# System of systems lessons to be learned in the development of air power for the future – a small state's perspective

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**Sweden, as a small alliance free state with powerful neighbors, has a military history of what we nowadays call systems of systems thinking. Since the beginning of the Cold War this has been expressed in an air force on the forefront of exploiting military innovations, not least with regard to sensor networks, datalinks, information sharing and distributed decision making. How can this history and the lessons learned come to use when future systems and technologies are to be developed to meet the uncertain future and changing threats? How does this fit with current trends such as capability-based approach and system of systems engineering methodology? What could this mean for the development of the next generation fighter aircraft - after the Gripen E and contemporary aircraft? These questions have been studied from both a government and industry perspective, following the trend in the defense sector of a more intertwined relationship between the two, necessitated by adopting a capability view on aircraft development. This paper presents preliminary lessons identified from a case study on the project *Flygvapnet 2000* (FV2000), which preceded the Net Centric Warfare era at the turn of the millennium. The analysis was based on characteristics of best practice systems of systems engineering derived from a review of literature presenting the methodology theory on capability-based approaches for analyzing, acquiring, developing, and managing military capabilities. The findings from this project will contribute to the development of systems of systems engineering methods and will spur proposals for future research.**

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## I. Nomenclature

| | | |
|---|---|---|
| *AEW&C* | = | Airborne Early Warning and Control |
| *CRC* | = | Control and Reporting Centre |
| *DoD* | = | Department of Defense |
| *DOTMLPF* | = | Doctrine, Organization, Training, Material, Leadership, Personnel, Facilities |
| *FMV* | = | Försvarets Materielverk (abbreviation in Swedish for the Swedish Defence Materiel Administration) |
| *FV2000* | = | Flygvapnet 2000 (abbr. in Swedish for *Air Force 2000*) |
| *MoD* | = | Ministry of Defence |
| *SE* | = | Systems Engineering |
| *STRIL* | = | Stridsledning och Luftbevakning (abbr. in Swedish for *Combat, control and air surveillance*) |
| *SoSE* | = | System of Systems Engineering |

## II. Introduction

The shift away from acquiring systems based on certain performance metrics and instead taking more of a capability centric approach has been a trend in the defense sector since the birth of the new millennia. The idea is to move away from acquiring platforms with performance requirements based on the performance of the adversary's corresponding platforms. Acquisition instead moves towards thinking of military units as systems with inherent capabilities, able to deliver a desired effect. Developing military units based on a desired capability, rather than on predictions of a threat, will provide the commander with more resilient, flexible and cost-effective units. This is considered beneficial in a time characterized with change and uncertain threats, in part, originating from an accelerating technology development [1], [2]. In accordance with these ideas the United States Department of Defense (DoD) has developed the Joint Capabilities Integration and Development System for identifying military capability needs, and the Defense Acquisition System for acquiring the needed capability [3]. The United Kingdom Ministry of Defence (MoD) have developed similar frameworks with the Defence Operating Model describing how policies and strategies on a government level can be decomposed into generation of military capabilities and conducting military operations [4].

The new approach to acquisition has also been adopted by the Swedish Armed Forces. Since 2005 their strategic planning has contained elements of capability-based planning [5, p. 29] and can now be considered fully implemented [6]. But, systems thinking is not new to the Swedish military sector. Sweden's small size, geographical location, limited defense budgets, and alliance free foreign policy seems to have created an environment within the defense sector spurring new and innovative solutions. Without the budgets and personnel means required to focus on quantity, the development of "tactical and technical superiority" [7, p. 3] has for decades been deemed to be the best deterrent factor preventing an adversary from using military means on Sweden. Already in the 1950s there was evidence of a budding systems thinking within the Swedish armed forces, as the STRIL 50 system (STRIL, Swedish acronym for combat control and air surveillance) was introduced. UK AMES Type 80 early warning radars were coupled with the air defense fighters via ground based fighter controllers for quicker response [8]. The next major version of the system, introduced in the 1960s, was STRIL 60. The System's effect was strengthened by introducing, among other things, a digital datalink between the ground-based fighter controllers and the new fighter aircraft, the J 35 Draken [8, p. 74]. This datalink allowed the fighter controller to send commands to the aircraft, instead of speaking to the fighter pilots over radio, which increased speed and robustness against jamming. More functionality was later added to include ground-based air defense units, and parts of the civil defense, suggesting a view of STRIL 60 as a rather complex system on Air Force system level. In the 1980s the development of the next generation, STRIL 90, started. It came to include constituents such as the multi-role fighter JAS 39, the S 100B Airborne Early Warning and Control aircraft , and a new Control and Reporting Centre technical system named STRIC. However, in the mid-1990's it seems the Swedish Air Force did not quite achieve the system's effect anticipated. An initiative that came to be known as the Air Force 2000 (Swedish acronym: FV2000) was launched in order for to address the challenge and possibilities with viewing the new air force as a system.

Today research in the field of *Systems of Systems Engineering* (SoSE) has shown that the engineering of complex systems, like FV2000, has its challenges if you try to apply traditional Systems Engineering. In a survey from 2012, supported by INCOSE, these so called *pain points* are elegantly captured by Dahmann [9] in the form of urgent research questions to be answered: *what are effective collaboration patterns in SoS?; how can SE address SoS capabilities and requirements?; what are effective approaches to integrating constituent systems, and; how can SE approach SoS validation, testing, and continuous learning in SoS?*

Given this background it is evident that the complexity of an air force, like the Swedish, has increased greatly since the middle of the last century, and that complexity will continue to grow. Today no western state seems to doubt that having a system of systems approach on capability development is the way to go. But with the challenges identified in the system of systems engineering field, how should it be applied? In addition, a recent review of contemporary research in the field of system of systems engineering, made by Axelsson [10], reveals that it is dominated by contributors having a U.S. or UK perspective. Few nations on his list of contributors are close to Sweden in size. This study therefore aims to learn from history to improve today's methodology on system of systems engineering for capability development. We ask ourselves – *which are the system of systems lessons to be learned, in the development of air power for the future, having a small state's perspective?*

The FV2000 initiative gave birth to a project with the same name, following on the STRIL 90 development. It took a systematic approach to develop the Swedish air force as a system of systems, before system of systems engineering was an established concept. In this study we consequently find FV2000 an interesting study object to learn from.

The Friedman & Sage's framework for case studies [11] is applied with a small expansion to better capture the perspective of system of systems, in a context with multiple actors responsible for different system levels. Lessons are identified from the development of FV2000, and finally conclusions are drawn to propose guidelines for future development.

## III. Theoretical framework

The theoretical starting point for this study is to view military capabilities as sociotechnical systems, and to view composite complex capabilities, like air power, as systems of systems. Having that view it is only logical to expect that progress in the field of System of Systems Engineering can be exploited in the development of future air power. This chapter elaborates the concepts introduced and forms the basis for the study design.

### A. A Capability view

The term *capability* has many definitions, and we can conclude that the meaning varies depending on community and context. In the military domain having a capability generally means being able to do something, that is, to be able to solve a task [12]. Consequently, a capability is always context dependent [13]. But, in our study it is also central to adopt a view of capability as the effect of a system of interacting social and technical components. One important implication is that technology only has value in the hands of well-trained operators, organized to make the most of a well thought out doctrine. This is nowadays a view on capability commonly accepted by most western military actors, also by the Swedish Armed Forces [14] [15, p. 9]. The U.S. DoD, for example, defines capability as "The ability to achieve a desired effect under specified standards and conditions through a combination of means and ways across doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) to perform a set of tasks to execute a specified course of action." [16].

### B. Systems Engineering

When analyzing successes or failure in the development of complex military products, Friedman and Sage has shown it is useful to compare observations with best practice systems engineering captured in 27 essential SE-concepts [11]. Our application of their framework is further described in section IV. Systems engineering is recognized in a large part of the defense materiel sector as the preferred way of acquiring complex military products. It can be described as an iterative process, involving both technical and management components, with the goal of providing a quality product that meets user needs [17, pp. 1–2]. Systems engineering is also a discipline focused on the design of a whole system, as distinct from its parts, and on the system's entire life-cycle, from the concept life cycle stage, through development, production, utilization and support, to retirement. It involves coordinating all specialist engineering activities, such as integrated logistics support and safety analysis etcetera. But, to our knowledge, hitherto the framework has not been used to analyze development projects on air force system level. We will therefore have to expand the framework to accommodate studies of *systems of systems*.

### C. System of systems

With the above systems view on capability follows that studies of more complex military capabilities, on tactical or joint command levels, benefit from having a system of systems view. According to the ISO/IEC/IEEE-21841:2019 standard a *system of systems* is a "set of systems or system elements that interact to provide a unique capability that none of the constituent systems … can accomplish on its own" [18]. This *unique capability* is often referred to as (1) *Emergent Behavior* and is one of the five characteristics of system of systems according to Maier [19]. (One should note that undesired behaviors might also emerge, e.g. traffic jams in a transportation system of systems.) Emergent behavior is however not unique to system of systems and can be observed at the systems level too. The characteristic of (2) *Evolutionary Development* means that the system of systems has functions and purposes changed, added, or removed over the life, based on the operational experience. (3) *Geographical distribution* is a characteristic also observable in systems. Development in information and communication technology over the last half century has enabled sharing larger quantities of information over greater distances between constituent systems and is therefore of interest for system of systems. The two of Maier's characteristics that are perhaps of highest significance for developing and operating the system of systems are (4) *operational* and (5) *managerial independence*. Different organizations own, manage, and operate the different constituent systems, and the constituent systems have their own purpose outside the system of system, which may at times affect their ability to contribute to the overall system of systems purpose.

Understanding the presence of different types of system of systems is also of help when studying system of systems and trying to understand their behavior. Maier proposed three types [19] which Dahmann & Baldwin expanded to four: *Directed*, *Acknowledged*, *Collaborative*, and *Virtual* [20]. The different types differ both in terms of who manages and operates the system of systems, and how it is managed and operated. Directed systems are those in which the integrated system-of-systems is *built and managed to fulfill specific purposes*. It is centrally managed during long term operation to continue to fulfill those purposes, and any new ones the system owners may wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose. Acknowledged system of systems have recognized objectives, *a designated manager* and resources for the system of systems, however, the constituent systems *retain their independent ownership, objectives, funding and development and sustainment approaches*. Changes in the constituent systems are based on collaboration between the system of systems and the system. Both *Directed* and *Acknowledged* system of systems have a type of central management with more influence over the constituent systems compared to other organizations, illustrated by Henshaw et. al. [21]. This central management is as close to a single crosscutting authority there is in the context of system of systems and can be referred to as a "SoS SE Team" [22] or a "SoSE Team" [23]. A *SoSE Team* has the most influence in *Directed* and *Acknowledged* system of systems, and has very little influence or is absent in *Collaborative* and *Virtual* system of systems. A *SoS SE Team* defines the system of system and directs the operation in a Directed system of system, while it in an Acknowledged system of system has more of a guiding leadership role.

### D. System of systems engineering

System of systems engineering is the "process of planning, analyzing, organizing, developing and integrating the capabilities of a mix of existing and new systems, including inter-system infrastructure, facilities, and overarching processes into a system-of-systems capability that is greater than the sum of the capabilities of the constituent systems" [18]. Comparing it to systems engineering, it is more of a bottom-up process where the starting point often is existing systems and the goal is to create a system of systems architecture in such a fashion that creates a desired emergent behavior or capability, while minimizing the need to introduce mediating systems and modifications to the existing constituent systems.

While systems engineering has its famous Vee-model for describing the materialization of a system, the equivalent for system of systems engineering is the *wave model* [22]. It was proposed by Dahmann et. al. as a better description of the evolutionary development characteristic of a system of systems. An earlier model was developed by U.S. DoD [24].

As touched upon in the introduction, challenges when applying systems engineering for development of system of systems have been surveyed and reported by Dahmann in the form of seven *pain points* [9]. An example of a pain point identified is that of system of system authorities. In systems engineering there is generally a single authority responsible for the entire system, which is not the case for a system of systems where the constituent systems have a managerial and operational independence. One consequence is that in system of systems engineering you may find that there are conflicting goals between the system of systems and its constituent systems. As a result the systems engineering method of decomposition from and integration towards an agreed upon common purpose may not work well in a system of systems context. In addition, having several authorities with separate budgets may very well result in conflicts - if an update is required in any one of the constituent systems to ensure the functionality of the overall system of systems. Systems engineering lack instruments for this kind of conflict management between authorities.

Given these pain points it will not be possible to do a case study on a system of systems like the FV2000 using a SE-case study framework like Friedman and Sage's [10] We believe that in order to show that system of systems engineering is useful in air power development we will at least have to capture lessons in five of their nine SE-concept domains: *Requirements definition and management*, *Systems Architecture and Conceptual design*, *Systems and* *interface integration*, *Validation and Verification*, and lastly in *System and program management*. In our application of the framework (Also see section IV) we have therefore supplemented the essential SE-concepts in these domains with proposed corresponding concepts on system of systems level. These SoSE-concepts were derived by simply compiling domain related text from the ISO/IEC/IEEE-21841:2019 standard *Systems and software engineering – Taxonomy of systems of systems* [18], the U.S. DoD *Systems Engineering Guide for Systems of Systems* [24], and from *An Implementers' View of Systems Engineering for Systems of Systems* by Dahmann et. al [22]. See Table 1.

**Table 1** Derived SoSE concepts to supplement the Friedman and Sage SE-case study framework

| **SE-Concept domain** | **SoSE-concept** (Compiled from [18], [22] and/or [24]) |
|---|---|
| Requirements definition and management | The government shall develop a basic understanding of the expectations for the system of systems and the core requirements for meeting these expectations. The system of systems capability objective should be codified. Once the system of systems capability objective is established, the system of systems SE team defines the functions required to provide the capability and the variability in the user environment which will impact the different ways these functions will be executed. |
| Systems Architecture and Conceptual design | The government shall develop an understanding of the systems involved in the system of systems and their relationships and interdependencies, including understanding the ensemble of systems that affect the system of systems capability and the way they interact and contribute to the capability objectives. The players, their relationships, and their motivations shall be understood so that options for addressing system of systems' objectives can be identified and evaluated, and impacts of external changes can be anticipated and addressed. The government shall establish a persistent technical framework for addressing the evolution of the system of systems to meet user needs, including possible changes in systems functionality, performance or interfaces. The architecture defines the way the systems work together to meet user needs and addresses the implementation of individual systems only when the functionality is key to crosscutting issues of the system of systems. |
| Systems and interface integration | The government is responsible for having a system of systems SE team leading the system of systems integration and test, developing data on system of systems performance and any unanticipated factors encountered. The system of systems SE team monitors implementations at the constituent system level and plan and conduct system of systems level testing, resulting in a new system of systems product baseline. The constituent systems implement and test changes at their level while the system of systems SE team monitor progress and updates the integrated master schedule. |
| Validation and Verification | The government is responsible for developing metrics and collecting data from a variety of settings over time to monitor the performance of the system of systems with respect to the user objectives. The systems engineer works with the test and evaluation community to establish technical performance measures and methods for assessing overall performance of the system of system. At this level, performance is measured in terms of the capability objectives with a focus on utility of the system of system capability to the user. |
| System and program management | The government is responsible, as the owner of the SoSE Team, for managing and coordinating the planning, analyzing, organizing, development and integration activities that create the needed capabilities using a mix of existing and new systems, including inter-system infrastructure, facilities, and overarching processes into a system-of-systems capability that is greater than the sum of the capabilities of the constituent systems. |

## IV. Research Framework

The research approach was based on a case study method as described by Yin [25]. It can be outlined as structured in five steps:

Step 1: Develop the theory necessary to answer the research question (section IV A)
Step 2: Choose your case and design protocols for data collection (section IV B)
Step 3: Collect data and consolidate results (protocols, not published)
Step 4: Do the analysis, to identify lessons (section VI)
Step 5: Modify theory, that is, propose ideas for guidelines on future air power SoSE (section VII)

### A. Case study analysis framework (Step 1)

Friedman and Sage's framework for systems engineering case studies [11] was selected for to structure data collection and for analysis. It has been used successfully by the U.S. Air Force to study development of complex military products from the perspective of best practice systems engineering. The framework is two dimensional with the first dimension representing *SE concept domains*, and the second depicting three *responsibility domains*: *government responsibilities*, *contractor responsibilities*, and *shared responsibilities*. However, in this study we propose the framework can be expanded to accommodate a system of systems view. Thus, we have divided the government responsibility domain in two, one on system of system level and one on constituent system level. See an illustration of the expanded Friedman and Sage framework in Figure 1.

| Concept Domain | Responsibility Domain | | | |
|---|---|---|---|---|
| | 1. SE Contractor Responsibility | 2. Shared Responsibility | 3. Government responsibility (CS) | 4. Government responsibility (SoS) |
| **A.** Requirements definition and Management | X | X | X | X |
| **B.** System Architecture and Conceptual Design | | | | X |
| **C.** System and subsystem detailed Design and implementation | | | | |
| **D.** Systems and Interface Integration | | X | X | X |
| **E.** Validation and Verification | | X | X | X |
| **F.** Deployment and Post-Deployment | | | | |
| **G.** Life Cycle Support | | | | |
| **H.** Risk Assessment/Management | | | | |
| **I.** System and Program Management | | | | X |

**Figure 1. Friedman & Sage's framework of key concepts and responsibilities, expanded with one government responsibility domain. Concept and responsibility domains analyzed in this case study are marked with an 'X'.**

In Sweden, and in the case study project FV2000, the government responsibilities are shared between two actors: the armed forces headquarter and Swedish Defence Material Administration (FMV). This division of responsibility is originally the result of new airworthiness certification regulation for military aviation adopted in the mid-1990s. The armed forces headquarter is responsible for level 1, the *Defense system level*, e.g. the air force. FMV is responsible for systems at level 2, the *Materiel system level*, e.g. the complete JAS 39 system. The industry is then typically responsible for systems at level 3, the *Equipment level*, e.g. the aircraft, and lower [26]. In this case study we view Level 1 as the system of systems level, while level 2 is the constituent systems' level.

Each matrix element marked with an X in Figure 1 is later populated with an essential SE- or SoSE-concept. To preserve space we have presented these as introductions to corresponding analysis result sub-sections in section VI. As discussed in the theory (section III D), only those concept domains we believe are necessary to show that SoSE is useful in air power development have been included. The key SE concepts for the original 9x3 matrix described in

[11] are used as is, while the key SoSE-concepts for the fourth responsibility domain where derived from the literature on best practice system of systems engineering presented in section III D.

Lessons from the FV2000 project regarding the efforts of engineering and testing a system of systems were found by matching case study data with applicable SE- and SoSE-concepts from the expanded Friedman & Sage framework. The observations for each concept and responsibility domain are presented in the Analysis section below (section VI).

### B. Case study data collection (Step 2)

The choice of the project FV2000 as a case of system of systems engineering has been thoroughly discussed in the introduction. A case description is presented in section V.

An advantage with case studies is that data can be collected from many different sources [25]. We chose to collect data both from interviews as well as project documentation. Data from project documentation served three purposes: (1) to support pre-understanding of the project in preparation of the interviews, (2) to support the identification of key persons to approach with requests for participation, and (3) to find support for statements from the respondents.

Key persons from within the FV2000 project were identified, approached for an initial contact, and if they were able to contribute, they were asked to participate as respondents. Participation was voluntarily and the respondents were free to leave the study at any time, and if desired they could have their records erased up until the publishing. In order for to collect data with different perspectives on the project, we chose to contact project participants from within the Swedish Armed Forces, FMV, as well as from within the industry. Common for all respondents is their insight in the development during different phases of the project, as well as knowledge on project management matters such as project planning and risk management.

The interview questions were formulated with the analysis framework described above in mind, to ensure relevance and maximizing the chance of finding data to answer the research question. In order to minimize the risk of inducing bias from the researchers, the questions were of an open nature. The respondents were asked to reflect on the different stages of the project, on the project as a whole, and to share their views on what can be learned for future projects, both in terms of positives and negatives. The interviews were audio-recorded, then transcribed and summarized. The respondents were asked to review the transcripts in order to decrease the risk of misunderstandings. A follow-up session was performed on one occasion where the respondent was asked to elaborate on some previous answers. In addition to provide direct information about the project, the respondents were also asked to recommend project documentation to be reviewed, or if they could recommend other project members to be included in the study. The FV2000 system of systems comprised of many constituent systems, why it was necessary to limit the number studied in this case study. We chose to focus on the JAS 39 and STRIC constituent systems since they were assessed to be central to the idea of a quicker response loop. We ended up with four respondents at the time representing the FMV and one respondent at the time representing the Swedish Armed Forces headquarters. The FMV respondents had the roles of lead or deputy project managers for the FV2000 or STRIC and the armed forces headquarters respondent was responsible for, among other things, the acquisition of STRIC. Several other respondents were contacted and considered for participation but deemed redundant with respect to the selected participants and the study aim.

## V. Research Case: FV2000

### A. Case description: the project called FV2000

In 1997 the commander of the Swedish Air Force, Gen. Kent Harrskog, published the launch of a concept he labelled *Flygvapnet 2000* (Swedish for *Air Force 2000*) [27]. A systems approach was made evident in the article's title: *FV2000 - a systems air force* [27, p. 24]. In the article he stated that the Swedish air force found itself in a transformation due to geopolitical changes, rapid development of information technology, and the societal changes following. In the information age, massing air power would be a doctrine of the past. Instead, with the FV2000 initiative, he wanted the organization to be permeated with a philosophy to continuously exploit opportunities made possible by the new complex technical systems entering service at the time and the information age ideas of decentralized information sharing and decision-making. By integrating technical systems and allowing people to cooperate effectively in networks he expected the Swedish air force to become significantly more effective and responsive - despite the fact that the number of platforms was decreasing (the authors' remark). Respondents testify that an idea illustrated with a system chart was central to progress. It has been recreated in Figure 2.

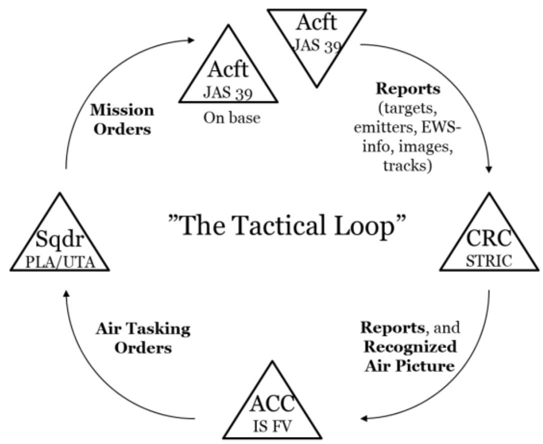


**Figure 2. Illustration of the *Tactical Loop* in the Swedish Air force as modelled in the FV2000-concept.**

The similarities with Boyd's OODA loop [28] brought with them a clear message – to speed up the "Tactical loop" by exploiting new opportunities for information gathering and sharing. The diagram indicates that the timespan from observation to new mission execution could, technically, be reduced to within that of one sortie. At the top of the diagram information is gathered on-board a JAS 39 aircraft and reports are generated in flight during a mission. The reports are then sent via data link to the C2-system (STRIC) in the Control and Reporting Centre (CRC), and are then forwarded to the information system (IS FV) in the Air Component Command (ACC) for assessment and for planning. The Air Tasking Order is thereafter planned in detail in the mission support system called PLA/UTA at the squadron. To complete the loop, the resulting mission order is finally sent via carried data media or data link to a JAS 39 aircraft, either on base or in flight. In the same journal volume as the initiative was launched [27], Col. Mats Hellstrand also published an architectural view of the system FV2000, adapted, translated and depicted in Figure 3. He describes FV2000 as a "system air force" where major system components such as the JA 37 and JAS 39 fighters are "systems in themselves" utilizing "modern information technology" where the information "flow between the computers, sensors and weapons" [27], enabling collaboration. Your authors find this statement in line with the system of systems definitions by e.g. Mayer [19], Dahman & Baldwin [20], and Boardman-Sauser [29]. Gen. Harrskog and Col. Hellstrand speaks about the air force as a system that can be designed top down, leading to the idea that FV2000 is best seen as a *Directed* system of systems. However, the way the acquisition organization of the constituent systems are setup, the type of *Acknowledged* system of system might suit better.

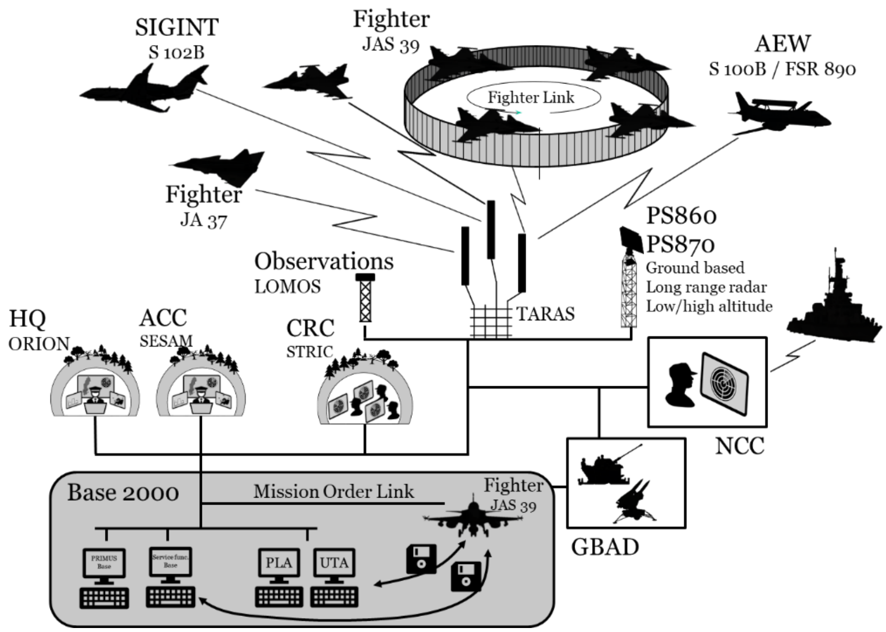


**Figure 3: FV2000 physical architecture, anno 1997. Adapted from** [27]

As part of the initiative FMV, was tasked to support the air force with managing its information critical technical systems as components in a system of systems.[6] In 1997 FMV therefore initiated a project called *VoV FV2000* to verify and validate functions made possible by these technical systems exchanging information via telecommunication networks or data links. This was the starting point for actually formally managing technical systems like: the new JAS 39 fighter, the new airborne early warning radar called AEW890, the new STRIC-system (CRC), the new digital datalink called TARAS, and the new IS FV-system (ACC), as constituent systems in a greater system – the FV2000. In the beginning only a few of the systems met the qualification requirements to be tested in a FV2000 configuration, like being able to present documentation regarding traceability to requirements and functional design on system of system level, and being able to present a satisfactorily tested functionality on constituent system level. Later, a couple of years into the new millennium, there had been progress and the FV2000 configuration had grown beyond what is depicted in Figure 3, to include all major information intense systems, or interfaces to them. In order to increase the systems effect of FV2000 closer to its anticipated potential it was decided that it was time to start defining systems requirements on FV2000-level, and thus to start developing FV2000, as one would any other technical system. Over time the project evolved and became a permanent part of the FMV organization with the intent to continuously manage the air force system level functionality. During this time the system also changed name from FV2000 into LuftT (*Luftstridskrafternas Tekniska system*, abbreviation in Swedish for *the Air Power Technical Systems*).

[6] Kent Andersson, one of the authors, participated in the project from 1998-2003, part of the time as PM

## VI. Analysis

### A. Observations and lessons

Observations from case study interview respondents and project documents are presented for five of the concept domains in the expanded Friedman & Sage's framework (section IV A). The observations are compared to literature on systems engineering, capability engineering and system of systems engineering.

#### *1. Requirements definition and management*

**Contractor**

*SE Concept: Requirements shall flow down in a coherent and traceable manner from the top level to all lower levels of the system being engineered [11].*

The contract for the STRIC system development was initially set up as a fixed price contract for the delivered system to meet specified technical requirements. At times during development, the project experienced rapid change in the surrounding environment, internal and external. As a result, the technical specification did no longer reflect reality and the project ran the risk of designing a system that would be obsolete upon delivery. Efforts introducing functions like a Configuration Control Board, aimed at speeding up the configuration change process were made, but the effect was not satisfactory. To solve the problem, a parallel development project was launched where the user needs, rather than the technical requirements, were the drivers of the design. The outcomes of this test project were successful and the resulting design from this parallel project was the one finally delivered to the customer. This resulted in a change in the way the requirements were written when contracts for STRIC-system upgrades were drafted. The armed forced headquarters could present their needs on a capability level and trust FMV and the contractor to come up with a good technical solution. Instead of a fixed price contract, the contractor was paid by the hour, and instead of rigid technical requirements, the specification focused on capability needs. According to respondents, this was possible due to the considerable trust that all parties had gained for each other over the years working together. All parties seem to have shared an objective to create the best possible system for the end user while spending the taxpayers' money the best way, but also acknowledging that a private company has a legitimate interest in making a profit.

**Shared**

*SE concept: Customer and contractor shall share with one another their knowledge of the state of technical maturity relative to the new, unprecedented systems being engineered [11].*

Respondents report generally of close collaboration between the three system levels (air force headquarters, FMV and industry). There where occasions where the gap between the air force headquarters and FMV (between system level 1 and 2) was perceived as large, which partly resulted in a lack of understanding of the higher levels of capability goals. This could in part be fix by having active or retired air force personnel participating in the project for definition or V&V phases.

During the timeframe studied in the development of constituent systems in focus, there were representatives from the respective FMV projects located on the respective industry sites. This shortened response times in communication and increased the projects' efficiency, according to the respondents. Much reporting of progress and of issues could be done quickly, and in an informal fashion, which was also reported as a positive. User-representatives were involved in the design, increasing the engineers' knowledge and understanding about the system usage. This increased the assurance that the system was built right, reducing the risk for reworking the design later in the process, after e.g. failed formal testing. However, it seems this informal way of working did not replace the formal periodic reporting from industry to FMV, and then to the armed forces headquarters, on the progress of the project with respect to maturity and budget.

**Government (CS)**

*SE concept: The government shall integrate the needs of its user organizations with the management activities of its developmental organizations. Often, the user and development organizations are separated by gulfs of culture and language. The development organization sponsors new technology and contracts out programs; the user organization*

*- the ultimate client - operates the new systems, trains the personnel, fights battles, and should be intimately involved in writing the requirements for new programs [11].*

Acquisition of constituent systems was done top down from the Swedish Armed Forces Headquarters, via FMV to the industry. Documents specifying needs on Materiel system-level (level 2) were provided by the materiel system managers in the Swedish Armed Forces headquarters, for the respective constituent systems. Materiel System Leads at FMV subsequently used these documents to draft system requirement specifications and contracts for system acquisition, then appointed project managers to form development projects. Before the initiation of and in the beginning of the FV2000 project, there was no requirement specification at Level 1, the system of systems level, known to Materiel System Leads at FMV. Consequently, at system levels 2 and 3 the focus was mainly on the individual constituent systems, and very little focus was invested in the goals of the system of systems, the air force level. As a result, respondents testify there was poor functional output from the air force, as a system, and relative expectations, when the JAS 39 first became operational. In the beginning of the VoV FV2000-project the poor performance also showed in difficulties to integrate constituent systems when performing V&V at system of systems level. This is further elaborated in sub-section 4 below.

In addition, in the 1990's, two new types of non-functional requirements gradually made their entrance: (1) Developments in information technology resulted in a new framework for requirements concerning cyber security, and (2) two accidents with JAS 39 aircraft during development changed the way military flight safety requirements and certification were regulated and managed. Some of the respondents acknowledge that some projects were slow to adopt in their development. In some cases the importance of the new regulation was downplayed resulting in too little attention. As a consequence, design was made at constituent level without a complete view of all requirements. This in turn presented difficulties when it was time for certification by the governing agencies. For some materiel systems, this resulted in late changes to the design while in some cases the systems could be delivered under a temporary exemption from the requirements until a fix was implemented. No doubt, it meant difficulties to establish a working Tactical loop.

In sum, these observations were ques for more effective coordination on system level 1.

**Government (SoS)**

*SoSE Concept: The government shall develop a basic understanding of the expectations for the system of systems and the core requirements for meeting these expectations. The system of systems capability objective should be codified. Once the system of systems capability objective is established, the system of systems SE team defines the functions required to provide the capability and the variability in the user environment which will impact the different ways these functions will be executed.*

During the first years of the FV2000 project, focus was on establishing a baseline for development on system of systems level. As there were no system of system requirements specified there could be no formal verification. The next best thing was to start documenting the configurations that could be established and to start validating. V&V activities are elaborated in section 4.

Development plans describing the high level intentions for the armed forces in general, and the air force more specifically did exist. However, the experience of respondents is that these plans had some flaws that effected the development of FV2000 in a negative way, e.g. there was no synchronized roadmap describing the development of the constituent systems in relation to each other, or when the different capabilities were to be ready for delivery at the system of systems level. Much of this knowledge existed to some extent within the organization but it wasn't an established truth and much of the initial focus of the V&V team within FV2000 was to create such a development plan, bottom-up based on the individual constituent systems' specifications and schedules. It required much coordination and communication with the project owners and managers of the constituent systems, bridging the stovepipe organization, and convincing them that alignment to an overall plan would benefit their individual project. In projects lacking fundamental configuration management, this work was harder but, in the end, succeeded thanks to strong project individuals working with quality control.

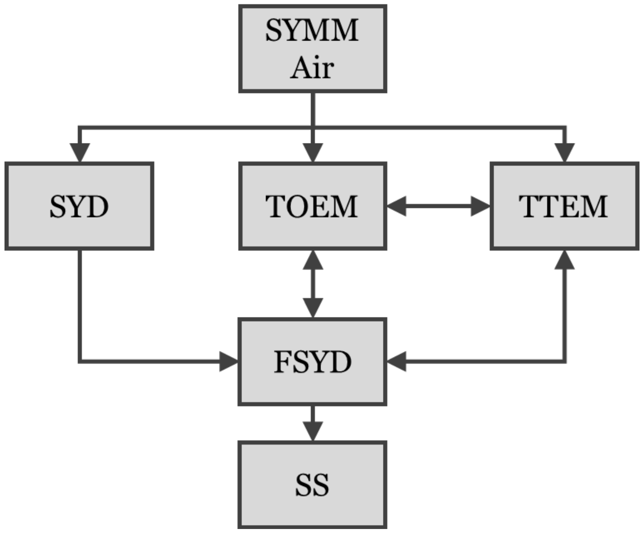


**Figure 4. The development of SYDs of different versions and the relationship with other controlling documents. Adapted and translated from** [30]**. SYMM Air – Airforce system goals. FSYD – Functional SYD. SS – System Specification.**

With no recognized requirement specification on system level 1, the constituent system's collaboration was mainly managed through interface specifications, describing hardware interfaces, messaging protocols, etc. Eventually, with beginning in 2002, a specification at the system of systems level was constituted - a *SYD* (System Definition). The SYD's relations to other requirement documents and plans are depicted below in Figure 4. The SYD bridged the earlier gap of the higher levels plans, and the stove pipe system specifications, enabling better alignment of constituent systems' plans and specification and coordination of projects. With this document the configuration control of the air forces' technical systems (LuftT) started. The document specifying version 4 of LuftT starts with an overall description of the organization and command and control structure, followed by specifying the four basic capabilities that the Swedish Air Force were to possess nationally. The capabilities needed to participate in peace enforcing and peace keeping missions were described in a separate document. The process described in the SYD for allocating capabilities to functions, and interface requirements to constituent systems, is depicted in Figure 5.

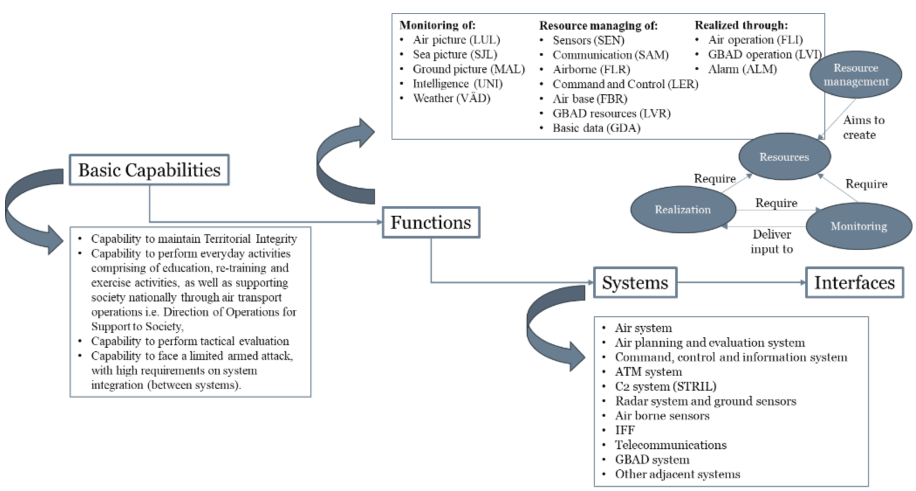


**Figure 5. Breakdown of capabilities into functions, systems, and interfaces. Adapted from** [30]

The SYD describes the constituent systems and their interfaces, including what information flow exists within the system of system, and to/from the external environment. That section in the SYD is followed by general requirements on system management, such as configuration management, airworthiness, security, reliability etc. The four basic capabilities are thereafter broken down into sub-capabilities in a chapter called *Scenario descriptions*. No actual descriptions of the scenarios are presented, and it is assumed that these are classified and thus not possible to present in the unclassified SYD. Then follow descriptions of the tasks for the strategic, operative and tactical commands within the four scenarios. The remainder of the document contains the allocation of functions, for each basic capability, onto the constituent systems.

*2. Systems Architecture and Conceptual design*

**Government (SoS)**

*SoSE Concept: The government shall develop an understanding of the systems involved in the system of systems and their relationships and interdependencies, including understanding the ensemble of systems that affect the system of systems capability and the way they interact and contribute to the capability objectives. The players, their relationships, and their motivations shall be understood so that options for addressing system of systems' objectives can be identified and evaluated, and impacts of external changes can be anticipated and addressed. The government shall establish a persistent technical framework for addressing the evolution of the system of systems to meet user needs, including possible changes in systems functionality, performance or interfaces. The architecture defines the way the systems work together to meet user needs and addresses the implementation of individual systems only when the functionality is key to crosscutting issues of the system of systems.*

The FV2000 inherited much of its architecture from earlier versions of the air force. The first version of the SYD was very much a description of the functional architecture at the time. One respondent noted that much of the FV2000 was about digitalization of the existing system of systems design, where speech radio, telephone and fax were replaced by datalinks. Enhancements and evolution came through bottom-up processes where visions of how new technology could be used led to both the implementation of new systems, sub-systems, information channels, but also to new ways of conducting operations and modifications to procedures. The tactical loop described in section V is an example of this. As FV2000 and LuftT evolved, the fundamental architecture was expanded, including both new constituent systems and interfaces to systems in the external environment e.g. to civilian air traffic controllers. Before the SYD was established to specify system configurations and interfaces, and before the change control management for STRIC was introduced, there appears to have been frequent mismatch between systems and interfaces.

*3. Systems and interface integration*

**Shared**

*SE Concept: The contractor and government shall assure that all systems are integrated within themselves as well as interfaced with other existing operational equipment and systems [11].*

In order to ensure efficient integration and testing, the constituent systems were required to present proof of integration testing and test of interfaces before they were allowed to participate in integration and testing at the system of systems level. The constituent systems were also required to clearly describe what in the system configuration was changed compared to the last version. *Difference awareness* was an expression invented and this was a theme during integration and testing. This was especially important when integrating systems delivered from projects with immature configuration management.

**Government (CS)**

*SE concept: The government shall assure that all its operational systems - in development, in operation, or in planning - are compatible and mutually supportive in a broad "system of systems" and "federation of systems" context [11].*

Compatibility between constituents was difficult in the beginning, as described above. Systems Engineering as a concept was not fully implemented within the armed forces, FMV and the industry early in the FV2000 project. Many systems projects had started working with processes according to ISO-15288, but configuration management varied a lot. One of the first objectives for the FV2000 project was to enforce configuration management on the constituents. With the aim to develop the air force's technical system as a system of systems, according to a development plan and with each system of systems release given a new version number, it was imperative that also the constituents did proper configuration management.

**Government (SoS)**

*SoSE Concept: The government is responsible for having a system of systems SE team leading the system of systems integration and test, developing data on system of systems performance and any unanticipated factors encountered. The system of systems SE team monitors implementations at the constituent system level and plan and conduct system of systems level testing, resulting in a new system of systems product baseline. The constituent systems implement and test changes at their level while the system of systems SE team monitor progress and updates the integrated master schedule.*

Systems Engineering was not a well-established concept within the government and industry in the early days of the FV2000 project. However, the team who took on the task to verify and validate FV2000, by necessity had to take on the role as SE team in order to structure their test object. It is evident from the study that they did work with SE concepts such as life cycle, decision gates, system qualification and the development Vee concepts of decomposition and definition, followed by integration and test. Many respondents give credit to a senior quality manager whose strong leadership enabled the introduction of effective configuration management and of other SE concepts that in the end were appreciated across constituent systems and made the FV2000-project progress more efficiently.

With the configuration control in place, an integrated master schedule on the system of systems level were created. It could be used to guide coordination among constituent systems as it described when and which technical systems where to be integrated, tested and delivered to the air force.

*4. Validation and Verification*

**Shared**

*SE Concept: Government facilities are often the most expensive and their use in the verification and validation (V&V) process shall be shared with the contractors. Test criteria shall be shared early [11].*

Factory Acceptance Tests were conducted at the constituent systems' contractors before the government accepted delivery. After delivery, Site Acceptance Tests, at the systems operational air force site, were conducted to make sure the systems behaved also properly in their operational environment.

**Government (CS)**

*SE concept: The government shall be the final word on the confidence levels derived from its testing during development, operational test and evaluation, and actual deployment and operational use. These require judgments at the highest levels, because not all operational conditions can be adequately tested and actual operations are frequently far different from what the planners initially imagined and intended [11].*

The two government agencies were responsible for two types of testing. FMV did acceptance testing, while the air force did operational test and evaluation at their *TU* units specialized in these tasks (*TU* Swedish abbreviation for Tactical Testing). Late in the period studied, when the FV2000-project was well established, the lion part of all complex testing with many constituent systems involved were coordinated in time and space with tests on system of system level. A lot of test resources could be saved.

**Government (SoS)**

*SoSE Concept: The government is responsible for developing metrics and collecting data from a variety of settings over time to monitor the performance of the system of systems with respect to the user objectives. The systems engineer works with the test and evaluation community to establish technical performance measures and methods for assessing overall performance of the system of system. At this level, performance is measured in terms of the capability objectives with a focus on utility of the system of system capability to the user.*

The project FV2000 created its own V&V process depicted below in Figure 6. After project initiation a V&V-masterplan was produced, specifying which tests were to be planned on constituent system level and which tests were to be conducted on system of system level. When a description of the system to be tested had been specified, preliminary test descriptions of V&V activities on system of system level could be produced. Then there was an informal test period with the purpose to mature test specifications. At constituent systems' delivery there were formal reviews to qualify constituent systems for test. Any residual deficiencies as compared to the respective system specifications were analyzed regarding consequences on planned formal testing. Then there was an integration period were constituent systems. It comprised of technical interface tests (networks, connections etc.) and functional interface tests. These tests were typically made in pairs of constituents. As more and more constituents were added, functional chains could be tested and verified, and finally *total system tests* at the system of systems level were conducted. Tests for non-functional requirements like safety, security and availability/reliability were conducted separately. Finally, a report on the total performance of the FV2000 release in focus was reported to the Swedish Armed Forces. It was used as a major part in the basis for decisions to take constituent systems into operational service.

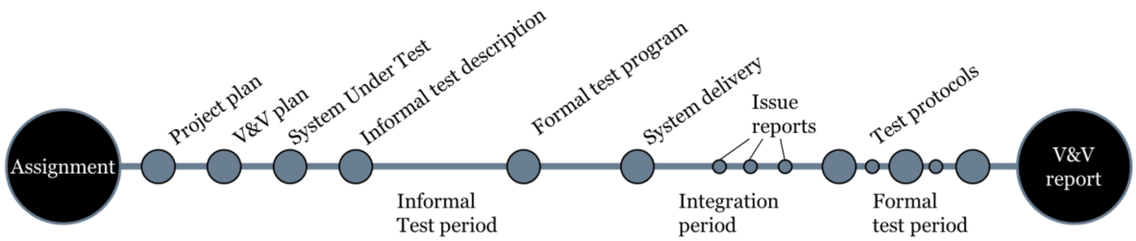


**Figure 6: V&V process – Adapted from** [31]

Lack of requirements on the system of systems level was managed by having experienced test personnel. Usually, they were either active or retired officers or operators. Their knowledge on how the systems were expected to work and interact, strongly contributed to the development of tests and acceptance criteria.

The V&V-process matured successively into that described above. The early versions of FV2000 only comprised of a few of the constituent systems in Figure 3. As the FV2000 project was gradually accepted by the constituent system development projects, the configuration grew release by release.

*5. System and program management*

**Government (SoS)**

*SoSE Concept: The government is responsible, as the owner of the SoSE Team, for managing and coordinating the planning, analyzing, organizing, development and integration activities that create the needed capabilities using a mix of existing and new systems, including inter-system infrastructure, facilities, and overarching processes into a system-of-systems capability that is greater than the sum of the capabilities of the constituent systems*.

An organizational outline describing the three main organizations, the Armed Forces head quarters, FMV and Industry, with some of their relevant departments can be seen below in Figure 7. Over the years of FV2000 and LuftT organizational changes were made, e.g. changing the names of the departments, but the general structure remained. The role of a SoSE Team actor fell on the Systems Management department and the FV2000 project. Although the responsibility at RML level 1 (system of systems level) lies with the air force, the task of defining, acquiring and testing the system of systems was delegated to the FMV.

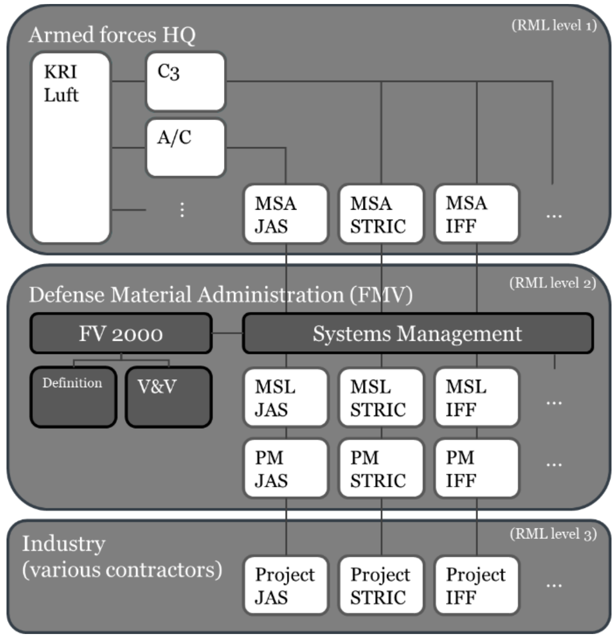


**Figure 7: Organizational outline describing actor relations at the end of the 90's. PM – Project manager.**

The Systems Management department at FMV was intended to bridge the stovepipe structure that had arisen within the materiel administration at the time. Early in the project, respondents testify, that role was not recognized. For example, when validation tests on air force system level, Level 1, first identified areas in need of improvement, the question rose which system was best suited to implement the corrections. Each constituent system development project had its own budget and could be reluctant to spend money on fixes to problems not necessarily caused by their system. The FV2000 project had neither funding nor mandate to decide. Eventually the Systems Management department received an improved mandate. An important improvement was the introduction of a change control board (CCB). Systems Management could then better coordinate with the respective materiel systems managers, at the headquarters, and the respective materiel system leads, at FMV, on how to best proceed when implementing changes. With a CCB in place the FV2000-project now had a recipient for reports and requests for changes. Traditionally the bonds between the materiel systems managers and materiel system leads have been very strong, and they were used to work in their stove pipes. Respondents testify that some projects did not see the purpose of system coordination at first, especially development projects with large budgets, like JAS 39. However, eventually they came around as they successively could see benefits of participation.

Many respondents have credited the physical closeness between representatives of the actors (sometimes even sitting in neighboring offices) and the informal relationship where e.g. engineers and users across organizations could collaborate without the involvement of higher management. Years of collaboration, with personnel continuity within FMV and within partner industries, built trust, which gave freedom, with responsibility, to craft good solutions from the user, the procurer and the contractor perspectives.

### B. Addressing the research question

What do these observations tell us on how FV2000 was engineered as a system of systems, before methods and processes for system of systems engineering were developed into what they are today? What are the lessons learned from FV2000 to be used in future developments? Even though Systems Engineering as a discipline was not fully established at the armed forces and FMV at the end of the 1990s, many of the observations show evidence of similar ways of working. The air force adopted the approach to view the entire air force as a system, where e.g. aircraft and ground based sensors are system components. They then recognized that the air force was actually more of a system of systems and tried to develop it using structured top-down systems engineering approaches. The efforts were in many ways successful in moving the development of the air forces' technical systems forward. But there were also issues along the way. Some issues were similar to what can be seen in other projects where Systems Engineering has been applied to tackle system of systems problems, and some issues had other origins. We believe observations of how this kind of issues were solved during the project can be sorted into three categories: (1) The knowledge and experience of the project members, and the culture in the Swedish defense sector, enabled them to overcome the lack of proper information or processes needed to tackle the problems, (2) the FV2000-project applied techniques and processes that we today recognize as part of system of systems engineering, and (3) they invented new techniques and processes that we can add to the field of systems of systems engineering. Our main conclusions from the analysis are derived below.

*1. The impact of trust for constituent system development*

Designing constituent systems for military system of systems to be operational in a world with changing conditions is challenging. Adversaries are constantly adapting in an effort to stay ahead, and other constituents with the system of system may evolve to better meet their individual goals. An acquisition process that relies on detailed technical requirements, and that takes longer time to complete compared to the rate of change in surrounding environment, risk to produce a system that is obsolete upon delivery. A solution to this problem observed in the acquisition of the FV2000 constituent system STRIC was to reduce the number of technical requirements and instead design towards higher levels of capability goals. The contractor payment process was also adjusted to better fit this approach. This implementation was possible thanks to the considerable trust between government and contractor, a good understanding of the end user higher level goals by the contractor, and the close collaboration between contractor, procurement agency and end user. The trust, and supporting payment structure, seems to have been instrumental in avoiding effects such as requirement creep, where a customer takes advantage of the vague requirements and ask for implementation of more and more functionality. The opposite case is also possible, where a contractor takes advantage and claims that a complete product has been produced and delivered, but where the government has difficulties to refute these claims because of the difficulty conduct thorough delivery acceptance tests.

There are some non-functional requirements perhaps are not suited for high level descriptions, open for different interpretations. Safety and security requirement for FV2000 were specified by organizations outside the air force and FMV. Requirements for information security was managed by MUST (the Swedish Intelligence and Security Service) while FlygI (the Swedish Military Airworthiness Authority) managed safety requirements. Early involvement of all stakeholders to capture their needs and requirements is part of good Systems Engineering practice. For some reasons the FV2000 project saw issues with trying to show safety and information security requirements compliance in the early phases of the project, which led to re-designs and delays. If the reason for this is lack of stakeholder involvement, failure to understand the stakeholder, or deliberate ignorance of stakeholder requirement cannot be determined, but the importance of understanding non-functional requirements such as safety and security is underlined.

Observation from the study indicate that system acquisition using higher levels of capability goals, rather than detailed technical requirements provide developers with a needed flexibility to face the dynamic changes in the surrounding environment. This approach seems to require close cooperation and a good amount of trust from both sides. There are some open questions still that should be addressed to build more knowledge on the subject: How can these findings be used for future acquisition programs and their processes? Can the approach of a capability centered system specification be utilized between government and contractors without a long history of collaboration that has resulted in considerable trust? Are there mechanisms that can speed up this trust building process? Is this approach unique for small nations with a more intimate, both geographical and cultural, relationship between government agencies and contractors, or can it be applied to larger nations and across national borders? Are there types of requirements, such as safety and information security, that are not suitable for this approach?

*2. The need for a clear vision and goal on the highest level*

In systems of systems where the SoSE Team actor lacks strong mandate to fully control the constituent systems' management organizations, observations suggest that the SoSE Team must use softer measures to convince the constituents to contribute to the overall purpose of the system of systems. A clear and outspoken vision of the purpose of the system of systems can help the constituents understand the benefits of participating in the system of systems. A roadmap is valuable when the constituents produce their development plans explaining the capability growth at the system of systems level, also describing the functional requirements, that this implies on the constituents, and also containing an integration and test plan..

The system of systems capability goals should be expressed in as quantifiable ways as possible. This will provide support during system of system V&V when the end user system utility is assessed. Experienced operators, with in-depth knowledge how the system of systems should behave, can to some extent make up for lack of quantifiable capability goals, but the V&V results risk being different for different operators. In FV2000, the SYD later came to the describe the desired capability, while also containing functional decomposition and allocation onto constituents, and interface descriptions. No real equivalent to the SYD has been found in literature on documentation in system of systems engineering, but its content had elements found in *SoS Mater Plan, SoS Architecture, SoS Technical baselines, Technical Plans* as well as *Integrated Master Schedule* reported on in *System Engineering Artifacts for SoS* by Dahmann et. al [32].

Respondents have indicated that SYDs are no longer used in the Swedish air force to define the capability needs and how these decompose into functions and technical systems. To investigate the reason for this was outside of the project scope for this case study, but is important to understand before making statements about the use of SYDs or similar types of documents in the system of systems engineering context.

*3. The importance of a SoSE Team when designing top-down*

The air force had a vision to design its technical systems top-down as a system. When realizing the vision, issues were revealed that in hindsight can be attributed to the fact that the air force's technical systems more resembled an acknowledged system of systems than a complex system. The operator and acquisition organizations were focused on their individual technical systems and had a stovepipe structure from user, and acquisition, down to the contractor. The stovepipe structure and constituent system's managerial became evident when the project started integration and V&V on the system of systems level. The project realized as the constituent systems had reached different maturity levels as a result from non-aligned development plans. The way this was managed was to give the Systems Management organization within the FMV increased resources and mandate, and they and the FV2000 project turning it into what we today call a SoSE Team. The study shows the importance of identifying and acknowledging when a complex system in fact is a system of systems, so that adequate measures can be taken to manage its development. In situations where incentive based constituent system's management, to ensure alignment towards the common goal, is insufficient, this study indicate that a SoSE Team need to have other measures to enforce its will.

*4. A system of systems development process*

The efforts of creating a system of systems based on the air force's technical systems started with the vision of the *Tactical loop*. The air force began the development from its legacy architecture and systems. The idea was that by adding information technology as mediating systems along with modern sensors that would improve information collection, the air force would significantly shorten *Tactical Loop,* i.e. the time from observation to effect on target. The implementation of this vision started on a small scale by integrating, testing and fielding a few constituents. Over time knowledge increased about both the behavior of the system of systems, and the organization and its processes. Test results from operational test and evaluation fed plans for future development of the system of systems. Development included upgrades of existing constituents, adjustments to the architecture and system interfaces, and introduction of new constituents. This approach of gradually increasing the scope of the system of systems, and letting the system of systems incrementally evolve over time, shares many similarities with the *Wavemodel* [24]. The respondents' acknowledgment that this approach worked well for the FV2000 project, suggesting support to the fact that the *Wavemodel* as a concept have utility when developing system of systems.

## VII. Discussion

Findings from the case study of the Swedish air force project FV2000 show evidence successful implementations of systems engineering and system of systems engineering - despite that the project was executed in the early days of systems engineering in Sweden, and before theory on system of systems and systems of systems engineering were developed and recognized. Friedman & Sage's case study framework is a well-established method for conducting case studies of systems engineering and management in systems acquisition. The proposed extension of the framework take recognized theory on system of systems engineering and map it onto the SE-concept domain, and on the government responsibility domain for a system of systems level. This proposed case study framework extension show promise and deserves further research to confirm its full validity.

The information analyzed in the case study is mainly from interviews of FV2000 project participants, with support from project documentation. The authors acknowledge that 10-25 years has passed since the start and finish of the project which impact how project members view and remember how the project unfolded. Some project documentation has also not been available for the researchers due to the change of document management system within the FMV, which meant that the documents requested was not located in the archives. With these caveats in mind, we still believe the case study provide interesting insights and ideas for future research to improve the knowledge on system on systems engineering and capability-based acquisition.

The project FV2000 have given us insights on what can happen if systems engineering methods (e.g. define, decompose, integrate and test) are applied when developing a system of systems. When the INCOSE System of Systems Working Group surveyed the community for their experiences on Systems Engineering for system of systems, they ended up with seven pain points and questions they pose, reported by Dahmann [9]. Three questions are discussed here based on the case study findings.

*What are effective collaboration patterns in SoS?* In the context of FV2000, collaboration effectiveness was a result of close collaboration, considerable trust and a good understanding of the overall system of system capability goal that all involved partied could strive towards. As the project matured, the role of the Systems Management group within the FMV evolved and together with the FV2000 project they took the form of a SoSE Team. Their roles were recognized with the different actors, and their ability to control the constituent systems' management organizations increased.

*How can SE address SoS capabilities and requirements?* The respondents in the case study agreed that having a clear vision of the purpose of the system of systems helped them understand the role of the different constituent systems. The *Tactical Loop* is one example that the respondent often referred to. This this vision was a help during the development as a common goal all constituents could strive for, but also during V&V when the system of systems was assessed. Everyone shared a common view of how the system of systems was expected to perform, which made the validation of desired capability so much easier. In addition, results indicate that a too rigid top-down breakdown of functions and requirements may not be beneficial. A flexibility for rapid response to environmental changes must be maintained. We believe that having a capability focus, rather than a focus on technical parameters, may help to achieve this. It will allow a search for a full DOTMLPF solution, that is, to include solutions exploiting adaptions in other capability components. The SYD document used in FV2000 could be one way to describe capability needs and decompose them into functions that can be allocated onto capability components. This area is worth further research in our view.

*How can SE approach SoS validation, testing, and continuous learning in SoS?* The lack of system of systems level requirement and capability descriptions early on in the FV2000 project was solved by including a mix of experienced and younger operators, when performing V&V. The different perspectives provided showed to be valuable during testing. Another benefit was that active operators got a sneak peak of the next version of the constituent system to be delivered, which meant they could start preparing for what would come.

Another concept to improve system of systems validation, proposed by one respondent, was to perform validation during large scale exercises. Setting up and performing test and validation on a complete system of systems may be a major and costly task. One respondent brought up an idea to perform test and validation when the air force anyway has gathered all resources for a training campaign or exercise. Adding necessary test equipment, and maybe adjusting some exercise elements to better meet the validation needs, could save the air force money. The feasibility of this idea is something that needs to be studied more.

This case study of the project FV2000, has resulted in several preliminary lessons to be learned for the development of air power for the future, from a small state's perspective. Close collaboration between actors was credited as a major success factor by the respondents. The geographical and cultural closeness, and the fact that the actors had a history of decades of collaboration, often with little personnel turnover on key positions, led to considerable trust. The results indicate that this trust could be transformed into more flexible contracts, which also has proven beneficial in periods of changing conditions. The actors could have the air force's capability as an end goal to design for, rather than designing towards technical requirements that after a while turned obsolete due to changes in the surrounding environment. Respondents say this efficiency, and this way of working, was made possible thanks to Sweden's small size. We believe further work is needed before we can make valid conclusions.

There were several positive effects identified from involving air force operators in the project. In early phases they contributed when formulating constituent system requirements. Later they participated in the development to make sure that the constituent system design progressed in the right direction, and lastly, they participated in the constituent system, and system of system, tests. When no requirements on the system of systems level existed, their experience and knowledge was valuable to design the validation test, and to assess utility.

Two important concepts in today's system of systems engineering appear to have been used already in the FV2000-project. First, SoSE Teams did direct the system of systems development, and second, a development process that resembles todays Wave model was used. Both concepts were highlighted by respondents as positives, which would suggest their validity in today's system of systems engineering field.

The study has also raised a number of new questions that we will need to address in the continued research project. How can these findings be used for development of future acquisition programs and their processes, allowing a more capability centered view in both government and industry? Can the approach of a capability centered system specification be utilized between governments and contractors that don't have a long history of collaboration that has resulted in considerable trust? Are there mechanisms that can speed up this trust building process?

## VIII. Concluding remarks

This paper presents the preliminary findings from an exploratory case study of the Swedish Air Force's project FV2000. The case study framework developed by Friedman & Sage was used and expanded to include system of systems concepts for a multi layered government organization. Data was collected from interviews and analysis of project documentation.

Findings indicate that (1) close collaboration and trust between actors on all system levels increase efficiency by speeding up development and decision making in the development of system of systems. (2) Use of experienced end-users can make up for lack of capability requirements on the system of systems level, when performing validation testing. (3) Before system of systems engineering was an established concept, the FV2000 project developed own methods and processes to overcome issues occurring in collaborating systems. These processes have common elements with concepts of today's system of systems engineering, which showcase their validity. (4) Directed and acknowledged systems of systems benefit from SoSE Teams with clear plans and mandate to ensure progress and alignment of constituents according to the overall system of system development plan. (5) Having a capability focus decreases the risk early system obsolescence due to changes in the surrounding environment. (6) In addition, one finding on the research method is worth highlighting. The Friedman & Sage's framework for case studies of systems engineering and management in systems acquisition was used with an expansion of the responsibility domain. The modified framework was a better fit for to study double government organizations, being responsible for the constituent systems, and for the system of systems respectively.

The preliminary findings are promising, but the authors recommend continued research to validate the results from the case study and to generalize the results to the broader scope of systems of systems engineering and capability-based acquisition.

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