A Case study report on signature engineering:
The SEP multipurpose armored vehicle and the Visby class corvette

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Commonly used abbreviations:

FMV:	The Swedish Defence Materiel Administration	SEP:	Multirole Armored Vehicle, also the name of the development program
FOI:	The Swedish Defence Research Agency	LOT:	Low Observable Technology
RSwN:	The Royal Swedish Navy	SAT:	Swedish for LOT
SE:	Systems Engineering	SES:	Surface Effect Ship
SwAF:	The Swedish Armed Forces		

Introduction

The aim of this report is to present consolidated results from case studies of the development processes of the SEP multipurpose armored vehicle and the Visby class corvette respectively.

The report is intended as an annex to a journal article named “Key requirements in the procurement of future Low Observable combat vehicles: A European perspective” published in the journal of Systems Engineering in 2017.

Results filtered from interviews and document reviews are presented based on the structure of the Friedman-Sage framework (Friedman & Sage, 2004) for case studies on systems engineering. Firstly, data collected from the two case studies are presented and then the lessons identified consistent with both cases. The sources, an overview of the two cases studied and the application of the framework are described in the journal article.

Data collected

Requirements management (A)

Contractor (A1)

“Requirements shall flow down in a coherent and traceable manner from the top level to all lower levels of the system being engineered.” *(Friedman & Sage 2004)*

SEP case:

In Systems Engineering (SE) requirements analysis by the contractor formally starts sometime after receipt of a request for a proposal and a systems requirements specification. However, Hägglunds, the SEP contractor, were already participating in the SEP project in the SwAF multirole study, and were also one of the contractors in the SAT/Mark program. Hence, the stakeholder requirements analysis in the contractor organization was considered relatively straightforward, especially since the government reused requirements from the SAT/Mark project with slight modifications.

The particular nature of the signature attribute, compared to other system attributes, had implications for the allocation of requirements to subsystems by the contractor. Given that signature is an attribute of the whole system of interest and that it is difficult to predict the exact effect of signature enhancement measures applied to subsystems at the system level, the design process and the allocation of requirements had to be iterative. Therefore, the first iteration of allocating system requirements to subsystems involved breaking them down into subsystem design guidelines, but with the ambition that the overall design met all system level requirements. After evaluation the allocation was adjusted for the second and subsequent iterations until system requirements were met. This design principle was also described in a conference paper (Olsson et al. 2003).

Visby case:

In the Visby case FMV, the government procurement organization, was also responsible for the system design and for system integration. Consequently, the contractor's role was that of sub system supplier. At the time Kockums AB considered the technological risks too high to accept responsibility for signature requirements at the system level, and experience in managing requirements for radar and infrared signatures was relatively low on both the government and the contractor side. The Smyge demonstrator project helped, but it was difficult to scale requirements up from the smaller demonstrator to the Visby class corvette, particularly in terms of the radar signature. Instead, to deal with these signature areas the government carried out systems modeling and simulations, tests on radar absorbing materials, tests on patterns for grilles on air intakes, tests on tolerable gaps between hatches etc., and transformed desired signatures into robust design rules. Hence, the requirements specifications handed to the contractor concerning radar and infrared signatures were at a detailed technical level. The alternative, simply stating an ambition to meet best possible signature levels, had been tried in earlier development projects with discouraging results. In the more mature signature areas, like magnetic or noise levels, the requirements could more or less be transferred directly from those stated by the customer representatives.

An illustration of the iterative allocation of requirements in the Visby case can be found in section (C1).

Shared (A2)

"Customer and contractor shall share with one another their knowledge of the state of technical maturity relative to the new, unprecedented systems being engineered." (Friedman & Sage 2004)

SEP case:

The government requirements analysis was supported by end-users, but also by scientists and industry experts working in teams during development of the customer requirements specification, thereby producing benefits from covering the entire technology readiness level scale (TRL), as highlighted by the respondents.

In the SwAF study Hägglunds contributed with an assessment of important technologies and at least twenty different concepts using an assessment model designed by FMV. The number of concepts was reduced to about four. SwAF and FMV refined the criteria in the assessment model and one concept was later chosen. Hägglunds built a first demonstrator to support the validation of desired capabilities. They then built a second demonstrator to de-risk the design because some of the technologies used were assessed as high risk. The system requirements were refined continuously during the process. In total, Hägglunds built three demonstrators before SEP development started in 2006, two to demonstrate function and one to de-risk technology. During this process Hägglunds were asked not only to design according to system requirements, but also to challenge them. Any consequences of design requirements, e.g. those having secondary impacts on other capabilities, were continuously reported back to FMV. Key requirements were allowed to have the impact reported, but others were modified.

The requirements process that emerges from the interviews was shaped during the demonstrator programs in an atmosphere of openness and cooperation between government agencies and industries. The respondents, both from the government and industry sides, endorse this cooperative approach as a success factor. However, this was largely the result of a national procurement strategy that had been in practice for decades. It allowed Swedish defense industry to benefit from development during government acquisition programs and to gather expertise to be used in export programs. In return this expertise could be called upon in the next government acquisition program. In practice this policy led to a sharing of systems responsibility between FMV and suppliers. Those were the prerequisites both for the demonstrator projects and for the SEP development project, but they changed due to a new strategic procurement policy in 2007 (SwAF 2007) before ordering the production vehicles. In the European Union today a similar approach is only possible for procurements of significant national security interest. To Sweden subsurface warfare and combat aircraft have qualified. Combat vehicles are not included.

Visby case:

The Karlskrona shipyard, part of Kockums AB since 1989, has a long history of developing and maintaining ships for the RSwN. In the Smyge demonstrator project they developed the SES technology and technology and methods for building large carbon fiber composite hulls, knowledge key to making the Visby class corvette a multi-role warship. The respondents testify that the close cooperation between industry, government agencies and the customer trials unit, established during the demonstrator project, was a key success factor for the Visby project. The mutual respect for each other's knowledge, the small size of the project, and the opportunity for all parties, including other contractors, to meet on a daily basis at the shipyard in Karlskrona greatly promoted informal discussions, which in turn contributed to a fruitful and pioneering spirit throughout the project. Decisions on such issues as design solutions or trade-offs could be made later in more formal and effective project management meetings at FMV.

Government (A3)

“The government shall integrate the needs of its user organizations with the management activities of its developmental organizations.” (Friedman & Sage 2004)

SEP case:

During the SAT/Mark program a requirements working group was established, with participation from SwAF, FMV, FOI and the industry. The aim was to develop a national standard for specifying relevant signature requirements for combat vehicles, like the SEP. The results were documented in FMV Guidelines for requirements on signature management (Restricted) (FMV, 2006). Below, the respondents have helped reproduce a non-confidential version of the requirements analysis process.

System requirements analysis should start with the analysis of relevant mission scenarios, including relevant sensor threats.

It was stated that the aim of LOT and signature management is for a platform to survive and accomplish its military task. This led to a conclusion that the advance to contact is the dimensioning phase of a mission since this phase is where the vehicle signature properties are most critical.

Consequently, requirements analysis has to start by analyzing tactically correct movement in typical situations since this will dictate the critical signature level. The working group came to a general conclusion that it is always important to decide upon dimensioning typical situations, i.e. those where signature management is important to mission success. General discussions about signature are futile. Hence, what are really needed from the customer for effective requirements analysis are relevant mission scenarios. From these typical situations, the sensor threat, the physical environment, the modus operandi, the vehicle operating conditions and the capabilities needed, can be derived.

It is particularly important to assess the probability of each sensor threat occurring in these scenarios. What sensors are volume threats, i.e. mass deployed sensors, and what sensors are exclusive threats or advanced sensors not yet common in the theatre? The working group arrived at the conclusion that the volume threat should be prioritized. From a technical perspective, one can always say that, if this or that sensor is available in theater, it will, or will not, be able to detect objects. However, the consequences for the total system of interest must be analyzed. If a new threat sensor appears in theater the system will have to adapt. This was also one of the lessons reported by Olsson et al. (Olsson et al. 2003).

Next the analyst has to consider the mode the threat sensors are working in when detecting the combat vehicle. Some sensors have an impressive resolution, but perhaps only if working in a very narrow field of view. For example, the scanning mode may only place moderate requirements on signature management. If the platform survives the first seconds of the threat sensor scanning the surrounding terrain, before it goes into high-resolution mode, then the time to detection is extended considerably. Different sensor types were discussed and tabulated by the working group, with typical resolutions, fields of view and working ranges.

The respondents conclude that it is not too difficult to get the scenario information needed from end-users to initiate the system requirements process. The challenge is instead transforming the mission scenarios or user needs into relevant technical system requirements. The experience of several respondents is that in many projects this transformation is often avoided by stating technically oriented requirements, such as the color of paint or the allowed temperature difference to ambient air instead of to background. The result is usually uncertainty about whether or not the requirements reflect real conditions. The preferred way to initiate analysis is to express the capability required in the most relevant tactical parameter.

The ‘Time to detection’ was found to be more important than detection range as the tactical parameter from which to derive vehicle system requirements. For example, in Swedish mission scenarios the range is usually much greater than the line of sight available on the ground. Hence, reducing detection range from five to one kilometer using signature management technology is of no use. Instead the contrast and the background statistics are the more important parameters. In addition, it was found impossible to do a relevant static comparison between the detection ranges of X-band radar and an optical high-resolution sensor. The X-band sensor is a quick scanning sensor, while the optical sensor has a limited field of view. Consequently, in scenarios covering threat sensor suites with different modes of operation it is necessary to formulate requirements for both detection range and time to detection.

'Time to classification' is another potentially important tactical parameter. In sophisticated sensor threat scenarios, it is difficult to delay detection at short range, but the military operator will probably not shoot immediately on detecting a target unless there is additional information. In order for the operator to classify or identify, the vehicle firing will have to move closer to the target, or wait until the target comes closer. Detection is about contrast between target and background, but classification is also partly dependent on contrasts within the target, and the latter is easier to control. In Olsson et al, 2002, it is stated that relevant tactical parameters have to be derived from the context in each case (Olsson et al 2003).

At the vehicle system level, the tactical parameters representing the capability needed have to be transformed into technical performance measures. The general measure of performance is object signature. However, how should this be measured? The SAT/Mark working group decided on a definition of signature that includes the objects interaction with the environment; "Signature is the contrast between object and background making the object detectable in any wavelength and characteristic" [9]. Radar cross section is consequently not a signature but a property of the object. For a SAR sensor the signature comprises the object and its shadow; for an IR sensor hot air from the object affects the background, and in the visible spectrum track marks in the background caused by the vehicle should be included. Hence, a signature requirement at the vehicle system level must be accompanied by a set of situational parameters, i.e. parameters defining the typical situation of interest. It is also evident that signature should be measured with a palette of contrast measures – with whichever has the greatest impact on measures of effectiveness at the top. One of the lessons, presented in 2002 by Olsson et al, suggests dividing these contrast measures into three categories because of their similarities across wavelength bands: spatial, spectral and temporal, and to take into account whether or not the target is detected by a passive or an active sensor (Olsson et al. 2003).

During this analysis another phenomenon was noticed; there is a risk of overstating signature management requirements. The challenge, when comparing signature to other attributes, is its statistical nature, i.e. its dependence on physical environment. One of the consequences described is the necessity to measure the signature of an object on several occasions and in different environmental conditions. This is necessary in order to find the extremes and hence be able to interpolate other parameter sets, and thus be able to assess the signature under any conditions. Another consequence is that it is sufficient to state requirements only for the dimensioning parameter sets. Overstating leads to unnecessary testing, possibly contradictory requirements and other project risks. Hence, at some point after the identification of typical situations, it is necessary to define the environmental parameters under which signature requirements should be stated. Finding extremes, and then finding matching relevant signature requirements, requires sophisticated systems modeling in both cases.

Unfortunately, the Swedish standardization work during the SAT/Mark program did not finish. And since the SEP requirements specification is confidential, it is not clear to the author whether the requirement guidelines stated by the respondents were applied in full.

Initially SwAF produced relatively basic high-level requirements in a document no longer than one page. These requirements were not quantified. Instead they were formulated in relation to what had been accomplished in the CV90 project. This was considered enough for the early studies.

In 2006, in conjunction with an FMV invitation to tender for the development of SEP, SwAF issued preliminary target capability documents[11] for the different roles of the vehicle. These, and the customer specification from FMV, were the only documents formally conveying SwAF capability requirements to industry. Documenting these requirements in terms of concepts of operations was considered, but it was decided that it was not worth the extra effort, because of strained resources.

In the preliminary capability target document for the SEP, SwAF needs were formulated using a configuration of threat sensors with different elevations and aspect angles, very much like the situation depicted in Figure 1 in Olsson et al., 2002 (Olsson et al. 2003). The measures of performance and situational parameters chosen are, however, confidential. The threat scenarios and tactical measures of performance, to be used in the requirements analysis, were then derived in integrated working groups, putting this threat sensor situation into a relevant context.

Visby case:

The concept studies for the next class of surface ships in the RSwN started in 1988. The early studies resulted in three types of vessels; one intended for combined mine counter measures and anti-submarine warfare, one smaller and one larger version of a surface vessel (Bergman, 2000:16). Eventually they merged into one multipurpose concept, later known as the Visby class corvette. The concept was developed by a relatively small group of people from the RSwN and FMV. The concept development was supported by wargaming. Based on the concept, a capability target document was developed, conveying the needs of the user organization to the development organization. Lessons identified during the sea trials of the Smyge demonstrator project were documented directly in the capability target document for the Visby class corvette.

Signature requirements for each signature domain were stated in confidential annexes to this document. In most signature domains the requirements were perceived as very specific. Generally, however, there was a lack of documented operational context. This sufficed for the mature signature domains, such as magnetic and hydro acoustic, where there was long experience and in-depth knowledge both on the SwAF and contractor sides. In these domains requirements were stated numerically in readily accepted and verifiable measures of performance, e.g. magnetic field strength in nano tesla and noise in decibel. When discussing these signature levels with the user organization, the development organization found strong tactical arguments to support them.

In the less mature signature domains, like radar and infrared, the situation was different. The respondents found that there were fewer advocates and weaker arguments to support requirements in these domains. This, combined with the lack of documented context, resulted in uncertainty when doing trade-off studies of signatures and the design of the many components mounted on the deck or hull of a ship, such as antennas, windscreen wipers, exhausts, lifeboats etc.

Radar cross section levels for the ship in free space were stated; these were derived from an idea of what was needed for effective missile protection. The signature levels were to be obtained in a number of low signature sectors with specified angular width. This made it theoretically possible during design to divert reflected energy into sectors with less rigid requirements. The free space requirements facilitated requirements analysis with the support of modeling and simulation, while also making verification measurements more difficult. Initially, whether the radar signature requirements were at all attainable was highly uncertain. However, the Smyge project verified agreement between design rules, modeling and simulation tools, and verification measurements.

A lesson learned from earlier development was that, if the radar requirement is not stated numerically, it is meaningless. On the other hand, a numerical requirement for both radar cross-section and IR, at the level the RSwN was aiming at, would never be accepted by industry.. The solution was, therefore, to buy a geometrical "shape" with robust design rules,, rather than requiring a signature. Hence, the numerically defined signature level was considered of fundamental importance to the successful end result.

In the infrared signature domain the RSwN requirements were vague and took the form of "do your best". In addition, unlike the magnetic or radar signature, the IR signature is dynamic in that it is highly dependent on background and changes in weather and visibility. The complexity, and the relative lack of input from the user organization, resulted in a system design rule of avoiding hotspots and numerical system requirements based on maximum local temperature differences. A decision support system for threat analysis during operations was discussed but not implemented.

The probability of different sensors occurring in the scenarios was taken into account in that the analysis always started by identifying any current or future threats in the wavelength region of interest. If no threats were foreseen, no requirements were stated. However, since Visby is a multipurpose ship, all known sensor types are primary threats in some mission scenario, and few sensors occur simultaneously. No good methods for prioritizing between them were found or used.

Systems Architecture (B)

Both system architecture and design activities enable the creation of solutions to a problem, or opportunity, expressed by a set of requirements. System architecture is, however, more abstract, conceptualization oriented, global, focused to achieve the operational concepts of the system, and focused on the high-level structure in systems and system elements. It addresses the principles, concepts, properties and characteristics of the system of interest. (INCOSE 2015:64).

Contractor (B1)

"The systems baseline architecture of complex programs shall be established early in every program and shall involve all dimensions of technical issues, as well as such enterprise architecture issues as customer needs and satisfaction, political pressures and continuity of funding. A properly executed systems architecture activity provides benefits of effectiveness far in excess of its costs." (Friedman & Sage 2004)

SEP case:

One characteristic of the SEP project was that signature requirements were among the key requirements dimensioning the system architecture as early as the concept stage. The experience of the procurement organization was that otherwise signature would ultimately suffer from being a low priority.

An important lesson learned from the SAT/Mark demonstrator project, put forward by the respondents, is that a lot can be achieved in signature reduction by using standard components – if signature management is allowed to influence design from the beginning. There is more effort in the systems engineering involved, but the unit price need not be much higher. As a result, during the requirements definition of radar signature the government and the contractor agreed to some trade-offs, in comparison to the demonstrator, because lowering the requirements made it possible to use traditional components.

Visby case:

Cost-effectiveness was the overriding consideration during the decades of evolution in Swedish warship design that led to the Visby class corvette. In 2000, when the Visby corvette was first launched, FMV actually described stealth technology as "an effective tool to achieve cost effectiveness…with a strong passive defense system it is possible to operate in a hostile environment without a first strike capacity as the main choice" (Bergman, 2000). The other focus areas for the overall design were survivability, flexibility, C^4ISR and endurance.

A handful of high-level technical solutions were decided upon early in the project, in order to meet the tactical needs for a multipurpose warship. The RSwN and FMV "had to work very hard in order to create a balance of technical and tactical solutions…"(Engevall, 2000) to find these solutions. The introduction of the carbon-fiber composite hull was key to realization of the concept. It has a favorable weight/strength/cost ratio while still having excellent shock resistant properties. This makes it possible to combine high speed roles, such as anti surface warfare, with mine counter measures. However, more importantly for signature management, it insulates heat, is nonmagnetic and makes very flat surfaces possible, which is necessary for low radar signature. Knowing that the contractor, Kockums AB, had the necessary knowledge and means of production for building large ships with this technique, from the Smyge project, the decision to go for the composite hull was taken by the system architects at FMV (Bergman; Engevall; Fagergren; Edvardsson in RSSNS 2000).

Shared (B2)

"The systems architecture should be established early for the reasons stated in (B1), and the best judgment of both government and contractor shall be employed across all the key issues, including the choice of employing newly developed or legacy systems."(Friedman & Sage 2004)

SEP case:

The initial purpose of the SEP was to replace a multitude of fighting vehicle types in the SwAF, in all their respective roles. The guiding principle was low cost through modularity and a high degree of component commonality. In the government design organization it was considered necessary to take full advantage of contemporary technology development. Therefore, all Swedish companies with the potential to contribute were invited to the study in 1995, including Volvo whose concept was based on a frame steer dump truck.. Soon, however, Hägglunds were the only company remaining.

Initially the wheeled and the tracked concepts were completely different, but combined efforts eventually led to the definition of a concept with the capability of having common role modules. Hägglunds solutions were considered too traditional at first, but innovative solutions evolved during the study encouraged by ideas from government design organization, such as electric hybrid drive and continuous rubber tracks. As it turned out the role module approach had a major impact on architecture – and on signature management. Developing a common role module required the design to be free of vital subsystems at the rear. Consequently, the engine and transmission were moved to the front. In order for there to be room for a crew of two operators at the front, the power generation requirements had in turn to be divided between two engines, and a further need to place these in the track sponsons at the side of the vehicle. This in turn made electric hybrid drive the only feasible solution for transmission, as only an electric cable was required rather than drive shafts etc. The remaining problem was that exhaust gases had to be let out at the sides of the vehicle, potentially creating hot spots for detection by threat sensors. However, this forced Hägglunds' designers to come up with a solution for the outlet of hot exhaust gases, which was later patented.

All in all the respondents on both the government and contractor side considered the close cooperation during the conceptual design one of the success factors for the SEP project.

Visby case:

The Swedish need for a cost effective fleet required the "possibility of combining the survivability, flexibility and endurance of a frigate all in the economy of a corvette sized warship” (Bergman, 2000). This required a series of technology breakthroughs: the composite hull, a highly automated sensor-to-shooter command and control system, the merging of MCM and ASW sensor systems into one, and dual use of some weapon systems (Engevall, 2000). The manager of the Visby program said that the close, formal and informal cooperation between the SwAF Headquarters, the RSwN, FMV and industry were key to success. However, he also pointed out the necessity to maintain well-defined responsibilities, particularly in times of down-sizing. He said the cooperation has to be “based on high levels of knowledge and respect”. Maintaining some degree of competition between the actors and their internal communities promotes sound arguments and keeps unproductive infighting to a minimum (Engevall, 2000).

The respondents corroborate this picture and endorsed the continuity of the small core team of system architects in RSwN and at FMV, and the close cooperation with the different industries involved, as important success factors behind the Visby corvette design. In a pioneering project like this it was absolutely essential that representatives of the government and the contractors were able to have informal discussions about possible solutions.

Government (B3)

“Total systems architecture shall be employed by the government for the reasons stated in (B1) in order to provide a sound basis of effectiveness across the broadest spectrum of contractors and operations.” (Friedman & Sage 2004)

SEP case:

In 2005 SwAF and FMV were authorized by the Swedish government to move on from the concept phase and award Hägglunds a contract for development of the SEP vehicle. Continued development after 2007 was, however, conditional on finding an international partner to share development costs with. The most promising cooperation at the time was with the UK. This started in 2001 within the framework of their Future Rapid Effect System (FRES), a program to deliver a fleet of several thousand armored fighting vehicles for the British Army. These discussions, and earlier discussions with other Nordic countries, influenced the concept’s architecture. The potential partner countries wanted more armor than was stated in the initial Swedish requirements, thereby moving the focus from tactical mobility to force protection. However, in 2007 it became clear that the UK intended to buy armored vehicles from the open market, because the British Army urgently needed them for operations in Afghanistan.

In parallel, a new strategic procurement policy, harmonized with EU agreements had been established where national development of new equipment only occurs as a last resort. Despite an investment of about one billion SEK in the development of a national concept, this new policy, and the lack of British commitment, resulted in the termination of the project in 2008. Instead the SwAF needs at the time were met by turning to the open market for the procurement of an armored wheeled vehicle (Lindström, 2011). In order to ensure several contenders, the requirements specification was modified and the signature requirements were toned down, as prescribed in the new policy. In the final round three tenders were considered qualified, one of them was a concept from Hägglunds. In the end though, the contract was awarded to Patria, a Finnish contractor.

The respondents on the government side stress that the SEP system architecture was considered a flexible solution balanced to meet all of the Swedish national requirements. Hence, the reasons to terminate the project were not linked to the technical design. In fact, one of the respondents praised the concept's modular architecture, and its survival through both the network based defense doctrine and the expeditionary force doctrine.

Visby case:

From the beginning of the concept study work for the next class of surface ships in 1988 until launch in 2000, there were changes in world security politics that led to downsizing of the SwAF, and affected the system architecture. Several types of ships were merged into one vessel intended for mine counter measures, anti-submarine warfare as well as surface attack missions. When Singapore came in as a project partner they wanted helicopter capacity on board. This resulted in an extension of the ship's length from 60 m to the 70 m of today. The resulting concept was a "combination of conflicting demands"(Bergman, 2000).

The entire project was completed before the new strategic acquisition policy was issued. Hence, it was understood from the outset that FMV would primarily turn to national defense industries for the development, as a consequence of the de facto strategy that had been in place the last half century.

System/Subsystem Design (C)

Contractor (C1)

"System design shall proceed in a logical and orderly manner through a process of functional decomposition and design traceability that originates with the system functional architecture and ultimately results in design specifications for the system to be engineered." (Friedman & Sage 2004)

SEP case:

The iterative design principle, also described in the requirements management section (A1), can be illustrated with an example from the SEP development - how to get rid of excess heat. One respondent explained how the system signature requirement was based on a certain level of acceptable heat emission. Firstly, the system designer distributed the permissible heat emission evenly to all surfaces of the vehicle. The system designer then realized that a larger part of the budget would have to be allocated to the designer of the exhaust subsystem, who was struggling to conceal the flow of one cubic meter of hot air per second. At this stage the system designer could no longer formulate requirements from a signature perspective, it did not make sense. Instead, the system signature requirements had to be transformed into concrete subsystem design guidelines. In this particular case Hägglunds used air contraflow, in a design that was later patented. However, they could not be sure of meeting the system requirement until a prototype of the complete system had been integrated and evaluated.

Another lesson identified at an early stage was the “work from the inside out” approach to design. The design organization should strive to meet signature requirements as early as possible during basic construction. One respondent explained how the order of priority is dictated by the consequences of correcting a poor design later on. During SEP design the order was Radar, TIR and then VIS (NIR-VIS-UV). Inappropriately designed inner corners, for example, are difficult to redesign later. Furthermore, if the infrared signature is considered at an early stage, it is easier to deal with the excess signature using coatings or mobile camouflage systems (MCS) later. It might be possible to go a long way with an MCS, but with poor basic construction, the design of the add-on becomes more complicated, and hence there are penalties in life cycle cost or other attributes of the combat vehicle system’s performance.

According to the respondents, very few trade-offs had to be made during the SEP design on the basis of signature requirements. The following trade-offs were referred to. As already mentioned some radar signature was traded for ease of production during architectural design. In addition, the low signature design of handles for hatches etc. on the demonstrator, made them difficult to use, e.g. forcing the operator to remove his or her gloves. Thus, the radar signature requirements were lowered a little more in order to enhance usability. A coating developed for the SAT/Mark demonstrator, reducing signature in the visible spectra, was traded for maintainability. Results from the design of controllable vehicle signatures in the demonstrator project were published in 2003 (Westin et al., 2003). However, the technology was considered too immature at the time for the SEP development.

Visby case:

The respondents confirmed that the design process for the Visby class corvette could also be described as highly iterative. The design originating from radar signature requirements was used as an illustration. The principle was to start with first order geometry, developed from simple design rules on how to minimize radar signature, i.e. knowing that you should: collect surface normals in a minimum of directions, avoid right angles and outer corners, etc. Hence, the first order geometry would theoretically have been a simple box, but that geometry would not make a good ship. In practice, the ship’s designer had worked out a feel for what worked during the Smyge project and brought that knowledge to the Visby program. He worked out an initial clean ship geometry; the geometry could be modeled, and its radar signature could be calculated. The subsystems to be integrated on the ship, and mounted on the hull or the deck, were then designed and added successively and iteratively to the clean ship design.

Consequently, the ship’s geometry, and thereby its radar signature, evolved throughout the design process. For example the exhaust gases had to be let out somewhere, and so a ledge was added in the aft where the exhaust gases were cooled with seawater; the integration of weapons required hiding them behind hatches, in turn creating gaps with potential impact on the radar signature. Radar absorbing materials were used when necessary, but kept to a minimum on account of cost, weight or short life-expectancy. In short, various solutions were continuously assessed in terms of their penalties on the overall signature. Pending the result of modeling, solutions were then either accepted or discarded, and the design process continued. As stated earlier, the requirements, including those emanating from design, were documented in relatively low-level specifications to be used as construction guidance by the contractor.

The Visby case also involved very few trade-offs regarding signature in favor of other properties. The respondents referred to two occasions. From a radar signature perspective, surface-effect-ship technology would have been better because such vessels are more stable at sea. The other trade-off mentioned related to the cone shaped dome of the ship surveillance radar. From a radar signature perspective that design was not optimal, but the radar system designer could only guarantee performance if a rotationally symmetrical cone was chosen. In addition, the respondents agreed that there were a few occasions when other functionality was traded for low signature. For example, some maintainability was traded when designing the lifeboat solution. However, as it turned out, the most difficult trade-off had nothing to do with functionality, but more to do with the look and feel of a traditional warship.

Shared (C2)

"Government customers and contractors shall have a contractually feasible sharing of systems design responsibility." (Friedman & Sage 2004)

SEP case:

Before FMV let a contract for the development of the SEP, a new commercial strategy was developed. These issues were in fact more in focus for the program manager than the technical challenges. Previous experience from projects with significant technological risks had shown that, for reasons related to the close relationship between the government and Swedish defense industry, there was a risk that the government would have to meet all costs in the event of all requirements not being met. Hence, the contract between Hägglunds and FMV included clauses about cost-sharing if requirements could not be met. A price was also agreed for future orders of production vehicles, and an agreement was reached on immaterial property rights, securing royalties for the government in the event of future export sales, etc. This was a new commercial strategy for the FMV fighting vehicle division, but it did increase insight into the development progress and one respondent said he was certain that the arrangement also increased the probability of meeting the design goals.

Visby case:

In the Visby case FMV took on the role of system designer and lead integrator, as mentioned earlier, partly because of the contractor's lack of experience in stealth designs.

Government (C3)

"The customer shall share high level measures of effectiveness with the contractor, thereby ensuring that the proposals selected for funding are those which are most responsive to all stakeholders, especially the operational organizations.” *(Friedman & Sage 2004)*

SEP case:

During development SwAF established a user group of personnel from the Army’s Land Warfare Centre, the logistics branch and from the Military Technical School. They met for two days every quarter to discuss requirements. Signature management was not always the center of discussions, but compared to earlier acquisitions this group had a good idea of what they needed, at least when it came to infrared signature requirements. During the 1990s SwAF had carried out a large number of field trials of Swedish combat vehicles and some from the former Soviet Union, with and without mobile camouflage systems. The need to avoid such things as hot spots and exposing the running gear became evident. As mentioned earlier, many of the requirements otherwise evolved as a direct result of experience from the SAT/Mark demonstrator. In parallel the chairman of this group participated in IPTs with the contractor and other government representatives. Had the development program continued to a verification phase, no doubt there would have been even closer collaboration between operators and engineers.

Hence, the main contractor gained an understanding of customer needs by early participation in integrated product teams, from the studies in the concept phase and throughout the program. The respondents pointed out that the contractor had a good starting point gained from previous projects, such as the development of the CV90.

When it comes to formal weighting of high-level requirements, the respondents stated that FMV provided the contractor with a concept evaluation model during the SwAF multirole study. It was used to select the concept later developed. The only evaluation model available to the author is, however, the one used for acquisition of the armored wheeled vehicle, i.e. the Patria, after termination of the SEP program (FMV, 2009).

In addition, as stated in Section (A3), the respondents found that, although end-users provide sufficient scenario information, there is still a challenge in transforming these into measures of effectiveness, and in turn, breaking them down into relevant technical signature performance measures.

Visby case:

A steering committee at the SwAF Headquarters was responsible for formulating the target requirement document and also for change management of requirements during the program. A working group of serving naval officers also met regularly with the FMV program management and with a trials unit. The trials unit was formed very early in the program. One of the initial tasks was to review the FMV system specifications from a tactical perspective. Specifically, there were four focus areas for close collaboration: the layout of the mooring stations, the bridge, the CIC and the engineering control room (Engevall, 2000). The trials unit personnel were more or less permanently based at the shipyard in Karlskrona during development, facilitating informal discussions with FMV personnel and sub-contractors on a daily basis.

As stated earlier, the respondents found that, for the mature signature domains, tactical arguments were easily found to support the quantitative measures of performance stated in the requirements; for radar and especially infrared this was not the case. One of the respondents in the design organization thought that had concepts of operations been documented, it would have been easier to discuss signature requirements in the latter domains, and design trade-offs with the trials unit. As it were, he found it difficult to understand the military needs. Tactical performance measures such as time to detection or time to classification were not discussed as far as the respondents could remember.

Verification and Validation (E)

Contractor (E1)

"Every requirement shall have a test and every test shall have a requirement, which requires validation and verification. The criteria for determining test success and failure shall be established early in the program, as shall verification and validation measures." (Friedman & Sage 2004)

SEP case:

In the SEP development phase, the respondents stated that there was no system level verification or validation campaign planned, because the project was terminated beforehand and no verification or validation criteria were formulated.

In broader terms the SAT/Mark demonstrators were used to explore and validate the use of technologies and production methods available for signature management. The SEP signature requirements were then derived from measurements and evaluations of the demonstrator project, with adjustments to take into consideration: the mission needs, the predicted likelihood of sensor and weapon systems in theaters during the SEP life cycle, and the cost of effective signature reduction in the respective sensor domains. Results also showed that there was a need to develop methods, both for relevant verification measurements in production facilities (e.g. of camouflage panels) and to validate system performance on the battlefield. Some FOI reports have been published on the subject, but these methods have not been validated and approved to the respondents' knowledge.

When asked for their views on future challenges, one respondent identified an interesting challenge in using modeling and simulation techniques for the verification and validation of signatures. One problem emerging, he said, is that signatures are now becoming very low, which is a real problem in modeling and simulation. Detection is a subtler phenomenon to simulate than before, because it has to be based, perhaps, on a glint from the target briefly showing a high signature aspect angle. Is it possible to identify and track that target, the respondent asked rhetorically, concluding that the system effectiveness measure will have to be more complex, and the simulations will require more detailed data to be relevant.

Visby case:

Smyge was a test vessel program originating from an idea to focus all research, development and testing in one program. FMV and RSwN had three main aims: to test different techniques for signature reduction on a stealth ship, to test and evaluate weapons and sensor integration in a stealth ship and lastly, to evaluate the surface-effect-ship technology (Bergman, 2000). For example, it was shown that radar signature reductions combined with countermeasures could have an effect on the sensor duel between a naval ship and an attacking radar missile. The respondents, however, highlighted the important pedagogical effect it had on the significant number of skeptics within the Swedish Navy. The four years of trials not only met the initial test objectives, but, perhaps most importantly, also showed that it was possible to sail and to moor a stealth ship.

As previously stated, there were quantitative requirements in most signature domains. The respondents stated that, in the mature domains, these requirements were also easily verifiable. There is a long tradition of the measurement of magnetism and noise in the RSwN. There are set test tracks and criteria for a ship's behavior during measurements. These are regularly used for all ships in service, and tests were easy to perform. The radar signature was expressed in terms of the radar cross section in free space and could only be verified by calculations. This was not regarded as a problem because so much about signature management in this domain was new, and, in any event, the RSwN did not really know what signature levels were critical. The respondents were confident that the final result was the best possible.

The respondents had no insight into the validation program for the Visby class corvette, nor was any documentation available to the author.

System and Program Management (I)

Shared (I2)

"The role of systems engineering in program development and management shall be recognized and supported." (Friedman & Sage 2004)

SEP case:

The development project at FMV was divided into subprojects dealing with SE, integrated logistics support, configuration management and quality, lifecycle cost management, and commercial management respectively (Lindström & Nilsson & Tapper 2009). About 20 specialists from different departments in FMV were associated with the SE subproject. One of them was a specialist in low observable technology and had been the project manager of the FMV SAT/Mark project. He was not involved continuously in the design process, but was consulted when needed.

At the same time, the contractor's program manager was also a specialist in signature engineering within the program. He had taken an active part in the SAT/Mark project almost from the outset. In 2003 representatives of the four major contractors involved in the SAT/Mark demonstrator project presented a paper promoting a systems approach to signature management on account of the systemic character of the signature attribute (Olsson et al. 2003). A systems approach was considered pivotal to success.

Visby case:

The FMV project manager appointed a signature coordinator to work closely with himself and across subprojects in the organization. The respondents stated that this approach was a success factor. It is important to promote a mindset throughout the entire project, and across the organization, that signature management is not a task that can be allocated to specific subsystems or subprojects – it has to permeate the entire design and all activities.

The typical work scenario for the signature coordinator started with a design solution to a function, with potential compromises, being put forward to the management group. The signature coordinator then had a week or two to evaluate the implications for the different signature domains. The result was typically either that the solution would never work, or that it would work if some changes were made. Often a cost estimation was involved. The issue was discussed within the project management group, decided upon, and then instructions were given to the shipyard.

Lessons identified

When comparing the data collected, the following lessons were found to be common in both cases.

Requirements management

Major enabling factors

A1.1 *An integrated product team approach* enabled representatives of the lower system levels, i.e. the design organizations, to participate in requirements analysis activities at a military mission system level as early as the concept stage.

A1.2 In order to identify dimensioning stakeholder requirements it was found necessary to *identify signature critical situations*, such as the advance to contact for the SEP or the duel with anti-ship missiles for the Visby class corvette.

A1.3 From these it was found to be critical for continued analysis to *identify the key measure of performance most relevant for the desired capability*. This link assures traceability between the system requirements derived and the stakeholder needs.

A1.4 The choice of key measures of performance at a tactical level, such as detection range, time to detection, or time to classification, was found to be heavily dependent on context. Hence, these measures can only be selected after *an analysis of the specific operational context of interest*.

A1.5 The derivation of verifiable system requirements was made possible by *selecting and specifying configurations with sets of situational parameters*. These sets had to include such parameters as sensor threat type, sensor elevations and sensor working modes, as well as target vehicle aspects, target working modes and typical backgrounds.

A1.6 *System requirements were expressed as signatures* in order to increase coherence between the stated platform requirements and the tactical needs that arise on the battlefield due to sensor threats. Signature was defined as "any property, or combination of properties, of an object, that makes it distinguishable from its immediate background by a sensor" (Bohman, 2003).

A1.7 *Signature requirements at the system level had to be formulated as design instructions* when allocating them to design at sub-system level, since signature requirements at the sub-system level did not make sense. Instead, the design instructions where iterated and reiterated until the system design fulfilled system requirements. This systemic nature of the signature attribute seems to distinguish it from most other requirement domains.

A1.8 *Being able to model a system and to calculate its signature*, e.g. the radar signature of the Visby hull, reduced uncertainty and hence the cost of iterations needed.

A1.9 *The demonstrator projects* played a major role in building the bank of knowledge necessary in the respective design organizations. In addition to the de-risking of technology and production methods, the demonstrator projects were crucial in forming viable design instructions and validating modeling tools.

A2.1 *The respondents stated that the national procurement strategy at the time* led to *close collaboration between the contractors and the government agencies*, and, in practice, to shared systems responsibility between the procurement agency and the contractors.

A2.2 The involvement of contractors in the early phases through *an integrated product team approach* promoted fruitful two-way communication. The contractor learned to better understand the needs and the procurer learned to better understand which requirements increased cost and complexity, and hence project risks.

A2.3 *Risk eliminating studies*, of such things as signature requirements, were performed continuously. The consequences of system requirements, e.g. secondary impacts on other capabilities, were reported to the procurement agency. Key requirements were allowed to have the impact reported, whilst others were modified.

A2.4 *Furthermore, the results of long-term research by the Defense Research Agency, were made available through the integrated product team, and contributed to boosting the competence of the contractors.*

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A3.3 *Furthermore, the results of long-term research by the Defense Research Agency, were made available through the integrated product team, and contributed to boosting the competence of the contractors.*

A3.4 *A standard for formulating signature requirements* (FMV, 2006), and *guidelines on the application of low observable technology* (Bohman, 2003) were developed during the SAT/Mark project. This body of knowledge undoubtedly influenced and supported the SEP development.

A3.5 *The military user organization provided scenarios for the stakeholder requirements analysis*. Ideally these comprise: descriptions of anticipated missions, own tactics and procedures, anticipated physical environments and anticipated adversaries, as stated in section A1.

A3.6 *Assessing the probability of various sensor threats occurring in the scenarios* was found to be of central importance because this ultimately guides the prioritization of any conflicting needs to be satisfied by the design (Olsson et al., 2003). In the SEP case, situations with common sensor threats, such as eyesight or infrared sights, were given more weight than situations involving the presumed presence of sophisticated field radar sensors. In the Visby case the discussion about the occurrence of sensors was more binary; either there was a sensor threat or there was not.

Major challenges

A1.10 *Expressing system requirements in a system signature format* was not easily accomplished for the radar and infrared sensor domains. In the Visby case the radar signature was measured in terms of the radar cross section of the ship in free space, which was advantageous for simulation purposes, but impossible to verify through measurements.

A1.11 Signature was found to be a contrast measure, not a technical parameter of the object itself, as stated in the definition. *The statistical nature of the background involved in signature measures* presents challenges, particularly in the infrared signature domain, as reported in both cases. For example, the thermal contrast to background changes quickly if the platform is first heated by sun and then cooled by rain, or if the platform operates close to wooded terrain or in open spaces. The problem is partly mitigated by stating situational parameters (above) along with system requirements.

A1.12 *Many different contrast measures are possible*. In the SEP case it was suggested that requirements should be categorized into three dimensions: spatial, spectral and temporal, for both active and passive sensors, thereby making it possible to state consistent signature system requirements regardless of sensor type. However, some of the resulting matrix elements lack relevant candidate measures.

A3.8 *Developing the documentation of input mission scenarios into concepts of operation*, as prescribed in current SE, would arguably be valuable. In the cases studied a lack of documented context seems to have been compensated for, to a large extent, by the long-term collaboration in integrated product teams.

A3.9 *Traceability between system requirements and stakeholder requirements* (mission success criteria) seems difficult to demonstrate, especially in the radar and infrared sensor domains. The challenges described in section A1 call for continued research.

A3.10 Assessing the probability of various sensor threats was found particularly challenging for *multirole concepts*. In each mission type scenario there is a new main sensor threat. This places conflicting demands on the design.

Systems architecture

Major enabling factors

B1.1 Establishing stealth as a high-level design goal from the inception of the development program was found to be critical. The arguments were, firstly, if stealth is not considered from the beginning, the end result will not be stealthy, and secondly, if considered at an early stage, the cost of stealth is significantly reduced. In the SEP case it enabled a stealthy design largely using traditional materials. In the Visby case stealth was put forward, along with counter measures, as the most cost-effective solution to the challenge of building a ship with acceptable survivability in future combat scenarios.

B2.1 It is evident from the results that *architectural principles were established early*, and that this had a significant impact on the technology used and innovations necessary to satisfy signature requirements. The modular principle of the SEP is one example, and the carbon fiber reinforced plastic hull of the Visby class corvette is another.

B2.2 It seems that innovation in both programs benefitted greatly from *sharing knowledge between agencies and contractors in close collaborative teams* (the integrated approach is elaborated in section A2).

Major challenges

B3.1 In the SEP case, a key issue for SwAF was finding a partner country to share development costs. This was a requisite from the Swedish government in order to sanction a second phase/stage of the SEP development program after 2007. This failed and the SEP program was terminated in 2008.

B3.2 It is, however, evident that involving a partner country might require compromises in the systems architecture. In the SEP program potential partner countries wanted more armor than stated in the initial Swedish requirements, thereby moving the focus from tactical mobility to force protection. In the Visby case, discussions with Singapore led to the inclusion of the high level requirement of being able to land a helicopter on deck, which in turn led to a longer ship.

System and subsystem design

Major enabling factors

C1.1 Functional decomposition was aided by a de facto rule for prioritizing efforts in some signature domains over others. Versions of the rule emerged in both cases based on *a principle of minimizing the risk of costly corrections later on*. Hence, in the case of the SEP, the designer addressed the radar signature first, then the thermal infrared signature, and lastly the visible and near infrared. In the handbook on LOT this was called the "work from inside out design rule" (Bohman, 2003). In the Visby case both the radar and magnetic signatures seem to have had high priority.

C1.2 *The early adoption of stealth as a key architectural principle* was recognized, resulting in few trade-offs or penalties on other attributes. In the SEP case there was some radar signature trade-off for ease of production during architectural design, and a low signature design of hatch handles was traded for functionality. In the visible domain a signature reduction coating was traded for maintainability. In the Visby case some radar signature was traded for lower technological risks in own sensor capability.

C3.1 In the two cases studied, the choice of contractors was based on previous Swedish national procurement strategy, built on partnership with national defense industries, and, as previously stated, *requirements were conveyed to industry through long-term collaborative work in integrated product teams*. Hence, there was no reluctance to share information.

Major challenges

C1.3 *Technology for controllable vehicle signatures*, developed in the SAT/Mark demonstrator project (Westin et al., 2003), was regarded as too immature for development of the SEP.

C2.1 *The close cooperation between industry and government*, based on the *national procurement strategy at the time, made establishing a sound business relationship a challenge.* The downside was that requirements could always be questioned. In the SEP case this risk was addressed in the contract.

C2.2 In the Visby case *the government itself shouldered considerable responsibility for the design,* thereby demanding unique expertise within the organization. Arguably this unusual situation can be attributed to the pioneering character of the program. The technological risk was not acceptable to the contractor.

C3.2 *Finding relevant measures in order to establish traceability between system levels*. See section A2 and A3.

Verification and validation

Major challenges

E1.1 The importance of the demonstrator projects to the outcome of the development programs cannot be overstated. They were used to test the limits of contemporary stealth technology, to evaluate methods for measuring relevant parameters, and to derive performance measures suitable for requirements. Nevertheless, the results indicate that research is still required in the radar and infrared signature domains. There seems to be *genuine uncertainty in how low the signatures in these domains need to be in order to provide the desired military utility*.

E1.2 Identifying relevant requirement measures is a challenge elaborated in sections A1 and A3. However, the selection of preferred measures is also dependent on *available measurement techniques and the availability of physical resources to execute measurement campaigns*. For instance, bidirectional reflectance measurements of large samples were suggested as a more relevant method for assessing surfaces than traditional measurements of gloss. Low availability of instruments was put forward as a counter-argument.

System and program management

Major enabling factors

I2.1 *Signature management was an influential and integrated element of the systems engineering organization.* In the SEP case, the program manager himself represented the contractor's signature engineering perspective. He was a member of the team of program specialists in the field. In the Visby case the FMV project manager appointed a signature coordinator to work closely with him, and across subprojects in the organization.

I2.2 *A system approach* was seen as a necessity. Respondents in the two cases seem to share a belief that signature management calls for "a particular mindset". As one of the respondents said, "It is not a task that can be allocated to specific subsystems or subprojects – it has to permeate the entire design and all associated activities."

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Interviews (Roles)

SEP program:

1. Head of plans and policies in the HQ of the Swedish Armed Forces
2. The Swedish Armed Forces Project Manager for the SEP program
3. The Swedish procurement agency´s project manager for the SAT/Mark demonstrator
4. The Swedish procurement agency´s project manager for the SEP program
5. A senior scientist representing the Swedish Defence Research Agency regarding threat assessments and signature requirements
6. The contractor’s project manager for the SEP program
7. A signature specialist representing a contractor in the SAT/Mark program

Visby program:

8. The Swedish Armed Forces product manager for the Smyge demonstrator
9. The Swedish procurement agency´s signature coordinator in the Visby program