	○		●		
13	○	58	2,00 %		▼	sec [SSS-JSM-1416/137/276]	Retarget/generate missile plan command response time	▽				○

Figure 10. Sheet 2 - SQCs, relationships and derived priorities

Interestingly, from the author's experience during the gathering, some of the views that emerged and were agreed upon during the meeting were contrary to previous information from the interviews. The participants at the workshop could not immediately identify anything wrong with the weighting of the quality characteristics at the end of the workshop. But few reactions were noted in regards to the SQC priorities, except someone who thought it could give some guidance to where we should be put the most effort during qualification and verification testing. The team agreed that especially the relationship matrix had been a good driver for discussing why KDA has, and cares about, these system characteristics. However, it was unclear how the SQC correlation matrix would provide any benefit. There was some confusion about the information that was entered there, mainly because the positive or negative effect was not mutual, and the method does not indicate in what direction the effect applies. Especially in these cases the information requires the reader to have sufficient domain knowledge to understand the effects the characteristics have on each other, in which case the information given is already known.

Positive and Negative Correlations: ++ + - - -

Row number	Quality Charateristics (a.k.a "Functional Requirements" or "Hows")	1 Flight time precision relative to estimation	2 Sea Skim altitude less than	3 Route planner connectivity planning	4 Route planner range estimator precision	5 Link 16 antenna efficiency	6 Link 16 tranceiver sensitivity	7 Link 16 output power	8 Maximum launch altitude	9 Minimum weapon range at sea altitude	10 Minimum weapon range from max launch altitud	11 Air speed	12 Velocity envelope (throttling capability)	13 Retarget/generate missile plan command respo
1	Flight time precision relative to estimation													
2	Sea Skim altitude less than													
3	Route planner connectivity planning													
4	Route planner range estimator precision													
5	Link 16 antenna efficiency													
6	Link 16 tranceiver sensitivity													
7	Link 16 output pow er						-							
8	Maximum launch altitude													
9	Minimum w eapon range at sea altitude													
10	Minimum w eapon range from max launch altitude								+					
11	Air speed								-	- -	- -			
12	Velocity envelope (throttling capability)	++			-							+		
13	Retarget/generate missile plan command response time													

Figure 11. Sheet 3 - SQC correlation matrix, or the traditional "roof" of HoQ

Discussion

Given the size and complexity of defense R&D projects and the significant investment from the customer, understanding their needs as early as possible and having a good base for communication is paramount in reducing risk and ensuring product value. Being systematic in capturing the qualitative perceptions of the customer should help both communication and the governance of the project direction, especially in an environment with long development cycles and the inherent challenges this brings. This research has shown that formulation of a customer needs hierarchy suitable for QFD is possible even for large and complex products. However, the experience of Kasser, Weiss, and Hari (2006) is that it should be kept at 15 to 20 at the most to keep the QFD from becoming too incomprehensible. The resulting size of the needs hierarchy presented in this study seemed to be a good compromise between detail and keeping the size manageable, at a total width of 19 elements. The response after performing the priority questionnaire is contrary to the experience of Kasser, Weiss, and Hari (2006), who concluded that AHP was helpful, but very time consuming. The participants in our study even reported that it could have included more elements if necessary without making the priority evaluation too difficult. We should note that Kasser, Weiss, and Hari did not specify the size or organization of the needs in the particular scenario they were studying, or how they attempted to implement the AHP evaluation. As previously described, the questionnaire would have been more than three times as large if not using the hierarchical representation to provide structure for the questionnaire.

The statistics from the questionnaire have convinced those who participated that KDS has something to learn from systematically establishing a view of the customer priorities. The questionnaire also shows an indication of contradicting views internally in the organization and that it could be beneficial to work on the internal understanding of priorities. In a project of significant size and distributed responsibility, a method for communicating these priorities is an important step to ensure that everyone is walking in the same direction. It was also discussed that it may be even more important as a tool for assisting the customers in understanding their own priorities. Finally, given the state of the JSM project, it has been shown that having prioritized needs can create talking points and provide interesting information even late in the development process.

The communicative benefits are shown to continue when developing the HoQ, especially when elaborating on the relationships between needs and SQCs. There was clear engagement and interaction during a workshop when participants were tasked with reviewing the relationships established by the author. The discussions demonstrated that the matrix communicated the information efficiently and that it facilitated learning about the system. The SQC correlation matrix however seemed to provide little usefulness. This observation is supported by Kasser, Weiss, and Hari (2006), who decided only to discuss the correlations that actually affect the decision on target values.

Other research also show that the relationship between SCQs and overall performance is not necessarily linear and symmetric (Matzler & Hinterhuber, 1998). The HoQ does model this aspect thus making the analysis less precise. Kano's model for characterizing customer needs could be integrated with the Quality Function Deployment to provide more detailed information regarding the effect of the different performance attributes as proposed by Chaudha A., Jain R., Singh A., and Mishra, P. (2011), or Matzler & Hinterhuber (1998). Kasser, Weiss, and Hari proposed a severe modification of the HoQ to facilitate decision making for quality characteristic target values, and by our experience this research also found that this is where the method falls short of its potential in the case of complex systems. Although we can learn something about the priorities of the customer through this exercise, the priorities provide too little information to effectively assist in establishing concrete goals for system characteristics.

Another example of this is the confusing representation of negative relationships between the needs and quality characteristics. This becomes obvious when including *cost*, or *affordability*, as a customer need as in the proof of concept presented here. It is unfortunate that the HoQ represents all relationships to needs as positive relationships. While it is true that a negative relationship still is a relationship with significance to the need, information that is immediately known by the one who is filling out the matrix, is lost. The resulting requirement importance is representing an absolute importance, but it can no longer be seen in conjunction with the denotation for desired direction of improvement; *minimize*, *maximize* or *target value*. The cost example is easy because increasing technical product performance usually has a negative effect on cost. If cost is more important, then suddenly the direction of desired improvement is effectively the opposite. This happens in regards to other less obvious needs as well, not just cost. While it is difficult to find any literature on the subject of handling negative relationships or cost in current literature, Ficalora and Cohen (2009) do propose one additional alternative for retaining more relationship information and presenting a summary of it per SQC. They propose extending the relationship scale with negative counterparts and having two summations done; the algebraic total as before, and the absolute value total. The differences between these represent how much the team is "challenged" to find a technical implementation that maximize the positive effects, and minimize the negative. This is an interesting approach, but it was not investigated in this proof of concept since it is not part of QFD in general literature.

Conclusion

One of the motivators for this research was to investigate if QFD could support KDS in making decisions efficiently and with confidence, especially when facing trade-off situations. Under the time period available for this research it was not possible to utilize all facets of QFD in a representative situation; however, the research have established a working toolset for supporting the QFD process and a proof of concept for what a QFD product can look like for KDS defence projects. Sadly, the product gives the impression that it will not be able to contribute significantly to decision-making in its current form. It will assist, however, in pointing out the related characteristics, and whether the characteristic in question is important for the perceived system quality, but not provide sufficient information to understand the effects of changing the target values one way or the other. The research have also shown that working with the qualitative customer needs during the QFD process, and working with the HoQ, can provide value to the project as a communication tool and facilitation for discussion.

In addressing the original research questions, it is likely that utilizing this method early in the product definition phase should provide greater benefit to the project and ultimately the customer because of its helpful characteristics as a communication tool, and the nature of the information being processed. Given the highly formal and systematic nature of defense contracts in general, and specifically the way the way that JSM was defined from the beginning, there was not much room for interpretation and innovation on the system concept level. Utilizing QFD in this setting could have facilitated both communications, and opened the opportunity to introduce innovations into the product in the earliest stages of the systems engineering development lifecycle.

Future research. Through implementing the methods in this research the author found areas where other supporting methods may have contributed to the value of the overall product. Further research could study the effect of implementing the following methods to elaborate the current implementation of Quality Function Deployment:

- Use of Multi-objective Value Analysis and the construction of value functions for the important system quality characteristics as suggested by Kirkwood in his book *Strategic Decision Making: Multiobjective decision analysis with spreadsheets* (1997). Can it fill the gap and provide the important and useful information necessary to support trade-off analysis?
- Use of Kano's model (C. Berger, 1993) to characterize customer needs. Possibly as an activity conducted before the aforementioned multi-objective value analysis to aid in communication with the customer. Can it give us a better understanding of the importance of a need?
- Implementing a representation of negative effect on needs in the HoQ, such as the one proposed by Ficalora and Cohen (2009). Does it improve quality of the HoQ product with regards to the understanding of SQC importance? Is it possible to make this effectively propagate to the design matrix?

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