National Defence University
Series 1: Research Publications No. 21

On the Military Utility of Spectral Design in Signature Management: a Systems Approach

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KENT ANDERSSON

ON THE MILITARY UTILITY OF SPECTRAL DESIGN IN SIGNATURE MANAGEMENT: A SYSTEMS APPROACH

Doctoral dissertation for the degree of Doctor of Military Sciences
to be presented, with the consent of the Finnish National Defence University,
for public examination in Sverigesalen, at the Swedish Defence University,
Drottning Kristinas väg 37, in Stockholm,
on Friday 13th of April at 1 pm.

NATIONAL DEFENCE UNIVERSITY
HELSINKI 2018

NATIONAL DEFENCE UNIVERSITY
SERIES 1: RESEARCH PUBLICATIONS NO. 21

FINSKA FÖRSVARSUNIVERSITETET
SERIE 1: FORSKINGSPUBLIKATIONER NR. 21

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National Defence University, Finland
Series 1: Research Publications No. 21
Doctoral dissertation

Finska Försvarshögskolan
Publikationsserie 1: Forskingspublikationer nr. 21
Doktorsavhandling

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Cover photo: Hans Liwång

The Cover photo shows a military patrol vehicle in the Stockholm traffic.

ISBN 978-951-25-2998-8 (pbk.)
ISBN 978-951-25-2999-5 (PDF)
ISSN 2342-9992 (print)
ISSN 2343-0001 (web)

National Defence University of Finland
Finska Försvarshögskolan

Juvenes Print
Tampere 2018

To Ulla-Britt, Anna, Amanda and Johanna

”The objective of stealth is to keep the adversary guessing until it is too late”
/David Lynch, Jr, 2003

ABSTRACT

There is an ongoing duel between military sensor development and developments in signature management. The last decade, with warfare characterized by joint expeditionary operations and asymmetry, has favored sensors. However, on account of the worsening security situation in Europe, there is now also an increasing interest in efforts to increase survivability of own military platforms. Spectral design is one of several promising technologies with extensive research potentially suitable for Low Observable platforms. It involves creating desired spectral optical responses from surfaces, in this case reducing contrast to background, by choosing suitable materials and structures.

The challenge to a military decision-maker, faced with inherent uncertainties concerning the future and with limited resources, is how to choose among alternative capabilities, technologies or equipment. Correspondingly, on account of the system character of the signature attribute, researchers in technologies for signature management has difficulties communicating relevant basis for these decisions.

The scope of this thesis is therefore to find and analyze patterns in decision situations involving technology or technical systems for military use, and the purpose is to propose conceptual and methodological contributions to support future decision-making. The technology focus is on spectral design and the application in focus is signature management of Low Observable military platforms. The research objective is addressed from a military system and capability centric perspective using methods from several disciplines in the military sciences domain. The result is synthesized from four separate studies: 1) on spectral design using systematic review of literature, 2) on military utility using a concept formation method, 3) on modeling for how to operationalize a link between spectral design and measures of military utility using methods of military operations research, and, 4) on cases of systems engineering of military Low Observable platform designs.

In summary, the result of the work presented in this thesis is a compilation of related work in military sciences, systems engineering and material optics into a framework to support effective decision-making in relevant contexts. The major contribution to theory is a proposed concept called Military Utility, capturing how to communicate the utility of technical systems, or technology, in a military context. It is a compound measure of Military Effectiveness, Military Suitability and Affordability. Other contributions can be expected to support decision-making in practice;

- the so-called Ladder-model is a template for how to quantitatively operationalize the military effectiveness dimension of Military Utility regarding the use of spectral design;
- an applied Ladder-model is demonstrated, useful for analyzing the military utility of spectral designs in Low Observable attack aircraft;
- a probabilistic framework for survivability assessments is adopted into a methodology for doing the analysis, and lastly;
- a generic workflow is identified, from relevant development programs, including decision-situations that can benefit from the adopted methodology.

Keywords: military utility, survivability, signature management, systems engineering, camouflage, Low Observable Technology, spectral design, multi-spectral.

SAMMANFATTNING

Det finns en ständigt pågående kamp mellan militär sensorutveckling och signaturanpassning. Det senaste decenniet, som karaktäriserats av asymmetrisk krigföring och gemensamma expeditionära operationer, har gynnat sensorerna. Nu har emellertid intresset för effektivare skydd av egna militära plattformar ökat till följd av den försämrade säkerhetssituationen i Europa. Spektral design är då en av flera lovande teknologier med potential att användas vid signaturanpassning och det bedrivs en omfattande forskning. Teknologin kan sägas omfatta tekniker för att skapa en yta med de optiska egenskaper som önskas. I den tillämpning som studeras i den här avhandlingen är syftet att minska ett objekts kontrast till bakgrunden, d.v.s. dess signatur, och det sker genom lämpligt val av ytors material och struktur.

Militära beslutsfattare står ofta inför en stor utmaning då de ska välja mellan framtida förmågor, teknologier eller utrustning. Sådana beslutssituationer präglas ofta av stor osäkerhet och en begränsad ekonomi. Sett från det andra hållet är det ofta svårt för forskare inom teknologier för signaturanpassning att kommunicera relevant beslutsunderlag, på grund av signaturers speciella systemkaraktär.

Avhandlingen omfattar en undersökning med syftet att finna och analysera eventuella mönster i beslutssituationer rörande teknologier eller tekniska system för militär användning. Målet är att lämna konceptuella och metodmässiga bidrag till stöd för framtida beslutsfattning. Teknologin i fokus är spektral design och tillämpningen är signaturanpassning av militära plattformar. Forskningsfrågan adresseras från ett militärt förmågecentrerat systemperspektiv med metoder från flera discipliner inom militärvetenskapen. Resultatet har sammanställts från fyra separata studier: 1) av spektral design med hjälp av systematisk granskning av tidigare forskning, 2) av militär nytta med hjälp av en metod för konceptformering, 3) av modelleringen av en länk mellan spektral design och mått på militär nytta med hjälp av militär operationsanalys, och, 4) av design av smyganpassade plattformar med hjälp av fallstudier.

Resultatet från studierna bildar sammantaget med relaterad tidigare forskning från militärvetenskap, systemteknik och materialoptik ett ramverk till stöd för effektivare beslutsfattning. Det främsta bidraget till teoribildningen utgörs av ett förslag till koncept kallat militär nytta. Konceptet fångar hur nyttan med tekniska system, eller teknologier, bör kommuniceras i militära sammanhang. Militär nytta är här ett sammanvägt mått bestående av militär effektivitet, av militär lämplighet och av överkomlighet. Andra bidrag förväntas stödja beslutsfattning direkt i praktiken;
- den s.k. stegmodellen kan användas som mall vid kvantifiering av den militära effektivitetsdimensionen vid värdering av den militära nyttan med spektral design;
- användningen av stegmodellen har demonstrerats i fallet med smyganpassade attackflygplan;
- ett sannolikhetsbaserat ramverk för överlevnadsuppskattningar har anpassats att användas som analysmetod, och till sist;
- ett generiskt arbetsflöde med relevanta beslutssituationer där analysmetoden kan komma till nytta har identifierats genom studier av tidigare utvecklingsprojekt.

Nyckelord: militär nytta, överlevnad, signaturanpassning, systemteknik, kamouflage, smygteknik, spektral design, multispektral

AKNOWLEDGEMENTS

I feel privileged to have had this opportunity to write a second thesis, this time on a subject of relevance to a profession in which I have been active for more than two decades. It could not have been done without the support of many people.

Firstly, I wish to thank my supervisor, Jouko Vankka, at the National Defence University of Finland for taking me on as student, despite knowing about the challenges involved in bringing Finnish and Swedish military-technology cultures together. I also wish to thank my supervisor at the Swedish Defence University (SEDU), Gunnar Hult, for believing this thesis project was possible, and for his guidance and moral support. I am also fortunate to have had the support of two assisting supervisors. I am deeply indebted to Hans Kariis, at the Swedish Defence Research Agency (FOI), for introducing me to the signature management discipline and to its national and international community, and to Hans Liwång, at SEDU, for his encouragement and committed monitoring of my progress on a daily basis.

When conducting the study, it was also necessary to have the support of researchers, stakeholders, and engineers in the problem domain. I wish to thank staff at FOI in Linköping, not least the members of the signature management project group, for making me feel welcome, for sharing their valuable knowledge and for reviewing my work. I am particularly grateful to Lars Bohman, Tomas Hallberg, Steven Savage, and Christina Åkerlind (co-author), for their valuable advice and comments. I also received much appreciated support from the Swedish Defence Materiel Administration, and, I am especially grateful to Ola Dickman and Anders Grop for their help in keeping me up to date with ongoing development projects. I am also very grateful to representatives of the Swedish Armed Forces, of Saab Barracuda AB, and of BAE Systems Hägglunds AB for generously involving me in activities and events of interest to my studies.

Most of the work was conducted at the SEDU in Stockholm and I am deeply grateful to co-authors, my colleagues and my students for making it such a friendly and stimulating workplace. However, I have leant on some friends and colleagues more than others. I especially wish to thank Martin Bang, Carina Marcus and Patrik Stensson, for fruitful cooperation and for valuable advice on my thesis summary. I am also deeply indebted to Stephen Henly for proofreading and commenting on everything I have written, from the PhD-program application to the thesis abstract.

Lastly, I wish to dedicate this thesis to my mother Ulla-Britt for her unconditional love, to my wife Anna for her love, and to my daughters Amanda and Johanna for making me want to earn their love.

The project was financially supported by the Swedish Defence University, within the framework of a joint doctoral program agreement with the National Defence University of Finland.

LIST OF APPENDED PAPERS

This thesis by Kent Andersson comprises a summary and the following six publications.

I. A review of materials for spectral design coatings in signature management applications
Kent E Andersson and Christina Åkerlind,
Proc. SPIE Vol. 9253, 2014

II. Military Utility, a proposed concept to support decision-making
Kent Andersson, Martin Bang, Carina Marcus, Björn Persson, Peter Sturesson, Eva Jensen and Gunnar Hult,
Technology in society, Vol. 43, November 2015, p 23-32

III. A systems approach to stealth on the ground revisited
Kent E Andersson, Hans Kariis and Gunnar Hult,
Proc. SPIE Vol. 9653, 2015

IV. An exploratory case study on Swedish development of Low Observable vehicles
Kent Andersson
Proc. of the International Conference on Military Technologies (ICMT), IEEE, Brno, June 2017, p 123-129

V. Balancing the radar and long wavelength infrared signature properties in concept analysis of combat aircraft – a proof of concept
Carina Marcus, Kent Andersson and Christina Åkerlind
Aerospace Science and Technology, Volume 71, December 2017, p 733-741

VI. Modeling the impact of surface emissivity on the military utility of attack aircraft
Kent Andersson
Aerospace Science and Technology, Volume 65, June 2017, p 133–140

The author's contributions to the respective appended papers have been:

I. Most of the research design, data collection and writing
II. Part of the research design and concept analysis, most of the writing
III. Most of the research design, data collection, analysis and writing
IV. The sole work of the author, though with valuable and acknowledged support from colleagues
V. Part of the research design and analysis, half the writing, and most of the infrared modeling
VI. The sole work of the author, though with valuable and acknowledged support from colleagues

LIST OF ABBREVIATIONS AND SYMBOLS

CCD, CC&D	Camouflage, Concealment and Deception
EoI	The Element of Interest in a capability system
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and education, Personnel and Facilities
IR	Infrared wavelengths
LCC	Life Cycle Cost
LO	Low Observable
LOT	LO Technology
MAM	Mission Attainment Measure
MOR	Military Operations Research
MoE	Measure of Effectiveness
MOME	Measure Of Mission Effectiveness
MoP	Measure of Performance
MoS	Modeling and Simulation
MWIR	the Medium Wavelength IR spectrum
NIR	the Near Infrared spectrum
OA	Operational Analysis
Q#	Used to reference a research sub-question
P_A	the probability a threat is active
$P_{D\|A}$	the probability of detection given the threat is active
P_H	the Susceptibility (the probability that a platform is hit)
$P_{H\|I}$	the probability of hit given a weapon intercepts
$P_{I\|L}$	the probability of intercept given a weapon is launched
P_K	the Killability (the probability a platform is killed)
$P_{K\|H}$	the Vulnerability (the probability the platform is killed given it is hit)
$P_{L\|D}$	the probability a weapon is launched given detection
P_R	the Recoverability (the probability the platform is recovered after hit)
P_S	the Survivability (the probability a platform survives)
P_{SS}	the Survivability (the probability a platform survives a single shot scenario)
SA	Systems Analysis
SAT	the Swedish abbreviation for LOT
SEP	Splitterskyddad Enhetsplattform (Swedish for Multipurpose Armored Vehicle)

SoI	The System of Interest
SWIR	The Short Wavelength IR spectrum
TEPIDOIL	Training, Equipment, Personnel, Infrastructure, Concepts & Doctrine, Organization, Information and Logistics
TIR	The Thermal IR spectrum (SWIR+MWIR+LWIR)
UV	The Ultraviolet spectrum
VIS	The Visual spectrum

CENTRAL CONCEPTS

Here the key concepts used throughout the thesis are presented and explained briefly in order to assist readability. The references indicate where in the thesis the concepts are defined or derived.

Capability means being able to do something in the military domain and being able to do it well. In the military science domain, one also speaks of *Fighting power* and *Warfighting capabilities* (Sect.2.1).

A ***Design*** is a solution that satisfies system requirements (INCOSE 2015). In this thesis, design also includes the process of synthesizing such a solution.

Engineering is used in the sense “the design and manufacture of complex products” (Merriam-Webster 2016b). In this thesis there is a hierarchy implied. Systems Engineering includes Survivability Engineering, which in turn includes Signature Engineering.

Low Observable Technology is used for passive signature reduction purposes. *Passive* signatures require external illumination (Lynch 2004, p.3). In this thesis, I have also included signatures due to thermal emissions.

Military Effectiveness is a measure of the overall ability to accomplish a mission when the Element of Interest (EoI) is used by representative personnel in the environment planned or expected for operational employment of the military force (Sect.7.2.1).

Military Utility is a central concept in this thesis. The definition proposed, and the interpretation used, is: “The Military Utility of an Element of Interest (e.g. an aircraft), to a military actor, in a specific context, is a compound measure of the military effectiveness, the EoI’s suitability to the military capability system, and of the affordability” (Sect.7.2.1).

A ***Model*** is a representation of reality. Examples are maps, process descriptions, miniature models, mathematical expressions, etc. (Sect.6.3).

Optical wavelengths ranges from ultra violet (UV) via the visible (VIS) and near infrared (NIR) to the thermal infrared (TIR) spectral bands.

Platform is used as a common term for any vehicle on land, at sea, in the air, or in space. Attack aircraft, naval ships and armored combat land vehicles are examples used in this thesis.

The ***Signature*** of an object in this thesis is understood as any characteristic of an object making it distinguishable from the background with a sensor (Bohman 2003). The focus is on the optical part of the electromagnetic spectrum (Sect.4.3).

Signature Management comprises actions taken to minimize the contrast between an object and its background (Bohman 2003). In this thesis the term *Signature Engineering* is sometimes used as a synonym to stress that the actions of interest are taken during development (Sect.4.3).

Signature Engineering, see Signature Management.

Spectral design is the technology in focus. It describes the ability to create a desired spectral optical response from a surface in favor of the application of interest by choosing suitable materials and structures (Ch.5).

A spectral design is the result of spectral design, such as a pigment or a paint coating. Spectral designs are applied in products such as platforms, uniforms, or camouflage materiel (Ch.5).

Survivability is the capability to avoid or withstand a man-made hostile environment (Ball 2003).

A ***System*** is a concept used in this thesis to describe both complex physical products, abstract constructions, such as warfighting capability, and human activities such as warfighting scenarios. When specifically discussing the engineering of a system, the following definition is used - “an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements” (INCOSE 2015). See section 1.3.1.

Stealth design involves reduction of both active and passive signatures (Lynch 2004, p.3).

Technology is used with the meaning "the practical application of knowledge especially in a particular area" (Merriam-Webster 2016c). The work reported here can thus be said to involve the study of the use of spectral design technology in the engineering of military products.

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1

INTRODUCTION

1.1 Background

Humans have used their cunning for concealment and deception in hunting, and in warfare, since the beginning of mankind. In a military context the term camouflage was first used during World War I. The French lexical meaning is ”to make up for the stage” (Hartcup 1979) and a military definition is ”the use of natural or artificial material on personnel, objects or tactical positions with the aim of confusing, misleading or evading the enemy” (NATO 2015; Conley 1988). It developed into a branch of warfare as it became evident that rifled guns could produce accurate long-range fire and as reconnaissance aircraft started to appear far beyond the frontline. During the two world wars huge efforts were made to conceal factories, airfields, ships, aircraft, troops etc., or to make them look like something else, uninteresting to the attacker. In its early days, camouflage was an art form developed and inspired by artists and engineers, and produced using paint and natural materials. During the second half of the twentieth century, with the development of sensors in spectra other than the visible, e.g. radars and infrared cameras, it has instead become a domain for scientists and technologists. The term *Signature Management* is now used to describe actions taken to minimize the contrast between an object and its background (Bohman 2003). The methods applied are described as Low Observable (LO), or stealth, technology. The military purpose, however, is still the same, to increase the survivability of platforms, soldiers and sailors in order to complete a mission.

In the air stealth aircraft, such as the F-117 Nighthawk and B-2, have proven effective (GAO 1997; Jenn 2005). At sea, stealth war ships seem to have won approval in navies all over the world, e.g. the Visby-class corvette in the Swedish Navy (2009), the Admiral Gorshkov-class frigate in the Russian navy (2013), and the Zumwalt-class destroyer in the US Navy (2016). On the battlefield, concealment still involves using creativity and natural materials such as covering vehicles with tree branches or moss, but also using technologically advanced camouflage nets and mobile camouflage systems. The threat to expeditionary forces is expected to increase and become multispectral, due to proliferation (including among non-state actors) of advanced optronic, infrared and microwave sensors (Bohman 2012). Consequently, during the last decade research into soldier-related materiel has increased, typically combat uniforms, aiming to reduce signatures in the face of new sensor threats. In addition, the worsening security situation in Europe has led to calls for prioritizing national defense and has also increased interest in high-end technology for land platforms, which is expected to capitalize on stealth technology developed for air and sea platforms[1].

Signature is a measure of an object’s observability and can be defined as any characteristic of the object making it distinguishable from the background with a sensor

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[1] Rickard O. Lindström, FMV (the Swedish Procurement Agency), personal communication, March 2015

(Bohman 2012). A ship, for instance, can be detected at different ranges, due to noise from engines and propulsion, fluctuations it induces in the Earth's magnetic field, signals emitted by its own sensors or communication systems, reflections from active enemy sensors, thermal radiation from heated parts of the hull and exhaust pipes, and simply due to reflected sunlight. From this, two fundamentals of signature management emerge: first, that signature reduction efforts are dictated by the sensor threat anticipated, and second, there is a *balance* to be found between signature reduction efforts in the respective sensor domains (e.g. (Lynch 2004; Bohman 2003)). Because implementing LO Technology (LOT), thus reducing the signature, will always be associated with a cost, measured either in monetary terms, or in penalties to other attributes of the object (Ball 2003). Consequently, one should not invest in signature reduction efforts in domains void of sensors, and there is no sense in optimizing one domain if this means that the object is easily observed in another.

Following on from these challenges, in this thesis LOT is considered to span not only domain specific design, production techniques and choice of materials, but also modeling, simulation and measuring for the purpose of evaluating or verifying signature reduction efforts (Bohman 2003). In the domains of electromagnetic sensors, radar and thermal infrared, signature engineering is, to a large extent, about construction efforts, such as shaping the platform or screening heat sources. However, in the optical part of the spectrum, from ultra violet (UV), via the visible (VIS) and near infrared (NIR), to the thermal infrared (TIR) spectral bands, the properties of the surface have a considerable influence on the signature. In this thesis, *spectral design* is the ability to create a desired spectral optical response from a surface, which benefits the application of interest, by choosing suitable materials and structures. The technique is used in several military applications, such as the optical filter on head-up displays, laser protective coatings on optics or heat radiation control on satellites. In this thesis, the focus is on using spectral design in efforts to reduce signatures.

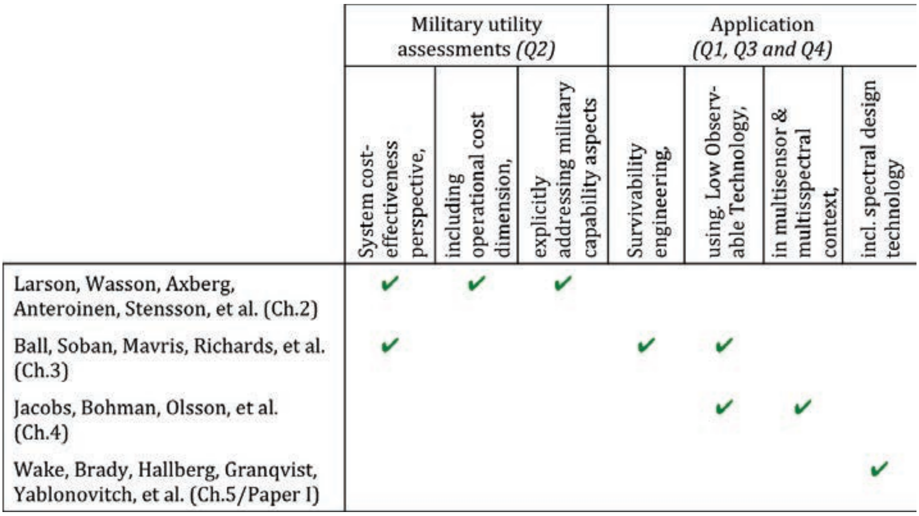
Research into materials and techniques potentially suitable for spectral design in the optical and thermal spectra is extensive, though not necessarily driven by military needs (Paper I). Designs for spectrally selective coatings can be divided into two categories, (1) paints and pigments and (2) periodic surface structures. The latter can be further divided into subcategories in order of increasing complexity: (a) one-dimensional structures, (b) multidimensional structures, and lastly (c) biomimic and metamaterials. The author presented a licentiate thesis in 1993, entitled *Preparation and Characterisation of Sputtered Titanium- and Zirconium Nitride Optical Films* (Andersson 1993), on work (Andersson et al. 1992; Veszelei et al. 1994; Veszelei et al. 1993; Andersson et al. 1994) in the 2a category. However, today important work is being done in all categories. Many researchers have taken on the challenge of combining the desired spectral behavior of dyes and paints in VIS and NIR, with low emissive properties in TIR - while maintaining resistance to wear and tear (Wake & Brady 1993; Hallberg et al. 2005; Rubežien et al. 2009). Interesting work is being done in electrochromic multi-layer coatings where researchers are pushing the envelope of being able to electrically control the optical response across a wide optical band width (Granqvist et al. 2009). In the biology and metamaterial category, researchers seem to be within reach of customizing optical spectral responses by combining relatively simple materials with advanced production methods from the electronic industry, with inspiration from biology (Yablonovitch 1987; Aliev et al. 2006; Sun et al. 2013). Some even believe it may be possible in the future to create invisibility cloaks of so-called metamaterials at optical wavelengths, at least in some respects and for narrow bandwidths (e.g. Chen and Alù (2011)).

Although developments in spectral design technology are potentially useful in military equipment, an interesting question has been raised in the combat aircraft community. ”How much stealth does a system (i.e. a platform, my comment) need?” (Lynch 2004, p.46). In the past it seems efforts have only been limited by the budget (Lynch 2004, p.46). Consequently, the cost has increased, a lot. The obvious answer, given the complexity depicted in the background above, is of course – it depends. As already stated, the value depends on the sensor threat, and hence the adversary. It is dependent on environmental conditions because signature is a measure of contrast with the background, be it in the desert, at sea, in wooded terrain, in winter, at night etc. Arguably, it is also dependent on the military actor using the equipment, i.e. what are the objectives of the mission, what tactics will be used, what risks are acceptable, and are there other means of survivability? Though seemingly intangible, the question has been addressed in a growing Survivability Engineering community. The preferred approach is linking technical performance to a platform’s effectiveness as a weapon system (Ball & Calvano 1994; Ball 2003; Soban 2001). So far, most of the research has focused on assessing features for reducing radar signature, or on other means of protection.

In order to utilize the potential of spectral design, it is critical that there is traceability between the military needs and the spectral design requirements. Otherwise, there is a risk that stakeholders will fail to properly convey needs to contractor design organizations trying to realize feasible solutions. Alternatively, seen from the other direction, there is a risk that researchers will fail to argue effectively for research and development projects, or important progress, that will ultimately have the potential to save the lives of soldiers and sailors. That traceability, connecting military needs and spectral design requirements, is either absent or vague today, which makes informed assessments and decision-making difficult. Table 1-1 shows previous research related to the problem and illustrates how the full breadth of the issue has not yet been addressed.

The complex problem depicted is by no means unique to the domains of LOT. It is but one instance of the more generic problem of how to assess the military utility of any technology, or equipment. This is a typical problem addressed in defense planning when military decision-makers choose between alternatives by working down a decision tree from capability gaps to a working solution. The traditional cost-effectiveness view is, however, questioned by researchers, who have elaborated the cost dimension (Larson 1996; Axberg et al. 2013; Sivertun 2012) and capability aspects (Anteroinen 2013). This is why the thesis problem aspects of Table 1-1 are divided into two categories, one concerning the specific area of application, and the other concerning assessing military utility in general. Related work is further elaborated in chapters 2-5.

Table 1-1 An overview of central work related to the thesis. The columns present aspects of the thesis problem and the rows present centrally related work. The Q1-Q4 notations refer to the research sub-questions presented in the next section.



	Military utility assessments *(Q2)*			Application *(Q1, Q3 and Q4)*			
	System cost-effectiveness perspective,	including operational cost dimension,	explicitly addressing military capability aspects	Survivability engineering,	using, Low Observable Technology,	in multisensor & multisspectral context,	incl. spectral design technology
Larson, Wasson, Axberg, Anteroinen, Stensson, et al. (Ch.2)	✓	✓	✓				
Ball, Soban, Mavris, Richards, et al. (Ch.3)	✓			✓	✓		
Jacobs, Bohman, Olsson, et al. (Ch.4)					✓	✓	
Wake, Brady, Hallberg, Granqvist, Yablonovitch, et al. (Ch.5/Paper I)							✓

1.2 Research purpose, objective and question

Given the problematic background, there is a long, uncertain and sometimes time-consuming decision chain between the military needs on the battlefield and an optimized platform signature adapted to the situation. This chain involves the balancing of needs and design choices for many different technical and tactical solutions. The aim of the research described in this thesis, from a practical perspective, is to propose methodological contributions to a framework for effective decision-making regarding spectral design in signature management. From a scientific perspective, the research attempts to develop a view of how military utility is affected by advancements in technology. The principle research objective is, therefore, to answer the following research question:

> - *How can the military utility of spectral design be assessed in order to support decision-making in the development of balanced Low Observable platform design?*

In order to divide the research into manageable focus areas, and to enhance traceability of results back to the principle objective, the research question is operationalized into a set of sub-questions. "Spectral design" represents the technology in question and "the development of… Low Observable platform design" represents its application. Thus, there is a question of how the two relate (Q1). One problem area is how to assess the "military utility" of the applied technology, which, firstly, requires a thorough understanding of the concept (Q2), and then requires an assessment method (Q3). Lastly, the demand for "balanced…design" requires study of the need for decision-making when balancing conflicting needs and requirements during development (Q4). Table 1-2 shows the derived research sub-questions.

Table 1-2 The research question divided into sub-questions

Q id	Research sub-question
Q1	How (technical parameters, techniques and materials) does spectral design affect Low Observable military platform design?
Q2	How should military utility be defined in order to support decision-making?
Q3	How can the military utility of spectral design in a Low Observable platform be assessed?
Q4	How can the proposed model support decision-making in the development process of Low Observable platforms?

1.3 The Interdisciplinary systems approach

The problem depicted is undoubtedly complicated. It involves understanding the needs of a military force engaged in battle with an adversary in some physical and social context. This military force is trying to defeat its adversary through effective allocation of its equipment and personnel. The problem also involves understanding the process of transforming military needs into the best possible choice of equipment, in this particular case down to the detail of the technologies to be used. We know from the background description that the equipment of interest is expected to be the result of balanced design, i.e. satisfying sometimes contradictory requirements. Furthermore, the problem also involves understanding how electromagnetic waves interact with surfaces of the equipment, in order to find the technical parameters of interest. In summary, the problem comprises sub-problems that are linked and interlock via different perspectives on military equipment. There is also a gradual increase in the level of detail. The complexity, the interlocking, the balancing of the design of complicated equipment and the recursiveness implied, are indicators that a *systems approach* is required (Churchman 1968; Ingelstam 2012, pp.12–33).

1.3.1 The system concept

Complex phenomena have characteristics or behavior that are lost in the examination of its parts. The classical example (Bertalanffy 1968) is an organism, such as a human being. It has life as long as all the organs function together. An individual organ, e.g. the heart, however, has no life and thus will only give limited information about itself. Thus, life is a property of the entire organism – an *emergent* property. An aircraft is another example. Correspondingly, it is characterized by its ability to fly cargo from point A to B (although it is heavier than air). However, if the aircraft is dismantled, this property is lost. In both cases, important information is lost if either the organism or the aircraft is studied simply as a collection of its parts. Instead, they should be studied as a whole – as *systems* of interacting elements having emergent properties. This similarity between organisms, and many other phenomena in society, was first pointed out by Ludwig von Bertalanffy in the 1920s. He is often referred to as the first modern system theorist and he was the founder of general systems theory (Lawson 2010; Ingelstam 2012).

From the 1950s onwards, system theory and application have developed and become established in many fields of research, including social sciences, engineering and management. Regardless of the disciplinary field, most system theorists agree on the use of the common set of characteristics below to describe a system (INCOSE 2015).

The first of these characteristics is that a system consists of some form of *elements*, and *relationships* between them (see the network diagram of a system on the left in Figure 1-1). Elements can be physical, e.g. a jet engine in an aircraft, or abstract, e.g. activities in a process.

Secondly, there is a *purpose* behind why these particular elements are interconnected, i.e. there is a system behavior or characteristic that would not exist unless these particular elements interact the way they do. See the discussion about the organism and the aircraft above. Of course, in a man-made system this purpose, or *objective*, is usually why the system was constructed in the first place.

Thirdly, it must be possible to distinguish the system from the rest of the world by identifying a *boundary*, which is defined by the interest, e.g. the responsibility, of the viewer. The elements and relationships within the system boundary are often said to belong to the viewers System of Interest (SoI).

Fourthly, elements and relationships outside the boundary, but of some importance to the system, belong to the *environment*. Consequently, elements within the system of interest have relationships with elements in the environment. These relationships form *interfaces* with the environment, and systems that exchange information or energy, in some form, with the environment are called *open* systems.

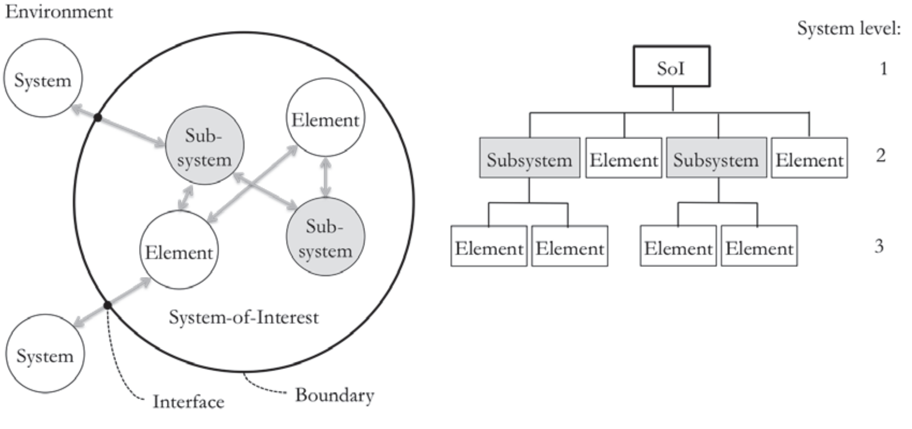


Figure 1-1 Illustration of the System concept. To the left in a network diagram and to the right in a hierarchy diagram.

Because of their complexity, it is often beneficial to view elements themselves as systems. On one hand, some might think a jet engine in itself is a complicated system. On the other hand, someone else views combat aircraft as elements in an air defense system. Therefore, there is a hierarchy within a system, which sometimes justifies discussing different *system levels*. A system hierarchy diagram is shown on the right hand side in Figure 1-1. Elements within the system of interest, that are themselves systems, are sometimes called *subsystems*.

Using a "systems approach" (Churchman 1968) acknowledges that the problem at hand is too complex to be solved directly since it is too intertwined with other questions, i.e. the problem has system characteristics. The problem solving then has two basic challenges. Firstly, the problem itself needs to be analyzed because the purpose or objective of the system is often unclear. Secondly, it is important to create an accurate model of the analyzed system as a system. Dependencies and interactions between elements often form the central properties of the system. According to Churchman, you then use the methods necessary to do the actual systems analysis.

1.3.2 The systems approach model

The systems approach applied to the problem in this thesis is based on the possibility of modeling military situations as systems and to recursively link effects to lower system levels, i.e. technical subsystem levels, and to technology levels. The idea is to be able to observe measurable changes in the military situation model at the top system level, when spectral designs are adjusted at the technology level. Given that we know how we would like to shape the military situation, and that we can monitor any changes due to spectral design, then it should arguably be possible to assess the military utility of such adjustments.

Applying the systems approach model, the problem depicted can be described as having (at least) three system levels: the military system level, the technical system level, and the spectral design technology level (see the illustration in Figure 1-2). The components and their relationships have differing characteristics at the different levels. Consequently, there is a need to borrow methods from various scientific disciplines to conduct the analysis.

At the topmost level a systems approach developed by Lawson (Lawson 2010, p.23) is applied. It explains how the military force of interest can be seen as a system responding to a problem, which in turn is viewed as a situation system. The latter comprises the military force of the adversary. Note that the model also accounts for the decision process of arranging the responding system from system assets. War is a social endeavor, which is why social science, especially *military science*, supports analysis at the military system level. Enhanced survivability requirements are presumed to emerge from interaction with the situation system, and from interactions between such things as equipment, operators, and doctrine, within the respondent system. Consequently, assessments of utility have to be made at the military system level. The science supporting quantitative decision-making at the military system level can be found in the field of *Military Operations Research* (MOR).

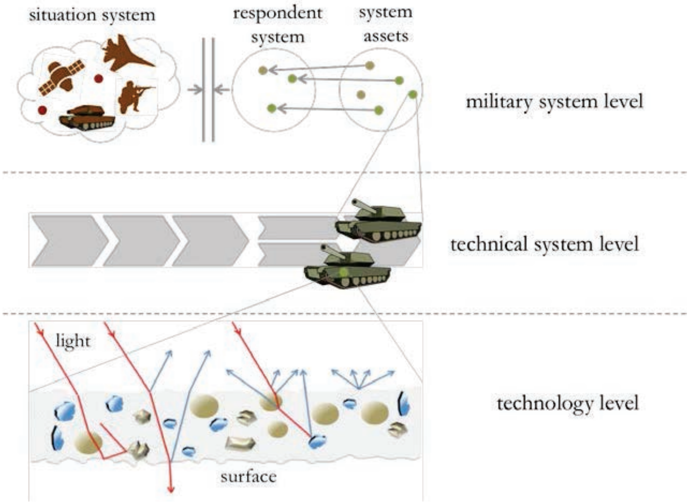


Figure 1-2 Model illustrating the systems perspective on the thesis research problem. The sub-model at the top illustrates that the military level of the system is adopted from Lawson (Lawson 2010, p.23)

At the middle level of the system model, military requirements are transformed into methods, organization - and technical systems, e.g. platforms, which are the focus in this thesis. This latter transformation is a core activity in *systems engineering*. In systems engineering, methods such as modeling and simulation are used to support requirements analysis, i.e. the central activity that links military system level requirements to lower level design requirements.

At the technology level, *signature management using spectral design* of surfaces conceals considerable complexity, which must be clarified in order to understand its relationship with the military platform design. Analyzing the optical response of a surface requires the application of *material optics*.

1.4 The research design

The division of the research question into four sub-questions has made it possible to address each research sub-question in separate studies, and to choose a method suitable for each study (Denscombe 2014, p.147). The thesis thus comprises four different studies, reported in six papers. The research sub-questions have largely been addressed in the order stated above.

The initial study, *the Technology study*, reported in Paper I, comprises a review of technologies and materials available for spectral design, and aims to identify those characteristics or technical variables relevant to the military application chosen – i.e. camouflage. A first order model of the systems engineering process, linking spectral design to military utility, is presented as a hypothesis in order to promote discussion among peers. Hence, Paper I address the first question (Q1) and ties earlier experimental research, reported in the licentiate thesis (Andersson 1993), to the research presented in this thesis.

The Concept development study, reported in Paper II, contains a concept analysis, which aims to answer the second research sub-question (Q2), and to propose a concept of military utility suitable for the first order systems engineering model presented in Paper I.

In *the Case study*, reported in Papers III and IV, the Systems Engineering processes of the Swedish multirole armored platform (SEP), and, in part, those of the Swedish Visby class corvette, were reviewed using a case study method. Lessons were identified from the modeling and evaluation of platform signatures and from the design activities, including relevant measures and requirements. The results were used as input to the Modeling study (Q3), but primarily as input to discussion of how to use the proposed assessment model in the systems engineering of Low Observable platforms (Q4).

In *the Modeling study*, modeling and simulation were conducted to show how the military utility can be linked to the surface properties of a platform using a quantitative model, thereby showing that effective evaluation is possible. In Paper V, the necessity of the systems approach is demonstrated by balancing the radar and infrared signature properties of a combat aircraft executing a mission. In Paper VI, the dependence of the IR signature on material emissivity is investigated. Together, these last two papers address research sub-question three (Q3).

1.5 Assumptions and delimitations

In this thesis, it is assumed that development programs in the near future will adhere to methods and principles developed in the field of systems engineering. Therefore, to be useful in practice, assessments of utility will have to support decision-making in the systems engineering process.

Furthermore, I assume that improved quantitative bases for decisions will assist decision-making in systems engineering. Discussion of human decision-making is not within the scope of this thesis.

Utility can be assessed from many perspectives, such as economic or game theory. In this thesis, I have limited the scope to assessment methods originating from the traditions of Military Operations Research (MOR) and systems analysis. These scientific disciplines are the roots of contemporary systems engineering practice. The quantitative character of MOR is, for example, necessary in requirements analysis, the core process in systems engineering. Requirements are responsible for communicating military needs to designers of technical systems, and they have to be measurable to be verifiable. Therefore, any proposals put forward in this thesis as a result of using these methods should increase the relevance of the results in practice.

The technological scope of this thesis is limited to the study of spectral design.

Spectral design is in turn limited to its use in signature reduction. In addition to the applications mentioned in the introduction, the use of spectral design for controlling the signature of decoys is perhaps of equally great interest.

1.6 Scope and structure

The scope of the extended summary in the thesis is more than a summary of the results reported in the appended papers. The aim is to report the results of an integrated research project based on the main research question, but using data collected from the appended papers.

The first five chapters form an extensive theoretical background to the thesis problem, including a review of related work. Due to the interdisciplinary approach, it is relatively voluminous. Figure 1-3 illustrates the scope of each background chapter in relation to the systems model approach. Chapter 2, *Theory: Military System Level*, presents important concepts and theoretical background necessary for analyzing the military level problem domain. Chapter 3, *Theory: Military Operations Research*, presents background and related work on how to quantitatively assess the performance of lower system levels at the military system level. Chapter 4, *Theory: Technical System Level*, presents concepts in Systems Engineering used to address the technical system level element of the research problem, including related work in the areas of Survivability Engineering and Signature Management. Finally, Chapter 5, *Theory: Technology Level*, introduces the application of spectral design in its context at the technology level, including fundamental concepts in material optics.

The last three chapters follow a traditional structure. Chapter 6, *Research Methods*, presents the methods used in the respective studies and discusses concerns regarding their feasibility. Chapter 7, a *Summary of study results*, consolidates the results necessary from the appended papers to answer the thesis research question. Chapter 8, *Discussion and conclusions,* answers the thesis research question and highlights the contribution of the thesis.

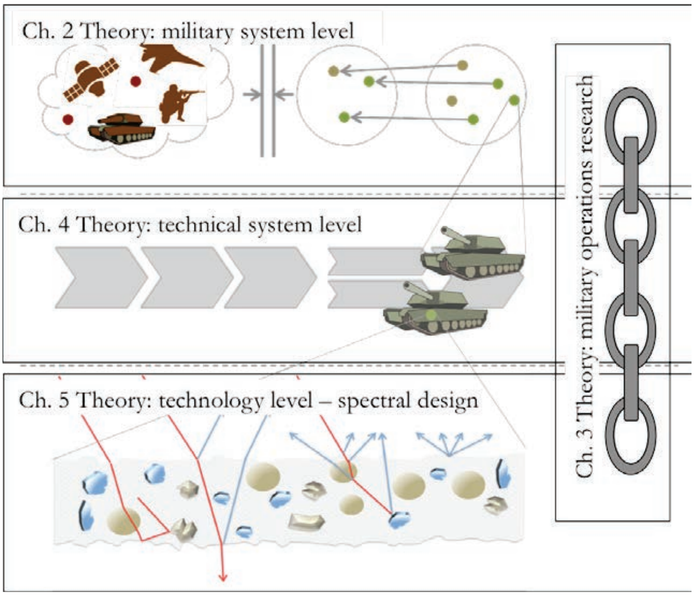


Figure 1-3 How the background chapters of the thesis relate to the systems model approach

2

THEORY: MILITARY SYSTEM LEVEL

When studying the utility of equipment for military purposes, logic says it is fruitful to start by answering the question: how should wars be fought? Therefore, this chapter presents important concepts and theoretical background necessary for the analysis of the military level problem domain. The chapter begins with an introduction to fighting power and warfighting capability, followed by a description of the *Principles of war*. In this thesis, the principles of war are then used as the theoretical foundation for the survivability attribute and for understanding the benefits of camouflage, concealment and deception. The chapter ends with a discussion of the role of military operational planning and a review of related work relevant to assessments of military utility.

2.1 Capability

The general meaning of the word *capability* is being able to do something (Merriam-Webster 2016a). In the military science domain, the ability to fight is defined by the *Fighting power* of a military actor. The fighting power in turn comprises three interdependent components: the conceptual component, (the thought process), the moral component (the ability to get people to fight); and the physical component (the means to fight) (DCDC 2014, p.25-). Hence, what the actor wants to do is a product of the conceptual component. The manpower and equipment required to do it constitute the physical component, and the resolve to do it is a product of the moral component. For the discussions in this thesis, the model is merely used to point out that there is more to fighting power than technology; however, equipment does affect both the way military fight and the morale of warfighters.

From a management perspective, fighting power can be viewed as a portfolio, i.e. a collection of warfighting capabilities (DoD 2008). Each warfighting capability might then refer to an objective, a task that needs to be accomplished in support of the objective, or the task force necessary to conduct these tasks. This view has developed within a concept called capabilities-based planning, since the end of the Cold War. The purpose is primarily to support military capabilities management in uncertainty (Fitzsimmons 2007). As an example, a Swedish traceability model has been implemented (SwAF 2011). Here warfighting capability is defined as “a specific activity, for which resources have been acquired and trained, in order to achieve a desired effect that varies depending on scenario and ambition” (SwAF 2011). An example from the portfolio, related to the Modeling study, is the engagement capability: The ability to suppress or destroy enemy ground based air defenses. Another example of direct interest is the protection capability: The ability to protect objects on the ground against attack (SwAF 2011). One of the merits of the above approach to capability, highlighted by Anteroinen, is that “it attempts to provide capabilities suitable for a wide range of challenges while working within an economic framework that necessitates choice” (Anteroinen 2013, p.16). This functional method of viewing and expressing capabilities highlights the broadening of missions for which forces should be prepared, and the joint perspective. An important result is that it shifts the generation of requirements away from a platform centric focus (Fitzsimmons 2007). Lastly, for the purposes of this thesis it is important to point out that the word *able* in the capability definition also means doing something successfully (Axberg et al. 2013, p.22). Hence, the survivability attribute, described later, is present in many warfighting capabilities. From here on, when the term capability is used in the thesis, it refers to warfighting capabilities in the sense described above, unless otherwise stated.

As identified by Anteroinen (Anteroinen 2013, pp.17–18), several nations have found it useful to think of and manage military capabilities as systems. In the US the system elements comprise; Doctrine, Organization, Training, Materiel, Leadership and education, Personnel and Facilities (DOTMLPF) (DoD 2008). In Australia the system elements are referred to as *fundamental inputs to capability*; these are: Personnel, Organization, Collective training, Major systems, Supplies, Facilities and training areas, Support, Command and management (AUS MOD 2014). Similarly, in UK the elements are referred to as eight *defence lines of development*: Training, Equipment, Personnel, Infrastructure, Concepts & Doctrine, Organization, Information and Logistics (TEPIDOIL) (Yue & Henshaw 2009). The common aim is to obtain a holistic view of capability development, thereby shifting attention away from the traditional platform centric approaches and towards non-materiel aspects. Regardless of the categorization of elements, we realize that any component in a system, e.g. the technical element, has dependencies on other elements. Consequently, and important in this thesis, a component only has military utility (See Paper II) if it is a contributing element in a *capability system*. The term *technical system* is used to label the technical element of an operational military capability system when it is beneficial to view the element itself as a system.

2.2 Principles of war

Many contemporary military doctrines refer to the so called *Principles of War* as guidelines to commanders and their staffs for the planning and conduct of warfare (e.g. DCDC 2014)). The phrase usually refers to the modern principles of war described by British General Fuller in 1916. His work was published in a journal article entitled “The Principles of War, with Reference to the Campaigns of 1914–1915”. No doubt his work was influenced by the writings of military theorists such as Sun Tzu, Henri Jomini and Carl von Clausewitz. However, Fuller considered this set of principles to represent the most important non-physical factors that affect the conduct of military operations at all levels. The widespread use of the principles in modern military doctrines a hundred years later seems to validate his view. The exact definitions and number of principles vary. In 1927 Fuller considered them to be nine (Fuller n.d.). In the 2014 British defense doctrine they are ten (DCDC 2014, pp.30–31): Selection and maintenance of the aim, maintenance of morale, offensive action, security, surprise, concentration of force, economy of effort, flexibility, co-operation and sustainability. *Security* is the principle of particular interest in this thesis.

2.3 Security, force protection or survivability?

A contemporary view of security is “providing and maintaining an operating environment that gives freedom of action, when and where required, to achieve objectives" (DCDC 2014, p.50). The principle entails balancing the likelihood of loss against achieving objectives (DCDC 2014, pp.30–31), i.e. warfare involves inherent risk. Consequently, it is impossible to avoid all risks, but such measures should be taken to ensure that achieving the mission is worth the anticipated cost in lives and losses in materiel. Managing these risks demands protecting high-value assets, be they troops or platforms, such as ships or aircraft. Within the framework of a military operation these measures are normally referred to as *force protection* – "the means by which operational effectiveness is maintained through countering the threats from adversary, natural and human hazards, including fratricide, in order to ensure security and freedom of action" (DCDC 2007). Instead, *survivability* measures are actions taken, for the same purpose, but during the engineering of equipment and platforms. Therefore, it is seen as an attribute of a military platform, e.g. a combat aircraft, a combat vehicle or a naval ship. As Survivability relates to security, it can be defined as the capability to avoid or withstand a man-made hostile environment (Ball & Calvano 1994; Ball 2003, p.1). This thesis focuses on efforts to *avoid* hostile threats.

2.4 Camouflage, concealment and deception

NATO defines camouflage as "the use of natural or artificial material on personnel, objects or tactical positions with the aim of confusing, misleading or evading the enemy" (NATO 2015). A typical example of camouflage is the pattern and colors chosen for combat uniforms. The aim is for soldiers to blend in with typical backgrounds in the presumed war zone. Another example is the use of dazzle paint schemes on naval and merchant ships during the First World War, to confuse German submarine commanders about such things as their type and heading (Hartcup 1979, pp.35–47). See Figure 2-1.

Although, in contemporary national doctrines, manuals and handbooks it seems the term camouflage is almost always used together with the terms concealment and deception, e.g. in the US DOD dictionary (DOD 2010). Hence, in military glossaries one has to look for the meaning of CC&D, or CCD. The term is, however, fre-

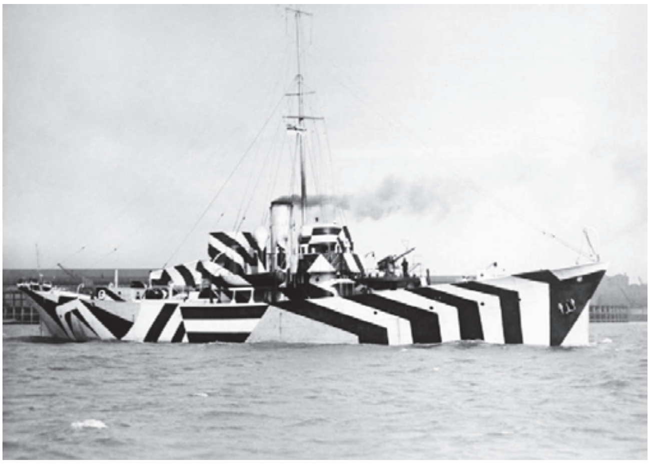


Figure 2-1 British Kil class patrol gunboat HMS Kildangan painted in dazzle camouflage. Photo: The British Government

quently used in the field of zoology. Hartcup concludes that nature's use of camouflage is really for the same purpose as in warfare, i.e. to survive by being inconspicuous (Hartcup 1979, p.9). The lion's color blends in with the colors of the savannah, as does the antelope's – and they are both there to eat.

In British doctrine, camouflage is given as one of the means of deception at the tactical level – "Tactical deception incorporates all measures to mislead an opponent in the battlespace, which are planned by component commanders and below, and may be used to complement an operational deception plan. Tactical deception is short-term and is usually based on physical measures such as camouflage, concealment, displays, feints or demonstrations." (DCDC 2007). Using decoys of soldiers, vehicles or weapons is one example of deception at the tactical level. The purpose can for instance be to confuse an adversary regarding the true size or intention of a military force. Again, turning to the animal world for similarities, one finds that deception is also used in nature. Some species of fish and butterflies, for instance, have patterns resembling pairs of eyes considerably larger than their own, to scare off species feeding on them.

The historical and natural examples have another factor in common; the sensors of interest, eyes or perhaps monochrome cameras, are only sensitive to the visible portion of the electromagnetic spectrum. In the contexts discussed in this thesis there are additional sensor threats in the battlespace. There are Night vision goggles sensitive to near infrared, and there are sights and imaging cameras sensitive to the short, medium and long wavelength infrared spectra. There are even *multispectral* sensors developed for field use, covering almost the entire optical spectrum (Sect.4.3.3). Consequently, means for camouflage, concealment and deception must develop accordingly.

In summary, the terms camouflage, concealment and deception blend together under the heading tactical deception. In this thesis, when the aim is specifically to analyze utility for camouflage, the aim is to evaluate the use of natural or artificial material on personnel, objects or tactical positions in order to reduce conspicuousness to military sensors.

2.5 Operations planning – the design of a respondent system

NATO allied joint publications define a military *operation* as the " military action or the carrying out of a strategic, tactical, service, training, or administrative military mission; the process of carrying on combat, including movement, supply, attack, defence and manoeuvres needed to gain the objectives of any battle or campaign" (NATO 2013). A *mission* is defined as a task with a stated purpose. As a key principal, NATO state that operations should be directed towards objectives contributing to achieving *a desired end state*, that is, an acceptable situation. Any operational planning process includes: understanding the (unacceptable) situation, identifying the desired end state, and designing an appropriate course of action that will make effective use of the limited resources at the disposal of the commander (See the NATO Comprehensive Operations Planning Directive for an example of a planning process currently in use). Thus, analogous to the military system model depicted in Figure 1-2, operations planning comprises decisions on the design of a suitable respondent system.

Given the description of capability (Sect.2.1), the alternative designs available to the commander and staff are limited by decision-making that took place years ago in the capabilities-based planning process, including whatever technical systems were developed and acquired. In turn, the performance of these technical systems is, at least to some extent, limited by decision-making that took place years earlier in the military technology research and development processes. Therefore, all of these decision situations involve assessing which combination of ends, ways and available means (including technical systems and technology, i.e. the focus here) will have the greater probability of success for a military force, in the same uncertain future situation. The main difference between the decision situations described is the time frame, and thus the degree of uncertainty in the assessments made. When planning an operation, the staff will probably have a good idea of whom the adversary is, the performance of their own equipment, and the conditions in the area of operations. However, when, for example, developing a low observable platform as part of developing a new capability, the scenarios will be thematic and perhaps both the threat systems and friendly systems will be conceptual. Consequently, the decision situations mentioned are variations of the same phenomenon – identified in this thesis as *assessments of military utility*.

2.6 Concepts of military utility – related work

In light of the discussion above (section 2.5), we expect an assessment of military utility to support an armed force's decision about which candidate technology to choose (seen as one of the technologies in a technical system, in turn seen as a component in a capability system), while balancing the desired effect against limited resources. Therefore, the question in this section is what definition of military utility to use in order to take account of all necessary aspects, and to provide a good basis for the decision-making in focus.

Traditionally in the military domain, analysis based on cost-effectiveness is used to compare the expected utility of different alternatives in order to support decision-making regarding the acquisition of materiel. In textbooks, this kind of assessment is called a *trade-off analysis* or an *analysis-of-alternatives*. See for example Lewis et al (2007). However, cost-effectiveness does not seem to be relevant in all the decision-situations depicted. Some scholars have, for example, found that in the operations planning situation, the cost dimension only makes sense if it has a wider meaning than purely monetary, such as loss of lives or materiel (Larson 1996; Axberg et al. 2013; Sivertun 2012).

The systems engineering community use a concept called the *operational utility*, which is "the degree to which the system in focus enables users to accomplish organizational missions and achieve stated goals and objectives, while posing no unacceptable safety, environment or health hazards or risks to its operators or public" (Wasson 2006, p.50). In this concept, the desired effects dimension, the undesired effects, and the limiting factors of an operation are considered in greater depth. However, there seems to be a need to develop the limited funding dimension and to specify the concept from a military organizational viewpoint.

The US Department of Defense uses a concept called *operational effectiveness*. The definition is “a measure of the overall ability of a system to accomplish a mission when used by representative personnel in the environment planned or expected for operational employment of the system considering organization, doctrine, tactics, supportability, survivability, vulnerability, and threat” (DoD 2012). The desired effect is defined as accomplishing the mission. In addition, it also seems to relate to the capability aspect, as it implies that a perfect fit with the organization, doctrine etc. is a prerequisite. The US Department of Defense also uses a concept called *operational suitability*. This is defined as “the degree to which a system can be satisfactorily placed in field use with consideration to reliability, availability, compatibility, transportability, interoperability, wartime usage rates, maintainability, safety, human factors, habitability, manpower supportability, logistics supportability, documentation, environmental effects and training requirements” (DoD 2012). Hence, in the context of this thesis, operational suitability could be considered a candidate concept for characterizing how well a technology, or a technical system, fits within a capability system. Thus, a combination of operational effectiveness and operational suitability seems to address both the desired effect and capability aspects of the military utility concept sought here.

Furthermore, the military-utility concept sought is required to enable quantitative assessments, as stated in the introduction (Sect.1.5), in order to support the systems engineering process. However, there are also important qualitative aspects to consider. Utility is in essence the quality of something being potentially useful (OD 2014; McLean & McMillan 2014). Stensson argues that having this focus promotes optimization of the design for those scenarios the design organization can think of in advance, at the expense of usefulness and safety in practice (Stensson 2014; Stensson 2015). He proposes a concept called *situated usefulness* with the aim of making designers aware of the problem, and promoting designs that enable the system’s operators to make full use of their skills, creativity and experience. He describes the concept as a field of two tensions. Too much focus on *calculative effectiveness* or *safety* will hamper the systems generative qualities, *potentiality* and *resilience*. This might render the system useless and the safety brittle in unexpected situations. In addition, too much focus on avoiding undesired effects, that is, focusing on safety and resilience, will hamper effectiveness and potentiality. Nevertheless, he stresses that designing in order to manage foreseeable situations is necessary; otherwise, the generative qualities might be completely irrelevant. However, there is a balance to be found.

When doing a literature search on the topic “military utility” on the web-of-science there are only thirteen hits[2], including Paper I. It seems the only previous formalized use of the term to be found is in the US Department of Defense acquisition process for assessing the operational utility of new technology in demonstrators. These assessments are called “Military Utility Assessments” (AcqNotes.com 2016). Their use is obviously related to the need for a concept in this thesis, but it does not fully cover all the necessary aspects.

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[2] June 1st 2017

In summary, we have found no concept that captures all the aspects important to the military decision-maker when assessing the military utility of technologies to be used in military technical systems, and then in capability systems. Therefore, the aim of the Concept development study (Paper II) was to propose such a concept, based on related concepts from the military and systems engineering domains.

3

THEORY: MILITARY OPERATIONS RESEARCH

In this thesis there is a need to use both qualitative and quantitative methods. The systematic literature review, the concept analysis and the case study methods used are typical examples of qualitative research methods, where the collected data is soft and rich – and not presented in numbers. However, as stated in the introduction, the methodological contribution is required to support the quantifying of military performance/needs at the military system level, and then to link these measures to those at more detailed system levels. These abilities are developed within the field of Military Operations Research (MOR).

In this chapter, military operations research is first defined and its merits are described in general. Next, the fundamentals of modeling and simulation are discussed, followed by an introduction to generic MOR studies. In the second half of the chapter a probabilistic framework, specifically suitable for survivability assessments, and used in the Modeling study, is first presented. This is followed by a review of related literature. The chapter ends with a discussion of the implications of uncertainty and complexity in warfare modeling.

3.1 Merits of quantitative assessments

At the beginning of the Second World War, the British government asked Professor P.M.S. Blackett and colleagues to support military operations. There were numerous cases where the tactical use of new equipment had not been optimal. In several of those cases, performance was enhanced significantly by the application of scientific methods. This event is said to mark the birth of MOR, or military Operational Analysis (OA) as the discipline is also known (Jaiswal 1997, p.3). It was acknowledged that scientific analysis, sometimes rather simple, could bring significant improvements to military systems and capabilities.

During the decade after WWII, military operations research was used to support decisions in current or near future military operations. Due to the increasing complexity in government technology programs at the beginning of the 1960s, such as Polaris and Gemini, there was a need to develop decision-making methods. The main challenge was the increasing timespan for the development of advanced military systems, and with it the need for life cycles in the 15-20 year range. The uncertainties arising from this perspective on weapons acquisition threatened to increase costs enormously. The answer was a new scientific discipline called *systems analysis*. It was defined as the “systematic approach to helping a decision maker choose a course of action by investigating his full problem, searching out objectives and alternatives, and comparing them in the light of their consequences, using an appropriate framework - insofar possible analytic” (Quade & Boucher 1968; Jaiswal 1997). Initially systems analysis supported military decision-making in the long term, while military operations research supported it in the short term. In the military domain today, however, systems analysis is regarded as an integral part of military operations research and the two labels are used interchangeably (Jaiswal 1997, pp.4–5).

Nowadays MOR analysts work both in military operational staffs and in supporting procurement agencies. Their work is similar to that of staff officers, i.e. to create bases for decisions. The difference is the sophistication in methods used, which are often based on statistics and mathematics (Loerch & Rainey 2007, p.4). The aim is to enable the decision-maker to make a rational, informed, decision about military issues. Jaiswal has illustrated the scope of MOR by presenting a set of typical questions to be answered, e.g. "What will be the consequences if the force levels are reduced on a unilateral, bilateral or multi-lateral basis?" or "If the various factors influencing the performance of a system can be expressed qualitatively, can the performance be quantified?" or; "What is the effectiveness of a weapon system or a tactical plan in a plausible combat scenario?" (Jaiswal 1997, p.1). Versions of the latter two are addressed in this thesis; e.g. see Papers I and VI respectively. The formal definition of MOR is "*Operations research is a scientific method of providing defense departments with a quantitative basis for decisions regarding the operations under their control*" (Jaiswal 1997, p.6) (Morse & Kimball 1951).

The key term is *quantitative*. The simple argument for using a quantitative approach, supported by the discussion above, is of course that it complements qualitative results obtained from other sources as a basis for decisions. Nevertheless, some of the merits of quantitative methods are highlighted below.

In Paper II it is pointed out that legislation demands *objective* evaluation of tenders for contracts to develop military materiel. The solution is to grade the design solutions in different aspect-areas (such as stealth), to give these areas numerical weights and compare the resulting compounded product of the respective tenders. Of course, there will still be some room for arbitrary judgements, but a quantitative model makes the procedure more transparent.

In Paper IV the focus is the requirements analysis process during the engineering of military materiel. Quantifying the needs of warfighters in the military domain, in order to be able to *communicate* them to the design organization, is the driver of the engineering process. Quantifying these needs using measurable metrics is also necessary in order to be able to *verify* that the product delivered satisfies the requirements. The results in Paper IV indicate that requirements that are not quantified may suffer from low priority during design. Use of MOR enables identification of these needs and relevant measures.

In Papers V and VI some aspects of the random nature of warfighting are modeled using *probabilistic* methods (which are particularly suitable when studying survivability, see Section 3.4). The duel between an aircraft strike package and a ground based air defense system is modeled in a quantitatively based scenario. This adds *flexibility* since it is possible to tune numerous tactical and technical parameters to monitor the consequences. Specifically, the procedure can be used to determine whether uncertainty in a particular parameter is great enough to influence decisions.

Lastly, it can be understood from all three examples that quantifying needs and properties forces MOR analysts to define the phenomena analyzed explicitly and unambiguously. This has been pointed out as a merit in itself. Loerch & Rainey stress that recommendations from MOR analysts are seldom the only basis for decisions available to the decision-maker. Decisions are often based on a combination of MOR-results and more informal information. However, not infrequently, decision-makers find that the most important contribution from MOR is in fact the structured framing of the problem (2007, chap.4). No doubt quantitative results can be used to support a qualitative discussion (Liwång 2015, pp.46–47).

3.2 Modeling

"Everything should be made as simple as possible, but not simpler" is a quote often attributed to Albert Einstein. The statement concerns scientific theories in general but is certainly appropriate when it comes to models and modeling. A *model* is an abstraction of reality and comes in many forms, such as maps, organizational charts, process descriptions, miniature models, analytic (mathematical) expressions, etc., and even notional forms. We use them because "the real world is too complicated for us to reason about and contains many details that that are not necessarily relevant" (Washburn & Kress 2009, p.1). Hence, any analyst is faced with the delicate challenge of finding a model that is both simple enough to understand, and, when used, produces relevant observations about the real world phenomenon of interest. If the model is too simple, the observations might very well be misleading. An important consequence is that an analyst has to understand the limitations of a model to use it properly.

Simulation should be understood as "an experiment where a model is used for the monitoring and understanding of the behavior and causality in a modeled phenomenon during a period of time" (Holm 2007, p.12) (translated from Swedish). The terms *modeling* and simulation are often used interchangeably in the literature. Modeling or simulations supporting military studies can be performed as any activity on a scale from a computer program to a war-game, or military exercise, involving human decision-makers (Washburn & Kress 2009, p.3).

Within the MOR community, the problem solving method in Papers V and VI would be referred to as an example of *warfare modeling*. This concept involves the broad scope of models and methods that are applicable to warfare lems (Bracken et al. 1995, pp.1–2). On the detailed end of a resolution-scale, *weapon system modeling* is used to assess certain system attributes by using analytic models of the systems, statistics and probability techniques. Next on the scale, *combat modeling* (Washburn & Kress 2009) is used to address operational problems related to force structure, combat development and tactics. At the low-resolution end, *theater-level modeling* is used to solve strategic issues, such as defense budgeting or analyzing arms control agreements. As a rule, more detailed models are used to produce input to those with less resolution. Consequently, the Modeling study is probably best described as a combination of weapon systems modeling and combat modeling.

The analytic models used in warfare modeling are either *deterministic* or *stochastic*. Deterministic models state exactly what will happen as if there were no uncertainties, while stochastic models assume uncertainties, use random variable inputs and make indefinite predictions of the results (Washburn & Kress 2009, p.2). The modeling in the Modeling study (Papers V and VI) falls into the deterministic category.

3.3 MOR studies

There are many versions of the scheme for OR studies in the literature (e.g. (Loerch & Rainey 2007; Jackson 2003)); they look slightly different as different scholars emphasize different parts, but the core is the same (see definition of systems analysis above). Here the version by Jaiswal (1997, chap.7) is reproduced and used for illustrative purposes, because it is generic in nature. See Figure 3-1.

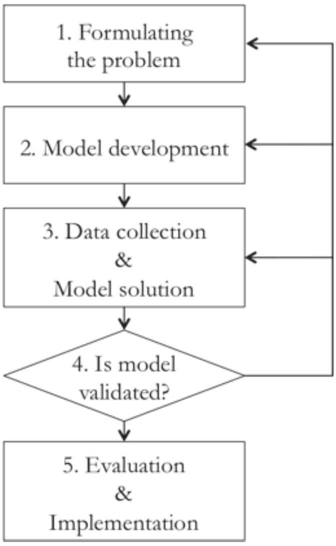

Figure 3-1 A generic scheme for OR studies

The initial step comprises activities for capturing and *formulating the problem*. If possible, it involves discussions with the decision-maker in order to understand the problem correctly. Then, the objectives of the study, variables affecting the study, and Measures of Effectiveness (MoE) are defined. The initial step ends with the identification of possible alternative solutions. In the Modeling study, measures of survivability were central. Alternatives were simply defined by varying size, speed, altitude, and the coating properties of the aircraft.

The second step comprises *developing a model* that can help answer the study question. In MOR, as stated above, analytic expressions producing quantitative results are preferred. In our example from the Modeling study, a mathematical expression for calculating the predicted loss of aircraft is formulated. This model, however, also needs input from models of the scenario, the combat aircraft, its coatings, its weapons, the adversary's weapons and sensors etc. (Sect.6.3, 7.3).

In the third step, the models are used to *collect data*. In some cases it is possible to find analytic solutions directly, but more often the models are implemented and executed in a simulation environment. Data to feed the models can often be found in experimental data. Jaiswal points out that in this step links are established between system variables and the top level MoE (1997, p.9). In the Modeling study (Papers V and VI) the overall aim is to show that it is actually possible to make an explicit link between a material's optical properties and the military utility of an aircraft.

When entering the fourth step, MoE values for the respective alternatives have been assigned, but are they useful in a comparison of alternatives? The models used have to be *validated*. Due to the nature of military systems, results from field trials for comparison purposes are scarce. Hence, according to Jaiswal, the validation methods available are usually expert opinions, sensitivity analysis or hypothesis validation (1997, chaps.9–10). Sensitivity analysis reveals whether uncertainties in parameters alter the relative priority of the alternatives. Hypothesis validation is understood as pairwise comparisons of high-level responses from the model with assessments of what would happen in the real world, given the same events. In Papers V and VI the model describing the military scenario model was validated in a discussion with military experts, while the more detailed models representing sensor and weapon responses were validated by comparing them with results reported in earlier research (Sect.7.3.2). If necessary, the analyst has to go back, modify, and redo earlier steps, as indicated in Figure 3-1.

The final step in the OR scheme illustrated is *evaluation and implementation*. In this step the resulting alternatives, and their respective MoEs, are compared, and conclusions are drawn. Finally, the MOR analyst synthesizes the analysis results, answers the study question and makes a recommendation to the decision-maker.

3.4 The probabilistic framework for survivability

By using a MOR approach to demonstrating the impact of survivability on military activities, we understand that there is a need to find measures and models to link them. The applicatory mission example chosen for the Modeling study is an air-to-surface air operation to neutralize a ground based air defended point target. For this particular situation, Robert E. Ball has worked out a theoretical probabilistic framework for survivability assessments (2003, chap.1.1).

3.4.1 The one-on-one scenario

Survivability is an attribute of a military platform defining its capability to avoid or withstand a man-made hostile environment (Ball & Calvano 1994; Ball 2003, p.1). Because of the random nature of combat, survivability is measured by a probability, P_S. The complementary event, where the platform does not survive, is described as a kill, and the *killability* of a platform is denoted P_K. Thus, in probabilistic terms survivability can be expressed as:

$$P_S = 1 - P_K. \qquad \textit{Eq. 3-1}$$

Survivability is in turn generally composed of three probabilities: the *susceptibility*, the *vulnerability* and the *recoverability* (Ball & Calvano 1994; Kim & Lee 2012). The susceptibility denotes the probability that the platform is hit by a weapon or by its parts, P_H, and the vulnerability denotes the probability that the platform is killed if it is hit, $P_{K|H}$. The recoverability refers to a platform's damage control and thereby its ability, including that of the crew, to reconfigure and continue its mission. In the aircraft survivability discipline (Ball 2003), survivability is often estimated without regard to recoverability and is hence given by:

$$P_S = 1 - P_H \cdot P_{K|H}, \qquad \textit{Eq. 3-2}$$

while in ship or land combat vehicle survivability disciplines, the kill is not necessarily total. For a more detailed discussion of the latter case, and recoverability, see Ball and Calvano (1994).

The expression "breaking the kill chain" is of uncertain origin, but is a useful concept for analyzing survivability measures. The kill chain epithet refers to the one path in a probability tree of events that leads to the platform being killed (Ball 2003, p.11). All the others lead to the platform surviving. In the Modeling study (Papers V and VI), the concept is applied to the probability of an attack aircraft being killed by an air defense surface-to-air missile, and this situation is used for illustration. In a scenario with one threat and one aircraft (The *One-on-One scenario*), the aircraft is killed:

- given that the threat is active, P_A,
- given that the aircraft is detected, $P_{D|A}$,
- given that a weapon is launched, $P_{L|D}$,
- given the weapon intercepts, $P_{I|L}$,
- given a hit, $P_{H|I}$, and then
- given that the aircraft is vulnerable to the hit, $P_{K|H}$.

If the kill chain (the product of the probabilities listed) is inserted into Equation 3-1, survivability can be written:

$$P_{SS} = 1 - P_A \cdot P_{D|A} \cdot P_{L|D} \cdot P_{I|L} \cdot P_{H|I} \cdot P_{K|H}. \qquad \textit{Eq. 3-3}$$

Thus, any tactical or technical measures taken to reduce probabilities in the kill chain will break the kill chain, or at least enhance the survivability. On-board electronic warfare can be used to prevent the surface-to-air missile system from being activated, thus reducing P_A; or, signature reduction efforts can be used to reduce detection range, thus reducing $P_{D|A}$, etc. This is the basic principle behind survivability engineering and signature management, which are further elaborated in Chapter 4.2 and Table 4-1.

3.4.2 The military systems study

The one-on-one scenario is often too simple a model. The survivability discipline stems from an understanding of the fact that the mission, the context and the adversary weapon systems all significantly influence the relative importance of each survivability enhancement feature, and from the fact that the attributes of a platform, e.g. a combat aircraft, naval ship or main battle tank, are *interdependent* (Ball 2003, p.44). Consequently, each feature used to enhance one attribute could have an undesired impact on another. In the following, these undesired effects are included in *secondary effects*.

A simple example would be the impact of adding armor to a patrol vehicle - the physical protection is enhanced, but mobility is reduced. There is obviously an optimal balance to be found in the effectiveness of attributes. Therefore, Ball advocates using a *system effectiveness* concept to study the overall utility of platforms in a specific military context, i.e. at the military system level illustrated in Figure 1-2. He argues that the system effectiveness of a military platform comprises three dimensions: *defensive survivability*, *offensive capability* and *availability* (Ball 2003, p.765). The prefix defensive is omitted in the following text. In order to study the effects of survivability measures in all three dimensions, Ball divides military activities into engagements, missions and campaigns. A mission comprises a series of engagements and a campaign in turn comprises a number of missions. A survivability assessment has to be conducted at the mission level, to take the secondary effects on offensive capability into account, and at the campaign level to take the secondary effects on availability into account.

At the engagement level, the one-on-one scenario is considered the basic element for the derivation of an analytic link between survivability and measures of mission effectiveness. The probability (P_{SS}) of one aircraft, flying within range of a Surface-to-Air-Missile (SAM) system, engaging with one shot, and surviving, is given by Equation 3-3. This is the most common measure of survivability, but since it is not the only one, Ball indexes it with *"ss"* for single-shot.

More generally, in multiple shot or multiple engagement scenarios there are two possible situations to consider. Either the outcomes of later engagements are affected by the outcomes of earlier engagements, or they are not. The probability of dependent engagement outcomes is rather difficult to assess; therefore, they are usually assumed to be independent (Ball 2003, p.18). One should, however, be aware of this simplification.

In a typical mission, several aircraft are involved in multiple encounters with air defense systems. Hence, the survivability measures of interest at mission level are the Loss Rate, LR, or the Survivability Rate, SR. These are given by

$$SR = 1 - LR = 1 - \frac{number\ of\ aircrafts\ killed\ in\ one\ mission}{total\ number\ of\ sorties\ flown}. \qquad Eq.\ 3\text{-}4$$

At campaign level, survivability refers to the probability of an aircraft surviving a campaign consisting of N missions. Campaign Survivability, CS, becomes

$$CS = P_{S1} \cdot P_{S2\dots} \cdot P_{SN} = (1 - P_{K1})(1 - P_{K2})\dots(1 - P_{KN}), \qquad Eq.\ 3\text{-}4$$

where P_{Ki} denotes the ith mission loss rate and P_{Si} denotes the ith mission survival rate. Thus, if A is the number of aircraft available initially, the number of aircraft remaining after a mission is $A \cdot LR$, and after a campaign, $A \cdot CS$.

In summary, survivability, the first dimension in system effectiveness, is measured using different metrics, depending on the complexity of the scenario. At engagement level, the measure most often used, according to Ball, is the probability that a platform survives a single shot P_{SS}, or the probability that it is killed $P_{K|SS}$. At mission level, the measure mostly used is the Survivability Rate, SR or the Loss Rate, LR. At campaign level, Ball argues that the most interesting measure of survivability is the number of platforms remaining at the end of the campaign.

The second dimension of system effectiveness, availability, is measured using the *likelihood the aircraft is available* for a mission, AA (Ball 2003, p.47). The third dimension, the offensive capability, is quantified using the *Mission Attainment Measure*, *MAM*, which ranges from 0 to 1. From a probability point of view the *MAM* is the conditional probability that the platform can successfully accomplish the mission, given that it survives (Ball 2003, p.48). Hence, when evaluating the *MAM* for a specific mission, the platform operates as if the threat were present, with appropriate tactics, but the killing effects of the threat are not considered. The compound *Measure Of Mission Effectiveness*, *MOME*, is simply defined as the product of survivability, availability and offensive capability.

3.5 Survivability assessments – related work

In MOR studies involving issues of survivability, a common denominator seems to be the application of Balls probabilistic framework (2003); this is seen in combat aircraft survivability analysis (Soban & Mavris 2001; Fielding & Nilubol 2004; Thokala 2009; Thokala et al. 2012; Soban & Mavris 2013), in naval ship survivability analysis (Ball & Calvano 1994), and in land combat vehicle survivability analysis (Guzie 2004; Goh 2014; Burgess & Svetoslav 2015).

Problems addressed in survivability studies are typically formulated with objectives related to measures of survivability and the overall measure of mission effectiveness. Measures of survivability, like the loss-rate, are normally used as constraints, but for unmanned aerial vehicles they can be used as possible trade-offs (Richards et al. 2009). In some applications the framework has also been adapted to include life-cycle cost as a constraint (Soban & Mavris 2000b; Soban & Mavris 2001; Fielding & Nilubol 2004; Thokala 2009). The idea is that, if it is possible to link platform designs to life cycle cost in a military campaign model, economic limitations will affect the availability of platforms, which will in turn affect the top level MoEs used for decision-making.

Modeling activity in survivability studies has been developed and thoroughly described by Soban and Mavris, in an effort to develop a methodological framework to support the preliminary (or conceptual) design process for combat aircraft (2000b; Soban 2001; 2001). Viewing an air campaign as a system is central. Figure 3-2 illustrates a basic example of a possible result of such modeling activity. It is a multi-level system model adapted from Soban and Mavris (2000a). The illustration shows how they link technical parameters (requirements, design limitations or economic variables etc.) to measures of effectiveness at the campaign level in two steps – firstly, via response functions in a technical system model, and then via response functions in a mission level model. For example, Figure 3-2 indicates how the lethality of an aircraft (a measure of performance (MoP)) depends on the technical requirements of payload and speed. The red graphs in the respective matrix elements are plots of the modeled response functions; for example, lethality is expected to increase with increasing payload or speed.

At the mission level, the MoPs then become input variables to response functions of output measures of effectiveness (MoEs). For example, it can be seen how losses are expected to increase as the detectability and range of the threat air defense system increase. At the top, mission level measures of effectiveness are combined into campaign system measures of effectiveness, such as the MOME (Sect.3.4.2). When defining response functions, Soban and Mavris use physics based calculations to find point values and then use regression analysis to extrapolate. Their justification for using regression analysis is that it minimizes calculation time.

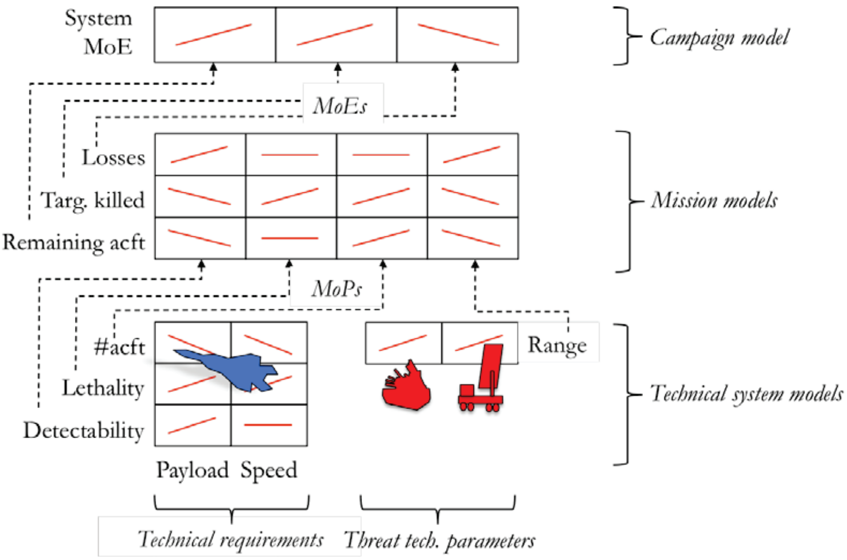

Figure 3-2 A basic example of a multi-level model linking technical parameters governing platform performance to measures of system effectiveness. The diagram is adapted from Soban and Mavris (Soban & Mavris 2000a). *The red lines in the respective models are graphs illustrating the model response to varying the respective input parameters.*

The modeling approach in this thesis is based on the framework proposed by Soban and Mavris, and is further elaborated in section 6.3. The rationale is that their analysis scheme was developed for survivability research, and they have shown that it can be used for evaluating both the system effectiveness and cost dimensions. Presumably, this latter property has potential in assessing military utility, a concept with more than one dimension (Paper II). Other academics have also used the framework, but their survivability models only seem to take into account radar signature and vulnerability reduction features (Fielding & Nilubol 2004; Thokala 2009; Thokala et al. 2012). The aim in this thesis is to contribute with an adaptation for use in applications to reduce signatures in the optical electromagnetic spectrum.

3.6 Uncertainty and complexity

The modeling approach chosen implies being able to predict the behavior of a military situation system, when adjusting some of its elements, i.e. it is assumed that it is possible to describe a military system using *linear* (causal) models. However, given the emergent properties of a system, and the inherent uncertainty about the future, is it possible to learn anything of value from such a model?

In his thesis on risk analysis, Abrahamsson (2002) made an excellent review of the characteristics of and methods for dealing with uncertainty in quantitative modeling. Basically, he concludes that obtaining acceptable reliability in model predictions requires managing uncertainties related to:

1. *specifying the correct problem* or scenario the model is intended to address (Otherwise the model "produces correct results for the wrong problem" (Abrahamsson 2002).)),
2. *formulating a conceptual model of the problem* taking all relevant entities, processes and interactions into consideration, whilst omitting the rest (See section 3.2.),
3. *formulating a computational model* with suitable resolution for the intended use of the model (i.e. the set of equations and parameters needed to obtain quantitative results),
4. *estimates of the input parameters* to the computational model, and finally,
5. *calculation and documentation of results*.

I have chosen to use Abrahamsson's classification to describe briefly how the corresponding uncertainties are treated in this thesis. Uncertainties of the first kind relate directly to difficulties in forecasting the future use of a technical system. The systems engineering approach chosen prescribes involving the end user organization when working out relevant scenarios and concepts of operation. The importance of this activity, success factors, and its role in the process of developing a low observable platform is discussed in the Case study (Sec.6.4). Uncertainties of the second kind are largely addressed through the application of survivability engineering (Sec.4.2), where identifying interdependent attributes and balancing requirements from a holistic viewpoint are central. The formulation of a conceptual model template for evaluating spectral design technology in the Technology study (Sec.7.1) and the Concept development study (Sec.7.2), comprising the Ladder-model and the military utility concept respectively, includes in depth discussions on the matter. The modeling study demonstrates how to apply the template in practice, including how to use influence diagrams to avoid formulating too simple a model (Sec.7.3). In this thesis, uncertainties of the third and fourth kinds are largely addressed using the probabilistic framework for survivability presented above (Sec.3.4). One advantage is the ability to represent natural randomness with probabilities or probability distributions in input parameters. The feasibility of this is demonstrated in the Modeling study (7.3). Typically, uncertainties of the fifth kind are managed by expert validation, comparisons with similar studies, peer reviews etc.

The approach described is not without its critics. Some academics in the field of *complexity theory* would consider a military situation system complex in a sense that makes OR, i.e. analysis through traditional cause-and-effect modeling, practically futile. Complexity theorists argue that there is a significant difference between complicated systems and *complex systems*. A combat aircraft, for instance, would be considered an example of the former, since it is possible to model its behavior using physical relationships. It is a complex product, but as a system it is merely complicated. Complex systems are "constituted of such intricate sets of non-linear relationships and feedback loops that only certain aspects of them can be analyzed at a time" (Cilliers 1998, p.3). Complexity is said to increase with the number of interacting elements, their diversity, their interconnectivity and their adaptability. From this perspective, complexity is usually associated with living things or social systems. Sociological systems are said to have strong *emergence,* when compared to physical-chemical systems. See Emmeche et al. (Emmeche et al. 1997) for an in-depth investigation of this property. In brief, sociological systems rely for their operation on the same laws that govern physical-chemical systems; however, physical-chemical laws cannot completely account for the operations of sociological systems, because such systems are also governed by biological, psychological and social laws. The main implication for the context of this thesis is that it will never be possible to predict the evolution of a comprehensive military situation using causal models. It is possible to model quite complicated technical systems and, in principle, to predict their behavior, because they obey physical-chemical laws. However, any military situation system comprises technical system components *and* human operators; hence, it qualifies as a sociological system and is already considered too complex to model, even when it comprises a small number of entities.

However, because even social systems have to obey physical laws, we should at least be able to use the results from causal technical system modeling as boundary conditions when modeling military situation system behavior in predetermined scenarios. In this thesis, predetermined scenarios typically have well-defined military objectives, predetermined tactical options, and rational operators, which is why the complexity of the military situation system is presumably manageable. The ambition of the approach described is to identify tipping points in military situation systems of predetermined scenarios, made possible by changes in the physical boundary conditions. For example, tipping points could present an operator with the opportunity to do something completely different, and presumably more efficient, in order to meet military system objectives. No doubt, technology enabling such a tipping point has military utility. As far as engineering technical systems is concerned, this ambition must be good enough. Design decisions have to be made before a system is actually used. Applied systems scientists have taken this path before. Flood and Carson say, we must agree goals and system objectives beforehand, because "drawing up a design assumes we know the purpose of that design" (1993, p.121). Jackson concludes that a unified systems theory is not possible. Therefore, taking the OR approach might be correct "assuming that people (i.e. shareholders (my remark)) share values, and that systems can be mathematically modeled" (1995, p.27).

In summary, my argument is that the modeling approach described will enable comparison of the benefits of different technical designs in military situations, and hence, potentially, assessment of their military utility - if only in relation to predetermined scenarios that are simple enough to model. Further discussion of the impact and possible mitigation of uncertainties related to each study can be found in the respective validity and reliability sections in Chapter 7.

4

THEORY: TECHNICAL SYSTEM LEVEL

When discussing military utility, ultimately only solutions that are feasible in the real world are of interest. If systems analysis is the science for understanding a complex real world problem and arriving at a conceptual technical solution, systems engineering is required to capture the concept and construct a working solution for the real world (Lawson 2010). In this chapter, general concepts of systems engineering are presented, followed by a presentation of the survivability engineering specialty, and the signature management discipline within that.

4.1 Systems engineering

In order to increase my chances of contributing to engineering practice, I have chosen to adopt the INCOSE (International Council on Systems Engineering) view of systems engineering. Their systems engineering handbook (INCOSE 2015) is considered best practice by many defense agencies and corporations worldwide, and it is consistent with the ISO/IEC/IEEE 15288:2015 standard. In the following, systems engineering is described from three different aspects: a perspective, a process and a profession.

Firstly, systems engineering can be described as a perspective, referring to its theoretical foundation in systems thinking: "systems engineering is an *interdisciplinary approach* and means to enable the realization of successful systems" (INCOSE 2015, p.11). The success-factors highlighted are: customer needs and the required functionality must be addressed early in development; the entire life cycle of the resulting system must be considered from the beginning; and all relevant engineering disciplines and specialties should be involved in a team effort. Here, survivability engineering and signature management are considered disciplines of special interest.

Secondly, systems engineering can also be viewed as a process: "systems engineering is *an iterative process* of top-down synthesis, development and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system" (INCOSE 2015; Eisner 2008). The systems engineering standard identifies four process groups: the technical processes, the technical management processes, the agreement processes and the organizational project-enabling processes. Paper IV examines the tailoring of these processes to fit the engineering of Low Observable military platforms.

Thirdly, systems engineering is a profession. It forms "a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect" (INCOSE 2015, p.11). In Paper IV, the effect of the mindset of the program management, and of the allocation of responsibilities to project members are part of the study.

Some terminology frequently used in systems engineering needs clarification. All man-made systems pass through a *life cycle*, from inception to disposal. In the systems engineering standard referred to here, the life cycle has been divided into a number of stages, each with labels characterizing the state of the system. See Figure 4-1.

Figure 4-1 The generic life cycle of a system according to ISO/IEC/IEEE 15288:2015

The *concept stage* (INCOSE 2015, pp.29–31) begins when the need for a new system of interest is identified. It ends with the selection of a high-level conceptual solution for development. In between, ideas, methods, new technologies etc., are explored and evaluated. One method used to evaluate concepts and to explore the use of new technologies is to develop concept demonstrator systems. The benefits of this method are discussed further in Papers III and IV in reviews of the Low Observable technology demonstrator projects *SAT/Mark* (armored vehicle) and *Smyge* (naval vessel).

The development stage (INCOSE 2015, p.31) starts with input from the concept stage. The aim is to develop a system of interest that meets stakeholder needs and the requirements of the subsequent life cycle stages. It ends with delivery of blueprints for the system of interest, and potential prototypes. Papers III and IV include reviews of the development programs for the SEP armored modular vehicle and for the Visby-class corvette.

In the *production stage*, the system of interest is manufactured; in the *utilization stage* it is used in its operational environment; in the *support stage* it is maintained, and in the *retirement stage* it is taken out of service.

However, after design (in the development life cycle stage) 80% of the total life cycle cost has already been committed (INCOSE 2015, p.13). This is the reason why this thesis focuses on the first two life cycle stages. This is where good decision-making is of the greatest importance. The *Life Cycle Cost (LCC)* should be understood as the total cost of implementation and ownership of a system over its entire life (SEBoK 2016), i.e. including development and use etc.

A *stakeholder* in a system of interest is any person or organization that has a legitimate interest in the new system or capability made possible. Sponsors of the development and users are typical examples, as are agencies responsible for inspections etc. Their "expectations, needs, requirements, problems, issues and perceived risks and opportunities" (INCOSE 2015, p.279) are termed stakeholder needs, or simply *needs*.

The *system requirements* are derived from needs identified through the technical processes of systems engineering. These are fundamental to the development process.

They define "what the system needs to do, how well, and under what conditions, as required to meet project and design constraints" (INCOSE 2015, p.281). System requirements are the formal communicators of customer needs to the design organization and, hence, they form the core of the contract between procurer and contractor.

As system requirements are allocated to subsystems, and to lower level elements, during the design process, they are broken down into greater detail. However, it is important to maintain *traceability* from each lower level system requirement to the original needs because each requirement carries a price tag. Contradictory requirements do occur and have to be subjected to *trade-off* studies in order to find the best obtainable solution.

Both the *system architecture* and the *design* activities in the technical processes aim to enable creation of the solution required. System architecture is, however, more abstract and addresses the principles, concepts, properties and characteristics of the system of interest.

4.2 Survivability engineering

The survivability engineering discipline was developed in the naval and aerospace engineering communities (e.g. Ball & Calvano 1994; Ball 2003). From the perspective of this thesis, the field has been formalized by academics, of whom one of the more prominent is Robert E. Ball. He defines survivability as "the capability to avoid or withstand a man-made hostile environment". Because of the random nature of combat, survivability is usually measured as the probability of surviving an engagement, a mission or an entire campaign; as discussed in section 3.4 above.

4.2.1 Interdependent attributes

As stated in the introduction, use of this discipline is justified by the interdependent nature of attributes in military platforms, and the fact that survivability enhancement features might have undesired effects on other attributes - and vice versa. Here *attributes* should be understood as an observable characteristic or property of the system of interest (INCOSE 2015, p.6), such as the speed of a combat aircraft. Survivability engineering is thus *not* about building the most survivable aircraft - or ship, or other combat vehicle – possible. It is about building a cost-effective military system.

Ball illustrates this point in a simple analysis of a combat air support mission. The two MoEs considered are the number of friendly aircraft lost (survivability), and number of enemy tanks killed (offensive capability) in a campaign. The two MoPs considered are the Radar Cross Section (RCS) and its effect on survivability, and the amount of antitank ordnance carried. However, because low RCS requires weapons to be carried internally, the amount of ordnance carried is limited, more sorties have to be flown and there is a trade-off to be made. Thus, survivability enhancement measures can affect the offensive capability to such a degree that the cost in terms of killed aircraft is higher than it would be with less survivable aircraft. "Setting the survivability performance thresholds too high can be fatal to an acquisition program; setting them too low can be fatal to the aircraft in combat" (Ball 2003, p.pxxxv). Hence, trade-off studies at several system levels, using systems analysis with its inherent decision-making, are an important part of survivability engineering.

4.2.2 Survivability enhancement features

Returning to the "breaking the kill chain" concept (Sect.3.4.1), it is understood that survivability is improved if any of the probabilities in Equation 3-3 are reduced. From here on, any particular characteristic of the aircraft (platform) (be it specific equipment, shaping, materials, armaments or tactics) that reduces probabilities in the kill chain, is referred to as a *survivability enhancement feature*. Some typical examples are listed in Table 4-1 (Adapted from (Ball 2003, p.35)).

Table 4-1 Typical survivability enhancement features in combat aircraft survivability engineering.

Kill chain probability		**Survivability enhancement features**
Susceptibility reduction	**P_{A}**, (Threat Suppression)	tactics, precision guided munitions, mission planning systems, fighter escorts, anti-radiation weapons, self-defense missiles and guns
	$P_{D\|A}$, (Detection avoidance)	stand-off weapons, night-time capability, on-board electronic attack, stand-off electronic attack, *low signatures*, terrain following, chaff, threat warning, situational awareness, good target acquisition, mission planning systems, tactics
	$P_{L\|D}$, (Engagement avoidance)	stand-off weapons, on-board electronic attack, stand-off electronic attack, *low signatures*, good target acquisition, situational awareness, chaff and flares, threat warning, speed and altitude, mission planning systems
	$P_{I\|L}$, (Threat avoidance)	on-board electronic attack, *low signatures*, chaff and flares, threat warning, speed and altitude, maneuverability
	$P_{H\|I}$, (Hit avoidance)	*low signatures*, chaff and flares, maneuverability
Vul. Red.	$P_{K\|H}$, (Threat or hit tolerance)	Fire/explosion protection, self-repairing flight controls, redundant and separated hydraulics, armor etc.

From Table 4-1 two points of interest to the thesis should be made. Firstly, it is evident that survivability has to be viewed as a capability, since it is affected by both tactical and technical features. Secondly, a low signature affects several links in the kill-chain, because not only does it reduce the probability of detection, but it also reduces the probabilities of being engaged, intercepted or hit.

4.2.3 Finding a balanced design

So far reports of experiences from survivability engineering, including signature engineering, have mostly come from the combat aircraft community. The design objective can be summarized as finding a balance in system requirements, given interdependent attributes, and the pursuit of an effective weapon system.

The most important success factors of the survivability engineering process can be listed as follows (Ball 2003, pp.44–50, 174):

- Measurement of the system effectiveness of a combat aircraft in terms of offensive capability, availability and survivability,
- Evaluation of the design of a platform as a component in a mission system,
- Consideration of survivability by the design team at an early stage, because retrofitting survivability features usually adds unnecessary penalties to the design, e.g. weight or cost, and
- Continuous close cooperation by survivability engineers with designers, program managers and operators, where all are allowed real influence.

In the Case study (Papers III and IV) these points are revisited in a comparison of results from a study of the survivability engineering of a combat vehicle and a naval vessel.

4.3 Signature management

The aim of signature management is to reduce the contrast between the object of interest and its background. Lowering the signature of soldiers or platforms reduces their susceptibility to enemy actions, hence improving security through enhanced survivability of one's own forces (Sect.2.3). Technology used to accomplish signature management with this aim, is referred to as *Low Observable Technology (LOT)*. This thesis focuses specifically on efforts made during engineering of a platform, on the threat from electro-optical sensors and on spectral design technology. However, because both the Technology study and the Modeling study relate to radar sensors and signature reduction efforts at radio frequencies, this section also includes some background on these topics.

4.3.1 Contrast – the technical performance measure

Figure 4-2 illustrates the typical scene of interest in this thesis. An imaging sensor is used at a distance to discriminate between an object and its background. Given the definition (Sect.1.1), signature is a measure of contrast. Consequently, an optical sensor has to measure the difference between signals from the object and its background. A common measure of contrast is the difference in *luminance* (luminous power per unit solid angle per unit projected source area) originating from the object and its background respectively (Bohman 2003, p.76). In practice, the sensor measures the difference in *irradiance*, i.e. irradiated power per unit area (White 2012),

$$C = E_{obj} - E_{bgnd}\ [W/m2], \qquad Eq.\ 4\text{-}1$$

where E_{obj} is the irradiance originating from the object, and E_{bgnd} is the irradiance originating from the background. This is the contrast measure used for the infrared signature modeled in Papers V and VI.

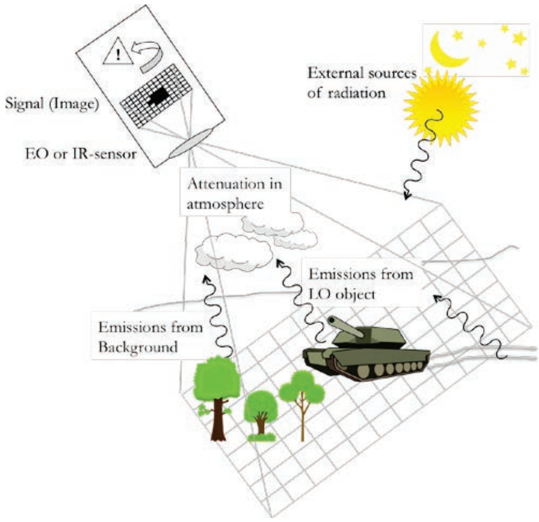

Figure 4-2 A typical scene with a sensor detecting an object at a distance.

However, it is possible to measure other contrasts with a suitable optical sensor (Bohman 2003, pp.76–86). *Gloss* and *color* are wavelength dependent and are examples of *spectral contrasts*. *Size*, *shape* and *orientation* are examples of so-called *spatial contrasts*. Finally, *temporal contrasts* detect movement or differences between images of a scene taken in sequence.

If the object is large enough, relative to the distance at which the signature is to be reduced, the object's *internal contrasts* also matter. A combat uniform, for example, typically comprises three different colors arranged in a pattern. Preferably, the colors are the statistically most common background colors in the area of operations, in order to reduce color contrast. However, the pattern also has to be chosen so that the internal *noise-level* of the object, as compiled by a sensor, is similar to that of the background. Noise-level comes under measures of spatial contrast.

The radiation emitted by an object in the scene in Figure 4-2 comprises both *reflected* radiation, originating from external sources such as the sun, moon or stars, and self-emitted radiation, so-called *thermal emittance*. The latter depends on the surface temperature and surface properties of the object. Consequently, contrasts, such as the difference in luminance between the object and its background, are bound to change during the course of the day, depending on changes in temperature, humidity and lighting conditions, etc. Before the radiation emitted is collected by the sensor, it is attenuated from *absorption* and *scattering* in the atmosphere (Driggers et al. 2012; Bohman 2003; Jacobs 2006). The physical processes discussed will be further elaborated in the next chapter, in relation to spectral design.

Given the inherent dependence on background, signature management and spectral design require a thorough analysis and characterization of backgrounds in the anticipated areas for military operations. For example, see work done by the Swedish Defence Research Agency, e.g. (Zdansky 2012; Kariis et al. 2013).

Papers III and IV report on lessons learned from signature management in the development of LO platforms, including the Technical Performance Measures (TPM) used in the signature evaluation of entire platforms. Paper I identifies the technical parameters that are most relevant to the spectral design of their surfaces.

4.3.2 Atmospheric windows

Figure 4-3 shows the wavelength dependent transmittance of the atmosphere and the spectra in which modern sensor systems operate (Jacobs 2006, p.xiv). For large parts of the electromagnetic spectrum the atmosphere is more or less opaque due to aerosol or molecular scattering, or absorption, which limit sensor range (Driggers, Ronald G.; Friedman, Melvin H.; Nichols 2012, chap.6). Other wavelength bands can be used as so-called windows, because the atmosphere does transmitt there. Consequently, the *sensitivity* of sensors is tuned to these wavelength bands in order to optimize range. For radio frequencies the atmosphere is almost completely transparent and hence suitable for such sensors as surveillance radars, with wavelengths ranging from centimeters to meters (Skolnik 2001, p.12). Given that this thesis focuses on reducing the optical signature of an object at a long distance from the sensor, the atmospheric windows define the wavelength bands of interest. The UV, VIS, NIR, SWIR, MWIR and LWIR atmospheric windows are indicated in the detailed diagram in Figure 4-3.

4.3.3 The sensor threat

The need for signature management is defined by the threat and, more specifically, by those sensors that alert an adversary. Sensors in the military domain are either used to collect data to support decision-making, or to guide weapons to targets. Military tasks such as surveillance, reconnaissance, navigation, early warning, fire con-

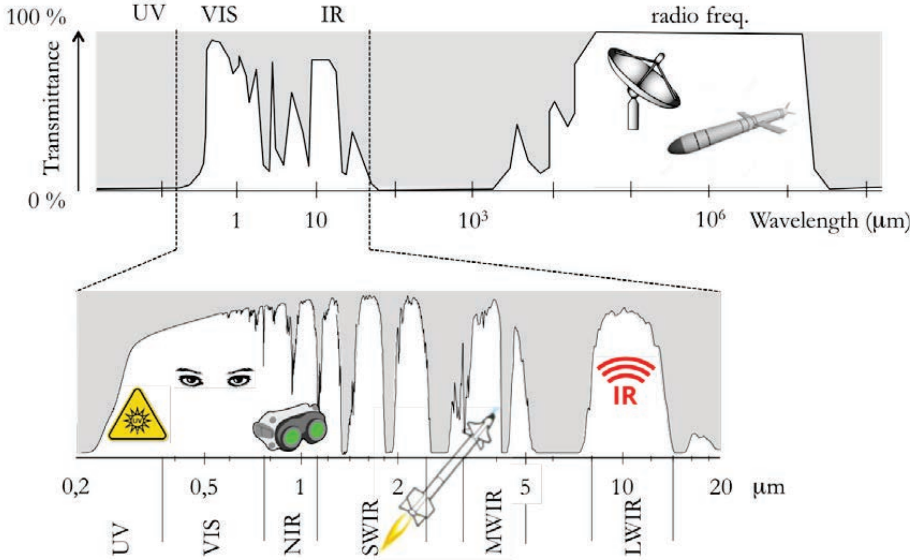

Figure 4-3 A diagram of the transmittance of the atmosphere to electromagnetic radiation. The optical part of the spectrum is highlighted. The respective spectra in which modern sensor systems operate are also indicated.

trol or tracking, place different demands on different sensor systems. Relevant MoPs at the technical system level are typically range, coverage, sensitivity, resolution and detection probability.

The demands on a sensor system often cause conflicting requirements and lead to compromises. Hence, to prioritize the need for LOT efforts, sensor systems are usually sorted into *primary sensor threats* and *secondary sensor threats* (Bohman 2003). Primary sensor threats have the capability to support *detection* while secondary sensor threats need guidance, but can be used for *classification, recognition* or *identification* of a target. Classification typically means distinguishing between a building and a vehicle; recognition means distinguishing between say, a truck and an infantry fighting vehicle, and identification means being able to determine the type and nationality of an infantry fighting vehicle. Rules of engagement based on the international laws of war require identification of an enemy target before engagement. In short, primary sensor threats aim to increase $P_{D|A}$ in the kill-chain, while secondary sensor threats aim to increase $P_{I|D}$. See Eq. 3-4.

A sensor is either *active* or *passive*. In the UV to SWIR wavelength band, sensors can detect an object by reflected sunshine, moonlight, starlight or sky-shine (Mahulikar et al. 2009). In the MWIR to LWIR wavelength band, a sensor can detect an object's (the target's) self-emitted thermal radiation (Jacobs 2006, chap.2). Hence, in the optical spectrum it is possible to use passive sensors (such as the eye, night vision goggles, or infrared cameras). In the RF wavelength band, on the other hand, radar sensors use actively emitted radiation to detect reflections off the target. The probability of detecting an active sensor is greater than that of detecting a passive one, because the actively emitted radiation can be used for locating or homing.

The *resolution* of a sensor is a measure of the smallest difference it can detect in the quantity that it is measuring. In the context of this thesis, it is an important measure of a sensor's ability to produce data for detection, classification, recognition or identification. An electro-optical imaging sensor, e.g. a digital camera, produces images of the scene on its focal plane array detector; see the illustration in Figure 4-4. The detector is comprised of an array of $N_H \cdot N_V$ detector elements. These elements are sensitive to photons at particular wavelength intervals, depending on the detector materials. For example, a b/w camera is a sensor where the detector elements are sensitive to photons in the 0.4-1.1 μm (VIS and NIR) wavelength interval. The photons received by each detector element are transformed into pixel signals, which are processed or presented to an operator on a monochrome display. The principle is the same in TIR (Driggers et al. 2012, chap.8). Electro-optical imaging sensors may have different modes or configurations for different tasks, e.g. a potential surveillance sensor will have a wider field-of-view (θ_H and θ_V angles in Figure 4-4), while that for a potential identification sensor will be narrower.

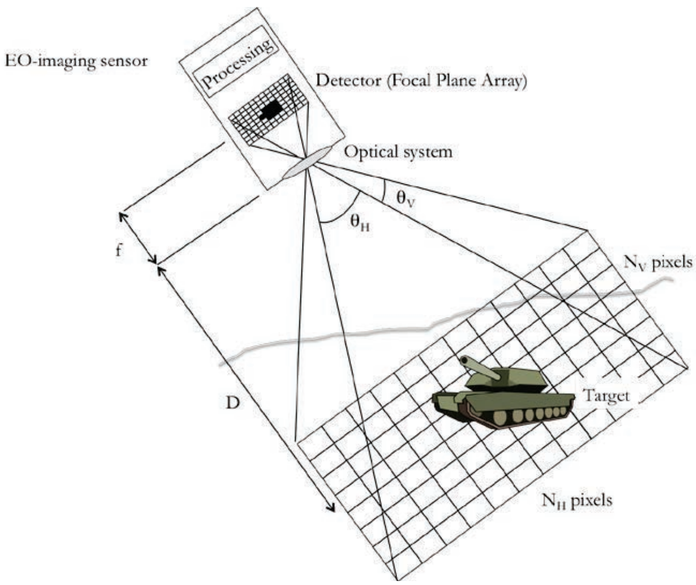

Figure 4-4 Illustration of an electro-optical imaging sensor viewing a ground target

According to the so-called Johnson criteria, the *spatial resolution* necessary for a human operating an infrared imaging system to identify say, a truck, is 8.0 pixels across its minimum dimension. The Johnson criteria for the recognition and identification of large numbers of targets were defined in the middle of the last century, with the support of field trials and human observers (Johnson 1958; Driggers et al. 2012).

The *spectral resolution* of a sensor is a measure of its ability to resolve features in the electromagnetic spectrum. Hence, with these sensors it is possible to distinguish between objects solely from spectral information. A digital color camera, for example, has detector elements sensitive to three different wavelength intervals in VIS: red (~0.7 μm), green (~0.55 μm) and blue (~0.4 μm). This very common type of sensor makes it possible to distinguish between say, a blue vehicle and a red vehicle. However, development is moving towards *multi-spectral* or *hyper spectral sensors*, able to resolve hundreds of wavelength bands across the optical spectrum (Hallberg et al. 2014, p.32 et seq). These sensors have the potential to produce unique spectral fingerprints of different surface materials. Hence, in principle it is possible to identify a target even if only one pixel of the object is in the line of sight, see the illustration in *Figure 4-5*. In the foreseeable future hyper spectral sensors are regarded as a rather exclusive threat, but if they start to appear on the battlefield in the future, they are expected to stretch signature management requirements for materiel (Bohman 2012, pp.64–65).

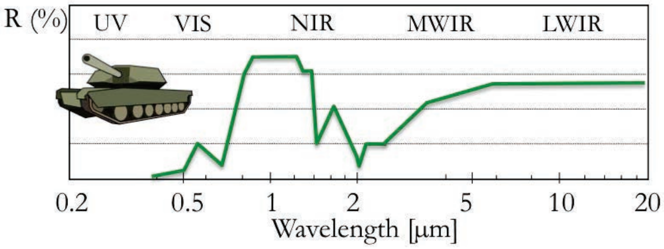

Figure 4-5 Illustration of the spectrally resolved emission of radiation by a fictitious target as recorded by a hyper spectral sensor.

A typical example of a sensor with *temporal resolution* is surveillance radar equipped with Moving Target Indication (MTI). It exploits the Doppler shift between the transmitted pulse and that received to detect a target radial motion towards, or away from, the radar (Skolnik 2001, chap.3). The use of MTI makes it is possible to filter out *clutter*, i.e. unwanted echoes from terrain, sea waves, clouds etc. For electro-optical imaging sensors, the methods are not that well established. However, by processing consecutive images of, for example, a camouflaged combat vehicle standing still at the edge of a forest, in principle, it is possible to detect the target simply because of the background vegetation moving in the wind. "The phenomenon could be described as Moving-Background-Indication"[3] (Lars Bohman, correspondence, 21-06-2016).

The theoretical maximum *detection range*, R_{max}, of a passive infrared sensor can be found using the equation (White 2012, chap.19):

$$R_{max} = \sqrt{I/E_{thr}}\ , \qquad \textit{Eq. 4-2}$$

where I is defined as the angular power density from the source [W/sr], and E_{thr} is the minimum detectable irradiance at the sensor [W/m^2].

The theoretical maximum detection range of a monostatic (both transmitting and receiving) radar can instead be found using (Skolnik 2001, chap.2)

$$R_{max} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right]^{1/4}, \qquad \textit{Eq. 4-3}$$

where P_t is the transmitted power [W], G is the antenna gain, λ is the wavelength [m], σ is the radar cross section (RCS) of the target [m^2], and S_{min} is the minimum detectable signal [W].

Lastly, the *false-alarm-rate* is an important characteristic of a sensor. The minimum detectable signal E_{thr} for an imaging electro-optical sensor (See Equation 5-2) is a system parameter tuned to balance the need for range with the probability of false targets (clutter). This threshold is determined for each task, i.e. separately for detec-

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[3] Lars Bohman, FOI (the Swedish Defence Research Agency), personal communication, June 2016

tion and identification (Jacobs 2006, p.21). The same is true for S_{min} in radar (See Eq. 5-3). When using spectral design for signature management purposes, the aim is to reduce the emitted signal from the target below E_{thr} or S_{min}.

In the Modeling study, reported in Papers V and VI, both radar and infrared imaging sensors are modeled as sensor threats to an attack aircraft.

4.3.4 Controlling signature in UV-VIS-NIR

If we assume measures have been taken to use no active emitters, such as headlights or taillights on a military platform, the information collected by a sensor in the UV-VIS-NIR part of the electro-magnetic spectrum originates from reflections. Consequently, the signal depends on the external source of radiation (e.g. the sun), on the size, shape and orientation of the reflecting surfaces in relation to the source and sensor, and on the reflecting properties of the surfaces. Therefore, signature management of a military platform in this part of the spectrum is largely about reducing its size (if possible), shaping, and using it wisely during operation. However, in common with all contrast measures in this part of the spectrum, signature management also involves controlling the reflective properties of the platforms surfaces. In the context of this thesis, this is achieved using spectral design, which is elaborated in chapter 5.

4.3.5 Controlling signature in TIR

When moving from the traditional UV-VIS-NIR region of interest to TIR, the self-emission component of radiation emitted from a surface, the thermal *emittance*, becomes important. Its spectral distribution and magnitude are essentially a function of the surface temperature, T, and the *emissivity*, $\varepsilon(\lambda)$. The total emittance within a spectral band can be expressed as (Driggers et al. 2012, p.126):

$$E(T) = \int_{\lambda_2}^{\lambda_1} \varepsilon(\lambda) \frac{c_1}{\lambda^5} \frac{1}{\left[e^{\frac{c_2}{\lambda T}} - 1\right]} \, d\lambda \qquad [\mathrm{W/m^2}], \qquad \textit{Eq. 4-4}$$

where c_1 and c_2 are Planck´s radiation constants; $c_1 = 3{,}7418 \times 10^8$ Wμm^4/m^2 and $c_2 = 1{,}4388 \times 10^4$ μm K.

The emissivity describes the surface emission characteristics. For perfect radiators, so-called *blackbodies* (e.g. the sun), the emissivity = 1. For real bodies the emissivity varies with surface properties and temperature. In practice, many materials can be approximated to so-called *grey bodies*, with constant emissivity, $\varepsilon < 1$, in TIR (Bohman 2003, p.134). Metal surfaces are typically highly reflective in IR and $\varepsilon < 0.05$, while for most naturally occurring materials $\varepsilon > 0.50$.

However, the thermal radiation leaving the surface of a real object is always the sum of self-emission and radiation reflected from the objects environment. Since an electro-optical imaging sensor cannot distinguish between the sources of radiation, the signal that can be collected is called the *apparent* emittance and is written:

$$E_{ap} = \int_{\lambda_1}^{\lambda_2} [\varepsilon(\lambda)E(\lambda, T_{st}) + \rho_l E(\lambda, T_{ae})]d\lambda, \tag{Eq. 4-5}$$

where ρ_l is the reflection coefficient for the long wave infrared interval of interest, λ_1 to λ_2, T_{st} is the surface temperature of the target, and T_{ae} is the apparent temperature of the environment (Jacobs 2006, p.11).

However, a useful thermal signature measure has to take the atmospheric transmission in the range of interest, $\tau(\lambda,R)$, into consideration. Thus, the thermal signature can be written:

$$\Delta E_{ap} = \int_{\lambda_1}^{\lambda_2} \tau(\lambda, R)[E_{ap}(\lambda, T_{st}) - E_{ap}(\lambda, T_b)]d\lambda, \tag{Eq. 4-6}$$

where T_b is the temperature of the background (Jacobs 2006, p.14).

In conclusion, to minimize signature in the thermal infrared region, firstly, basically two technical variables must be controlled: the surface temperature and the surface properties of the object. In signature management, these are tuned to match the apparent emittance of the target with that of its background. Secondly, the acceptable tactical detection range determines the acceptable residual contrast.

Controlling the surface temperature of a platform is largely about managing heat flows to and from the surfaces. Because thermal energy is transported in three ways, - conduction, convection or radiation - measures are preferably taken during construction using isolation, ventilation and shielding technologies. Figure 4-6 is a principle diagram illustrating heat flows, denoted *Q*, and possible measures to reduce them. The theory of heat and mass transfer from a signature perspective is thoroughly covered by, for example, Bohman (2003) and Jacobs (2006).

Controlling the thermal signature by tuning a surface's optical properties is achieved using spectral design techniques, which are further elaborated in chapter 5. Figure 4-7 is used here to illustrate the concept. It comprises two pictures of the same can

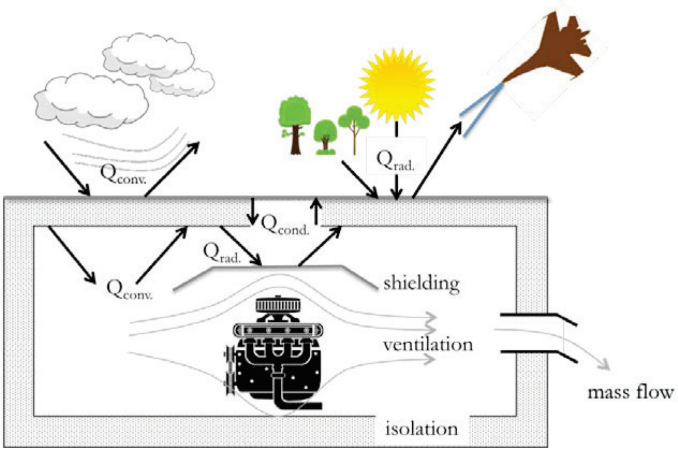

Figure 4-6 Illustration of principal heat flows inside a military platform, and heat exchanges with the environment to and from the surface of the platform's hull (Bohman 2003, p.90; Jacobs 2006, p.30).

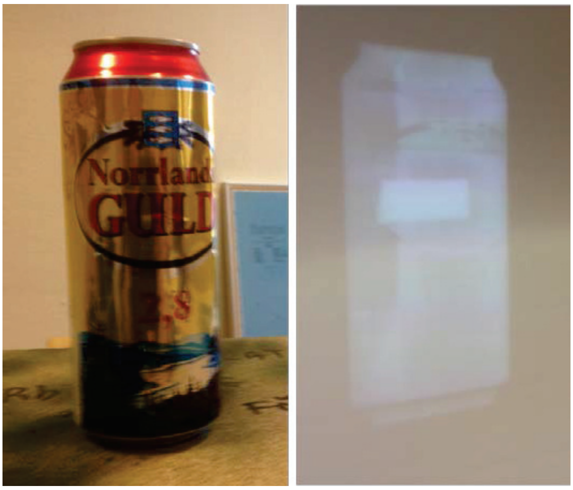

Figure 4-7 Two pictures of the same can filled with hot water. To the left a picture taken with a color camera. To the right a picture taken using the LWIR sensor of the Bill missile system (RBS 56). A small piece of transparent household tape is covering the brand name. Photo: the author.

filled with hot water.

The picture on the left in Figure 4-7 was taken using an ordinary color camera. The picture on the right was taken using the sight of a Bill missile system (RBS 56). The sight is sensitive in the LWIR wavelength band, 8–12 µm. A small piece of household tape was put on the can, covering some of the text. It is transparent and cannot be detected in the left-hand picture, which only covers the visible part of the spectrum. However, in the right-hand picture there is considerable contrast between the tape and the bare surface of the can. Although the surface temperature can be expected to be the same for the entire can, the tape obviously emits with much greater intensity than the aluminum surface. This is due to the difference in surface emissivity, probably below 0.1 for aluminum, but around 0.9 for plastic tape. Evidently, thermal signature is greatly affected by surface properties and hence can be influenced through spectral design.

In conclusion, thermal emissions from a surface depend on both the temperature of the surface and the emissivity of the surface. Measures for controlling the temperature, and hence creating the best possible conditions for spectral design, have to be taken during basic construction of a platform. These engineering principles are discussed in the Case study in Papers III and IV.

4.3.6 Controlling radar signature

The radar signature is usually expressed using a target's radar cross section, RCS. See Eq. 5-3. The basic monostatic definition is "the ratio of the scattered power to the incident power in the direction of the observer at infinity" (Lynch 2004, p.34).

In the monostatic case, convenient for this principle discussion, the aim is to avoid backscatter towards the transmitting radar. Consequently, the most important means for signature reduction is shaping, e.g. avoiding surface normals, edge normals, dihedrals and visible cavities in anticipated threat directions (Lynch 2004, pp.35–36).

In order to reduce the RCS further, it is also possible to exploit radar absorbing materials (RAM) (Saville 2005). There are usually drawbacks in usability or maintenance when using these materials (Cho et al. 2015), but if applied on critical parts of the construction they can reduce radar signature considerably (Lynch 2004, p.45). However, in order for absorption to take place the incident electromagnetic field must penetrate the material without scattering at the surface (Lynch 2004, p.45).This has implications for spectral design. A thin metallic conducting film, deposited on areas with RAM to reduce the optical signature, would ruin efforts to reduce the radar signature.

5

THEORY: TECHNOLOGY LEVEL – SPECTRAL DESIGN

Spectral design is "the ability to create a desired spectral optical response from a surface, which benefits the application of interest by choosing suitable materials and structures" (Sect.1.1).

In the previous chapter we learned that signature management in the optical wavelength region is largely about controlling properties such as the shape, size and surface temperature of the object of interest (a military platform). We also understand, from the discussion about survivability engineering, that these properties in turn are products of compromises during the systems engineering process. However, in the optical part of the electromagnetic spectrum, surface properties also have a great influence on a platform's signature. This is why spectral design is an interesting option for reducing the residual optical signature to acceptable levels, particularly if it can be assumed that a platform's surfaces only have a marginal effect on functional performance. Despite important progress in materials science in recent decades, the sensor threat in military theaters in the near future makes this ambition challenging, as discussed in the introduction. In principle, it requires the signature of a military platform to be reduced multi-spectrally, from UV to LWIR. See the illustration in Figure 5-1.

The Technology study, Paper I, comprises a review of potentially useful techniques and materials, and identifies those characteristics of a surface that must be controlled, given advances in sensor technology. Furthermore, the Modeling study, in Papers V and VI, presents proposed models of the optical response of the surface of an aircraft. This chapter is an introduction to central concepts, and the physical phenomena exploited, in controlling optical signatures using spectral design. The chapter ends with a short overview of possible applications in military materiel. The purpose is to provide the background necessary for summarizing the results of the studies mentioned above (Ch.7).

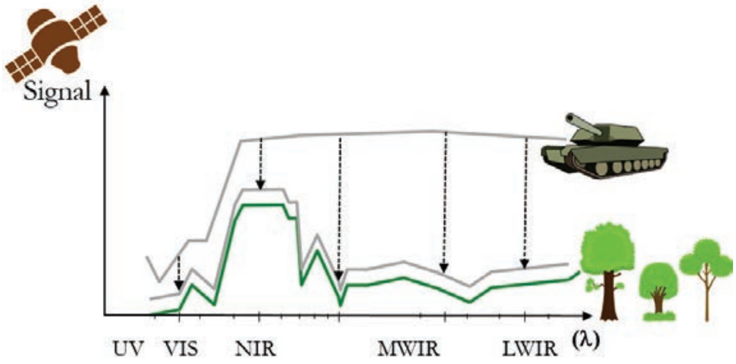

Figure 5-1 An illustration of the effect of using spectral design to reduce the signature of a platform multi-spectrally, from UV to LWIR. The signature should be understood as the contrast between platform and background, i.e. the difference between the respective signals picked up by a multi-spectral sensor. In principle, the signal originates from any characteristic that can be detected, e.g. the irradiance. λ denotes wavelength.

5.1 The optical constants of a material

Light is electromagnetic radiation with wavelengths within the visible region of the electromagnetic spectrum. The interaction between electromagnetic radiation and matter is described by Maxwell's equations (Born & Wolf 1970, p.1). For optical wavelengths the magnetic interaction is considered negligible and one solution obtained is the *transverse monochromatic plane wave* (See e.g. (Arwin 2014, pp.94–95))

$$\boldsymbol{E}(z,t) = \boldsymbol{E_0}\, e^{-\frac{2\pi kz}{\lambda}}\, e^{i\left(\frac{2\pi nz}{\lambda}-\omega t\right)}, \qquad \text{Eq. 5-1}$$

with wavelength λ, propagating along the z-axis. The square of the amplitude, $|E|^2$, is proportional to the *intensity* of the radiation and is easily measured. The *refractive index*, n, and the *extinction coefficient, k,* are characteristics of the medium and are referred to as its *optical constants* - although they both vary with wavelength. The first exponential function has a real exponent and damps the wave as it propagates through the medium. This is why k is used as a measure of attenuation, or absorption. The second exponential function produces a phase shift, if compared to the same wave traveling the same distance in a vacuum.

Note that it is sometimes convenient to compound the optical constants in the so-called *complex refractive index*, $N = n + ik$.

In a *dielectric* (non-absorbing) material, the extinction coefficient is negligible.

To conclude, the optical constants of a material have a great influence on the application of spectral design. Choosing materials with optical characteristics suitable for the application is key. The licentiate thesis covers the characteristics of thin films of titanium- and zirconium nitride, and how to determine the optical constants of the respective materials (Andersson 1993).

5.2 Polarization

If the x and y components of the electric field vector of a light wave propagating in a z direction, $\boldsymbol{E}(z,t)$, are completely correlated the light is said to be totally *polarized*. If there is no correlation, the light is said to be *unpolarized*, like radiation originating from the sun or ordinary lamps (Arwin 2014). Polarization features arise from the geometrical orientation, shape, shading and roughness of an object surface. In general, man-made objects with smooth surfaces have more defined polarization signatures than natural objects, and tend to take on a polarized component in reflected or emitted radiation (Bergström et al. 2012). The ratio of the intensity of polarized light to the total intensity of light radiated from a surface, is called the *Degree of Polarization* (DoP) (Arwin 2014). Paper I proposed low DoP as one of the technical performance measures for materials and structures suitable for signature management purposes.

5.3 Reflectance and transmittance

If Maxwell´s equations are used to solve the boundary problem of a propagating wave at a smooth surface between two media, the Fresnel reflection and transmission coefficients are obtained (Born & Wolf 1970, p.40),

$$r_p = \frac{N_1 \cos(\theta_i) - N_0 \cos(\theta_t)}{N_1 \cos(\theta_i) + N_0 \cos(\theta_t)}, \; r_s = \frac{N_0 \cos(\theta_i) - N_1 \cos(\theta_t)}{N_0 \cos(\theta_i) + N_1 \cos(\theta_t)} \text{ and} \qquad \text{Eq. 5-2}$$

$$t_p = \frac{2N_0\, cos(\theta_i)}{N_1\, cos(\theta_i) + N_0\, cos(\theta_t)}, \; t_s = \frac{2N_0\, cos(\theta_i)}{N_0\, cos(\theta_i) + N_1\, cos(\theta_t)}, \qquad \text{Eq. 5-3}$$

where r_p and r_s are the reflection coefficients of light polarized parallel to and perpendicular to the plane of incidence, respectively. The angle of incidence to the surface normal is denoted θ_i (The angle of reflection $\theta_r = \theta_i$ in Figure 5-2 a) and the angle to the normal for refracted, transmitted, light is denoted θ_t. The Fresnel expressions show the relationship between the observable *reflectance* of a surface, $R = \boldsymbol{r} \cdot \boldsymbol{r}^*$, and its optical properties, where N_1, for example, is the complex refractive index of a coating material and N_0 is that of the ambient air. Similarly, the *transmittance,* $T = \boldsymbol{t} \cdot \boldsymbol{t}^*(N_1/N_0)$, can be obtained from the ratio of transmitted power to incident power.

Intuitively, the reflective properties of a surface are important because reflected light is the reason we human beings see objects (that do not actively emit radiation themselves) with our eyes. One of the technical performance measures proposed in Paper I is *spectrally selective reflectance.*

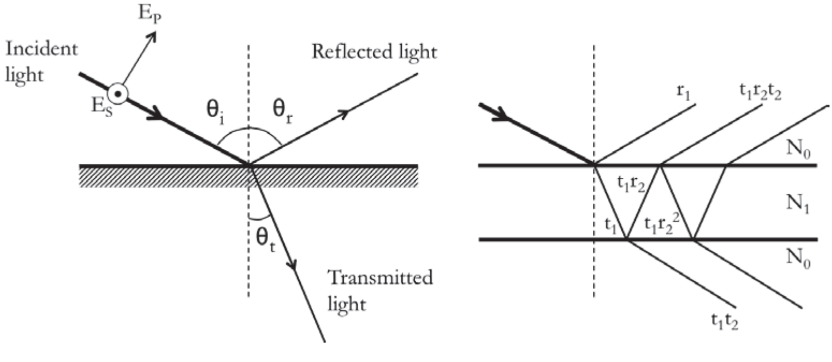

Figure 5-2 a) An electromagnetic plane wave, with components polarized parallel (P) and perpendicular (S) to the plane of incidence, reflected and transmitted at a smooth boundary. b) Multiple reflections in a thin film.

5.4 Interference

In the case of a thin film, i.e. when the film thickness is comparable to the wavelength of the light, there will be two boundaries to consider and hence multiple reflections. See Figure 5-2 b. Part of the light transmitted through the first boundary will be reflected at the second, and so forth. In summing up these contributions one will have to consider their phase. This phenomenon is called *interference*. If the contributions to the light interfere destructively, the waves will be canceled out, and if they interfere constructively, they will enhance the reflectance. For example, when designing anti-reflection coatings using a thin film of a dielectric (often an oxide), the physical thickness, d, is chosen so that the optical thickness, $d \cdot \lambda$ is a quarter of a wavelength. This will result in destructive interference, and if the extinction coefficient in both the thin film and the substrate is negligible, the reflectance at this particular wavelength will be zero.

Techniques exploiting interference in applications of spectral design are described in Paper I and in the licentiate thesis (Andersson 1993; Andersson et al. 1994).

5.5 Photonic crystals (PhC)

If the periodic structure is developed from the 1-dimensional (1-D) case of a multilayer coating (above), to 2-D or 3-D, the result is called a Photonic Crystal (PhC) (Yablonovitch 1987; John 1987; Prather et al. 2009). Depending on the optical properties of the two materials involved and the periodicity of the structure, the propagation of light within a certain electromagnetic wavelength band is prohibited. A so-called *band-gap* appears. Thus, the material becomes a perfect reflector in this part of the spectrum. Hence, by using the right combination of dielectric materials in suitable structures, it is theoretically possible to create materials that are reflective in a wavelength band of choice, but which transmit in all other parts of the spectrum. In addition, if the structure is 3-D, the angle of incident light is not an issue. Academics believe that developments in PhC will benefit greatly from production techniques used in the electronics industry (Prather et al. 2009).

5.6 Polaritonic materials

There are materials that exhibit forbidden band-gaps similar to PhCs, which do not originate from interference. In some materials, light of specific wavelengths can cause lattice vibrations, called *polaritons*. The optical consequence is an interval of high reflectance, known as the *reststrahlen band* or the *polaritonic bandgap,* that is characteristic of the bulk material (Sigalas et al. 1994). Sigalas et al. studied GaAs, but in Paper I, other materials more suitable to signature management applications, are mentioned.

5.7 Absorptance

The fraction of radiant flux neither reflected nor transmitted is absorbed in the medium, and is usually transformed into heat. This fraction, A, is called *absorptance* and the conservation of energy requires that

$$R(\lambda) + T(\lambda) + A(\lambda) = 1. \qquad \text{Eq. 5-4}$$

5.8 Scattering

Radiation (light) reflected from a smooth mirror-like surface is specular, i.e. the angle of reflection is the same as the angle of incidence, as in Figure 5-2 a ($\theta_r = \theta_i$). Light reflected from a rough surface is *diffuse*, i.e. scattered in all directions. In a signature management context, the former surface is denoted *glossy* and the latter as *low gloss*.

A perfectly diffuse surface, a *lambertian* surface, scatters with equal intensity in all directions, regardless of angle of incident light. See the scatterer furthest left in Figure 5-3. In Papers V and VI the aircraft skin is modeled as a lambertian surface.

When the wavelength of incident radiation is the same size as the scattering particle, the interaction is described as *Mie* scattering (Born & Wolf 1970, p.652-; Hallberg et al. 2014, p.16-). The direction of scattering is primarily forward. Solar scattering in mist, or clouds, are illustrative examples.

Scattering against particles considerably smaller than the wavelength of the light (typically less than a tenth) is described by *Rayleigh scattering* (Born & Wolf 1970, p.652-; Hallberg et al. 2014, p.16-). Backscattering is significant and the attenuation by scattering is proportional to $1/\lambda^4$. The Rayleigh scattering phenomenon can, for example, be used to explain the blue color of the sky and the red color of the sunset. In the former, the short blue wavelengths are scattered heavily as sunlight passes through the atmosphere; in the latter, primarily the long red wavelengths pass through the thick atmosphere to the observer as the sun is close to the horizon. Scattering phenomena are used in this thesis when discussing the attenuation of optical wavelengths in the atmosphere or the properties of paints; see Papers I, V and VI.

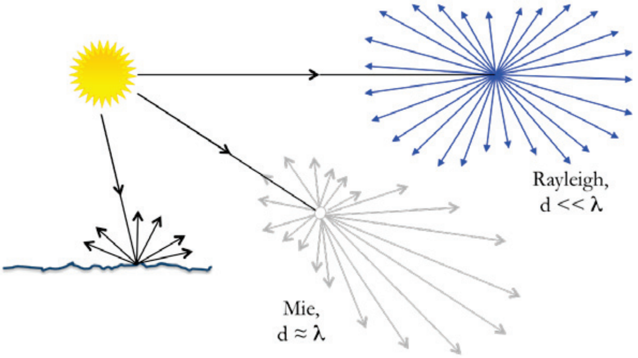

Figure 5-3. Illustration of scattering phenomena: diffuse scattering from a rough surface, Mie scattering from a spherical particle with diameter approximately the same size as the wavelength, and Rayleigh scattering from a particle much smaller than the wavelength of incident light.

5.9 Emittance and emissivity

The emissivity, $\varepsilon(\lambda)$, describes a surface's emission characteristics, as discussed in section 4.3.5. For real bodies the emissivity varies with materials and coatings, but also with structure and temperature. The emissivity equals the absorptance according to Kirchhoff´s law of thermal radiation and, for opaque materials, the following expression can be obtained from Equation 5-4:

$$\varepsilon(\lambda) = 1 - R(\lambda). \qquad \textit{Eq. 5-5}$$

Thus, the emissivity of a material can be measured indirectly by measuring the reflectance. In practice, many materials are approximated as gray bodies (Sect.4.3.5).

5.10 Applications in military materiel

The most common means for reducing the signature of military materiel is to apply suitable paint. Paint coatings generally consist of pigments and a binder. The optical response is the sum of several phenomena (Wake & Brady 1993; Hallberg et al. 2005); see Figure 5-4.

The incident light is either, absorbed in the coating, reflected at the binder boundaries, transmitted into the coated material, or scattered through reflection at the pigment boundaries. Part of the optical response from the surface is also due to thermal emissions.

In spectral design these phenomena are manipulated. Transmittance and reflection at the binder boundaries are affected by the choice of binder materials, usually a resin or a polymer. However, the main purpose of the binder is to provide adhesion to the coated surface, to protect the pigments and preserve their optical properties. Generally, the optical response is tuned by controlling scattering, reflection and absorption from pigments within the coating. Hence, in an ideal case, the desired multispectral response is obtained by mixing pigments of suitable size, shape and materials. Consequently, the binder's absorption should be as low as possible throughout the wavelength region of interest. Emission from the surface due to backscatter will

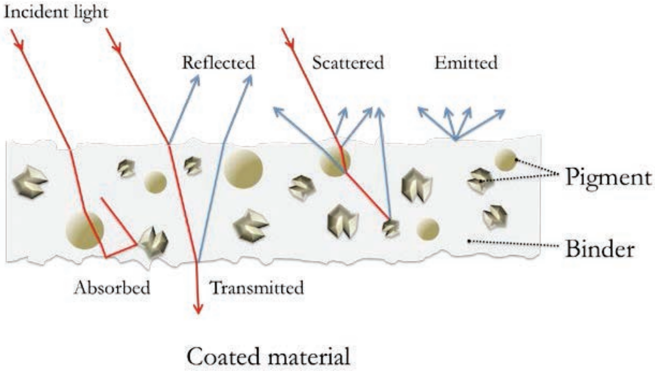

Figure 5-4 Illustration of optical processes in a paint coating, which together create the optical response of a painted surface.

increase if materials are chosen whereby the ratio of the refractive index of the particles to that of the binder increases.

Designing and applying paint coatings is a commonly used technique for spectral design, because it is relatively easy to apply, protective properties can be built in and it is fairly cheap. However, as requirements extend to thermal infrared wavelengths, there are challenges. A typical requirement is to reduce the thermal signature of a platform that is warmer than its background. Part of the solution is to apply low emissive paint, thereby lowering the apparent temperature contrast. Traditional organic and inorganic pigments used to damp reflectance in VIS cannot be used, since they also absorb TIR and thus cause high emissivity (Wake & Brady 1993).

For example, if a coating comprising multiple layers of thin films, of suitable materials and thicknesses, is applied to a smooth substrate, it is also possible to exploit the interference (Sect.5.4) phenomenon for spectral design purposes. In my earlier research (Andersson et al. 1992; Veszelei et al. 1994; Veszelei et al. 1993; Andersson et al. 1994), for example, the application was to design heat mirror coatings for window glazing in warm climates. In order to reduce the need for air-conditioning, only the visible wavelengths of the solar radiation should be transmitted, while all other wavelengths should be reflected. Hallberg et al. (Hallberg et al. 2005) report having used this technique to tailor the spectral reflectivity of pigments in low emissive paints for camouflage purposes in the infrared wavelength region. The metal-based multilayers were broken down into pigments and applied in a binder.

Hence, spectrally designed materials can be used as pigments to be applied in paints. There are also other applications. Pigments can be melted into, or coated onto, fibers used in the fabric of combat clothing; materials can be applied in structured coatings directly onto a protected surface; spectral designs can be applied in decals or on panels, which in turn are mounted on the protected surface, etc. The pictures in Figure 5-6 and Figure 5-5 show examples of spectrally designed products used in camouflage applications in the field.

Figure 5-5 Combat vehicles concealed with camouflage nets and soldiers in combat uniforms during a Swedish army exercise in 2015. The camouflage paint on the vehicles, the nets and the uniforms are all examples of spectral design applied to reduce signature. Note that in this picture we can only assess the result in the visible wavelength spectrum since the photographer used a common color camera. Photo: Anna Norén, Swedish Armed Forces.

Figure 5-6 Main battle tank during a Mobile Camouflage System (MCS) field trial. Photo: Mats Carlsson, Swedish Armed Forces.

6

RESEARCH METHODS

The purpose of this chapter is to describe the choice of research methods for the different studies in the thesis, and their consequences for the interpretation of results.

The systems approach described in the introduction (sect. 1.3) was chosen to enable analysis of the military system level, the technical system level and the technology level parts of the research problem separately, but with clearly recognized relationships linking them together. The overall aim is to develop and demonstrate a valid method for assessing the military utility of spectral design, and a relevant and useful definition of the key concepts, that assists decision-making in the systems engineering of LO military platforms.

The research design presented in the introduction (Sect.1.4) takes advantage of being able to address the four research sub-questions in different studies, choosing methods suitable for each study.

6.1 Systematic literature review (Q1)

6.1.1 Aim and rationale

In the Technology study (Paper I), a systematic literature review method was chosen with the aim identifying: 1) relevant technical variables affecting signature management, and, 2) tentative techniques and materials for spectral design. The difference between a systematic review and any traditional literature review is simply transparency regarding how decisions about the selection of sources are made, and how the search is conducted (Denscombe 2014, chap.9). The benefits are reduced potential for bias and increased reproducibility.

6.1.2 Possible consequences

One obvious limitation to the method is that unpublished research evidence will not be included (Denscombe 2014, chap.9). Thus, the method works best for research areas that have already attracted a lot of attention. Another challenge is limiting the scope of the review without missing important results.

6.1.3 Approach

The technical parameters were derived from an analysis of the sensitivity of potential sensor threats at tactical distances. Hence, the analysis was based on the logic that only those properties of emitted radiation from an object that can be detected by sensors must be controlled using spectral design. Potential sensor threats were identified using a report on the development and proliferation of contemporary sensors for ground targets issued by the Swedish Defence Research Agency (Bohman 2012).

The technical parameters identified were then used in the second step to form an indicator instrument to probe research databases. The uncertainties introduced by relying on one source for the sensor threat were assessed to be acceptable for the technology study because the overarching goal is methodological. The literature review method allowed probing of civilian progress as well as military progress, but had to be limited in scope. Articles were filtered in several steps, first by title, then by abstract. For some research areas, review articles were used in order to limit the need to go further back in time.

The literature review method used is described in detail in Paper I, including keyword-patterns for database searches, accessed databases, and filtering criteria. The validity of the approach and the reliability of the Technology study are discussed in section 7.1.4.

6.2 Concept analysis (Q2)

6.2.1 Aim and rationale

In the Concept development study (Paper II) the aim was to develop a concept for military utility, suitable for technology assessments, using the systems approach model and MOR. The approach chosen is generally called *concept analysis*, a process where the characteristics of a concept, and its relationships with other relevant concepts, are clarified. There are two fundamentally different approaches (Goertz 2006). The first and traditional type aims to capture how a concept is used in practice. The other approach focuses on the phenomenon of interest, i.e. first, a useful concept is developed - and then it is labeled. Given the objective described above, we chose the second approach. The rationale was that the aim is not to understand how other academics use the term military utility, but to develop a concept useful in the context defined by the problem. The specific method applied supports both the capture of specific phenomena and of reliable measurements (Goertz 2006; Goertz 2012).

6.2.2 Possible consequences

One disadvantage of choosing a method that focuses on the construct of a useful concept, rather than semantics, is that there might be a discrepancy between the resulting definition and how the term is usually perceived. Another disadvantage, of quantifiable concepts, is the well-known risk of choosing indicators simply because they are measurable, and not because they capture the phenomenon. A third disadvantage of the method described, as it relies on a large group of practitioners working in the problem domain, is the foreseeable risk of ending up with a consensus solution – which is of little real use to anyone.

6.2.3 Approach

The analysis process used, following Goertz’ guidelines (2006), is divided into three phases. The first phase is ontological in that it focuses on what constitutes the phenomenon of interest. The second phase asserts causality by identifying those attributes of the phenomenon central to forming hypotheses or explanations. The third phase involves an empirical analysis of the phenomenon and an operationalization of the attributes identified. The resulting concept is a multi-level structure, involving at least three levels, with a clear declaration of inter-level relationships. The first and secondary levels constitute the theory of the concept, while the lower levels constitute links to data collection. In our application of the method, the analysis was conducted in a series of seminars attended by teachers, officers and scientists well acquainted with the phenomenon of interest. In order to mitigate foreseeable weaknesses in the method, we first included a literature search with the aim of adhering to the use of related terms in the military and systems engineering domain. Secondly, we chose not to include explicitly the use of specific indicators in the concept, but instead made the selection of indicators part of problem assessment. Thirdly, in order to avoid the down side of consensus solutions, the chairman of the Concept development study (the author of this thesis) was given the final say. The applicability of the concept was validated in a comparison with a decision-situation from a 2008 case of the procurement of Swedish platforms.

The detailed application of the method used to produce the proposed military utility concept is presented in Paper II. However, the final phase of the formation of the concept has only been completed in connection with the modeling activity, because it comprises the choice of indicators. One example is presented in Papers V and VI. The validity of the approach and the reliability of the Concept development study are discussed in section 7.2.2.

6.3 Military systems modeling and simulation (Q3)

6.3.1 Aim and rationale

In the Modeling study (Papers V and VI) the aim was to demonstrate how the optical properties of a spectrally designed platform surface (Paper I) can be quantitatively linked to the proposed concept of military utility (Paper II), while using the so-called Ladder model as a conceptual template for the applied model (Paper I). The purpose was to answer sub question three, and hence show that effective evaluation of spectral design is possible. Choosing a MOR approach is justified by its central role in systems analysis and systems engineering (Sec.1.5). The general merits and limitations of a MOR approach were discussed in chapter 3.

6.3.2 Possible consequences

The literature highlights a few challenges to be aware of when assessing the validity of a warfare modeling activity. Firstly, as discussed in some depth in section 3.6, a real combat situation will always differ from its model, because of the inherent complexity and uncertainties of military situations. Therefore, it is important, somehow, to validate that the model is good enough for its purpose.

Secondly, a multi-stage model, like that used in the Modeling study, requires that at least the outer attributes of the most detailed objects modeled are well understood and described (Holm 2007, p.10).

Thirdly, from a complexity or cost-effectiveness viewpoint, it is often tempting to exchange stochastic variables with their expected values. In some situations however, the results might be misleading (Bracken et al. 1995, p.2; Washburn & Kress

2009, p.5).

Fourthly, when using stochastic models it is convenient to assume that events are independent. Often this is not a bad assumption about the real world, and the probability theory is simpler. However, when modeled events are not independent, the results might be misleading (Washburn & Kress 2009, p.6).

Lastly, when encountering a poorly understood or controversial phenomenon during modeling, the easiest solution might be to ignore it. Washburn & Kress call this the *Ostrich effect* (2009, p.8). Whether or not any omissions may be harmless must be taken into consideration.

6.3.3 Approach

The Ladder model, proposed in the Technology study, is a developed version of the systems approach model, which specifically describes the relationship between the spectral design technology and military utility. It is presented in detail in section 7.1.1 and Figure 7-1. The Ladder model makes the system levels and the relevant inter-level parameters explicit. It also integrates the view of capabilities as systems discussed in chapter two, thereby incorporating a new capability system level between the technical system and military mission system levels. The expected advantages of using the Ladder model as a template when analyzing a problem are, firstly, that it highlights the quantitative link between technical parameters at the technology level and mission measures of effectiveness at the top system level, and secondly, that the interfaces between system levels become explicit. In the context of systems engineering, this is beneficial because it assists traceability and coherence in requirements analysis, and it clarifies design responsibilities.

The duel between an attack aircraft and a ground based air defense system was chosen as a demonstration. The case is relevant for at least two reasons: there is a debate about the value of stealth, given the cost of reducing radar signature, and there seems to be a development in the use of LWIR sensors to complement radars in air defense. This raises the question of the military utility of reducing the aircraft's LWIR signature using spectral design.

The analysis scheme chosen is similar to the Soban and Mavris framework for survivability assessment and probabilistic modeling (Sec.3.5). There are four phases to the scheme, the first three of which are part of a modeling activity. Given the problem, the first phase comprised establishing reference baseline features and performance for the modeled attack aircraft, choosing input and output variables for all modeled technical systems and the military mission model, and defining a suitable scenario with a relevant task and relevant tactical strike options. Input was gathered by interviewing military subject matter experts. In the second phase, key decision nodes in the mission system, and how they were to be modeled, were defined for the strike options studied in the scenario. Operator decisions were modeled according to crude doctrines. In the third phase, a simulation environment was established. This included the identification of physics based response models for the different system level components and their creation in Matlab™. In the fourth and final phase, the model was used and the results were analyzed.

The modeling is the primary result of the Modeling study and is described in more detail in section 7.3.1. The validity of the approach and the reliability of the Modeling study are discussed in section 7.3.2.

6.4 Case study research (Q4)

6.4.1 Aim and rationale

In the Case study (Papers III and IV), the aim was to identify lessons as input to a discussion on how to use military utility assessments of signature reduction efforts to support decision-making in the systems engineering process (Q4). Because the literature on the topic is scarce, it was necessary to do an empirical study. The systems engineering processes of two LO platform development projects were reviewed using a case study research method. The method was chosen because it is commonly used for studying processes, an in-depth study of just one or a few particular cases can be used as a basis for generalization, and because it supports data collection using multiple methods (Yin 2013; Denscombe 2014).

6.4.2 Possible consequences

There are a few general, well-known drawbacks to the method (Denscombe 2014; Yin 2013). Firstly, case studies tend to be vulnerable to criticism of the credibility of any generalizations drawn from their findings. One remedy is to carefully demonstrate similarities or contrasts with other cases of the same type. Secondly, in some applications it can be difficult to define the boundaries of the cases included and, hence, to decide which sources of data to include or exclude. Thirdly, the use of qualitative data and interpretive methods might draw criticism from academics using quantitative data and statistics. Denscombe states that this can be countered with "careful attention to detail and rigor in the use of the approach" (2014, chap.64).

6.4.3 Approach

In the Case study in this thesis, we used interviews of key personnel for data collection, complemented by document reviews.

The two cases, the SEP combat vehicle and the Visby class corvette, were chosen on the basis of three criteria: 1) the prominent role played by signature management in the respective development programs, 2) the fact that the resulting designs are considered balanced, and 3) sufficient data could be collected. The object of study was limited in time and scope to the development of a design and the relationship between government and contractor. In order to support generalization, possible lessons were filtered from the data collected, using an analysis instrument based on the fundamental concepts of systems engineering (Friedman & Sage 2004). In addition, only lessons common to the two cases were considered as lessons identified.

The method is described in detail in Paper IV. The validity of the approach and the reliability of the Case study are discussed in section 7.4.2.

7

SUMMARY OF RESULTS FROM THE STUDIES

The aim of this chapter is to present a summary of results from the four studies necessary to answer the corresponding research sub-questions. Each section focuses on one of the studies performed and ends with a discussion of the validity and reliability. The appended papers are referenced. In the next chapter the results are synthesized and discussed in relation to the main research question.

The main contributions from the respective studies are presented in Table 7-1, with references to the appended papers.

Table 7-1 A summary of results from the respective studies and appended papers

	Approach	**Results in summary**	**Paper**
Technology-study (Q1)	Hypothesis	A proposed model, called the "Ladder model", for linking spectral design performance to military utility.	I
	Literature review	A proposed set of technical parameters for spectral designs in signature management applications.	I
		A systematic review of materials and spectral designs suitable for signature management applications.	I
Concept-study (Q2)	Concept analysis	A proposed concept called "Military Utility"	II
Modeling-study (Q3)	Modeling and Simulation	A proof-of-concept using the Ladder model applied to assessment of the military utility of spectral design in the development of Low Observable combat aircraft.	
		-The first decision situation is a tradeoff between efforts to reduce radar signature, and those to reduce infrared signature.	V
		-The second decision situation is maximizing the use of low emissive properties.	VI
Case-study (Q4)	Case study research	Identification of lessons from the development of Low Observable combat vehicles.	III, IV

7.1 The Technology study (Q1)

Q1: "How does spectral design affect the design of a Low Observable military platform?"

The first research question was addressed in three steps. Firstly, by forming a hypothesis to quantitatively link spectral design, and the military platform design, to a notion of military utility. Secondly, by identifying those technical parameters relevant for spectral design. Thirdly, by identifying materials and techniques for controlling the performance using the systematic literature review method described in section 6.1. The results are presented in that order.

7.1.1 The Ladder model – linking spectral design to military utility

The core of the interdisciplinary systems approach (Sect.1.3) can be formulated as follows: in many scenarios it is possible to find a set of relevant measures at each system level (see Figure 1-2) to link spectral design performance to mission measures of effectiveness, thereby making it possible to quantitatively assess the military utility of spectral design using military operations research methods. Hence, the first research sub-question addresses the technology system level.

In Paper I the interdisciplinary systems approach was developed into the so-called *Ladder model*. The version illustrated in Figure 7-1 is from a later date, after development in Papers V and VI. The model represents the signature management process as a balancing of needs and design choices in several activities, at different system levels. At the lowest level, the technology level (compare with Figure 1-2), spectral design activity maximizes the potential of material properties to obtain the

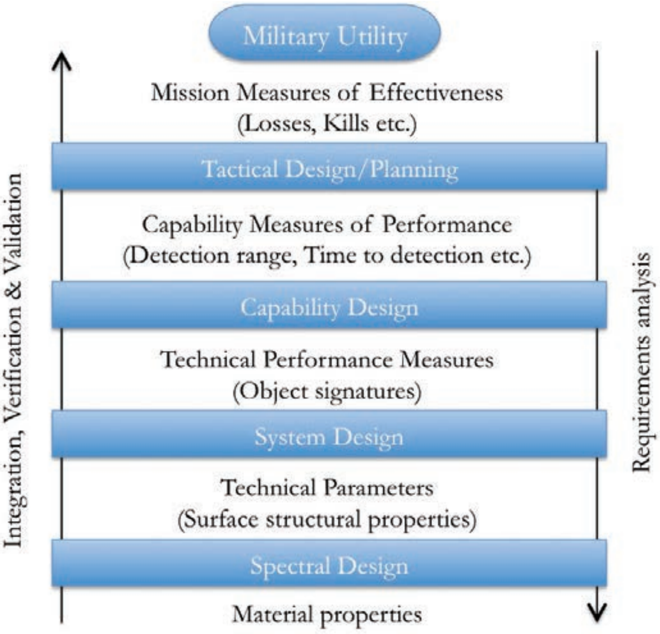

Figure 7-1 The Ladder model - a proposed model for linking the performance of spectral designs to military utility. Application specific parameters are in parentheses.

desired surface structural properties. At the technical system level, the system design activity utilizes the surface structural properties obtained by balancing all signature reduction efforts to obtain the desired object signatures. In the Ladder model, the military system level of Figure 1-2 has been divided into two system levels, the capability system level and the mission system level. The capability system level is to acknowledge that a system responding to a situation (a respondent system) consists of, not only several capabilities comprising technical systems, but also of personnel, methods and organization, in accordance with the theory in section 2.1. Hence, at the capability system level, the capability design activity takes maximum advantage of a military platform's signatures in the development of tactical procedures and the training of operators. Then, at the mission system level, a respondent system in the form of a military task force, with the desired capabilities, is designed through a planning process. A military situation system is formed when an adversary is engaged.

Furthermore, the Ladder model proposed (see Figure 7-1) assumes that systems engineering is used to develop military technical systems and capabilities, in accordance with the theory in chapters 4 and 5. Hence, on the right hand side there is an arrow pointing downwards, illustrating the requirements process allocating requirements to the design activities at different system levels (climbing down the ladder). Correspondingly, on the left hand side there is an arrow pointing upwards, illustrating the integration, verification and validation processes of systems engineering (climbing up the ladder). In the development phase of a military platform, it is presumed that an effective requirements analysis process will result in a sufficient set of quantitative, verifiable, requirements at each system level. In earlier phases, the process will instead deliver key measures of performance sufficient for decision-making.

7.1.2 A set of technical parameters

The following six characteristics are proposed (Paper I) as sufficient definition of the optical response of a surface (the "Technical Parameters" in Figure 7-1) in Low Observable applications:

1. Spectrally Selective Reflectance
2. Low Gloss
3. Low Degree of Polarization
4. Low Emissivity
5. Non-destructive Properties in Radar
6. Controllability

It was found that the first four characteristics were easily parameterized, while the last two depend heavily on application.

7.1.3 A review of materials and spectral designs

Trends were identified using the literature review method described in section 6.1, and the most interesting materials and spectral designs are presented with relevant performance metrics. The results are summarized in the diagram in Figure 7-2.

As far as paints are concerned, there is great interest in combining pigments and binders in systems that achieve a synergetic optical response throughout the spectrum from VIS to TIR. The best coatings identified in the survey are based on coated flake pigments of aluminum. Challenges that remain are adhesion, high reflectivity in the visible spectrum and a tendency to form electrically conductive coatings, which destroys radar signature properties. In research into multi-layered structures, challenges to paint are addressed using several approaches. One is tailoring the reflectivity by breaking metal-based multilayers into pigments. Another is to use non-conducting bandgap materials, either naturally polaritonic materials or photonic crystals, or a combination of the two. However, so far there have been no reports of any paint coating system that meets the potential of the respective components separately.

Another possibility is to exchange paints for electro-chromic coatings, thereby making the transmittance controllable to a certain extent across optical wavelengths of

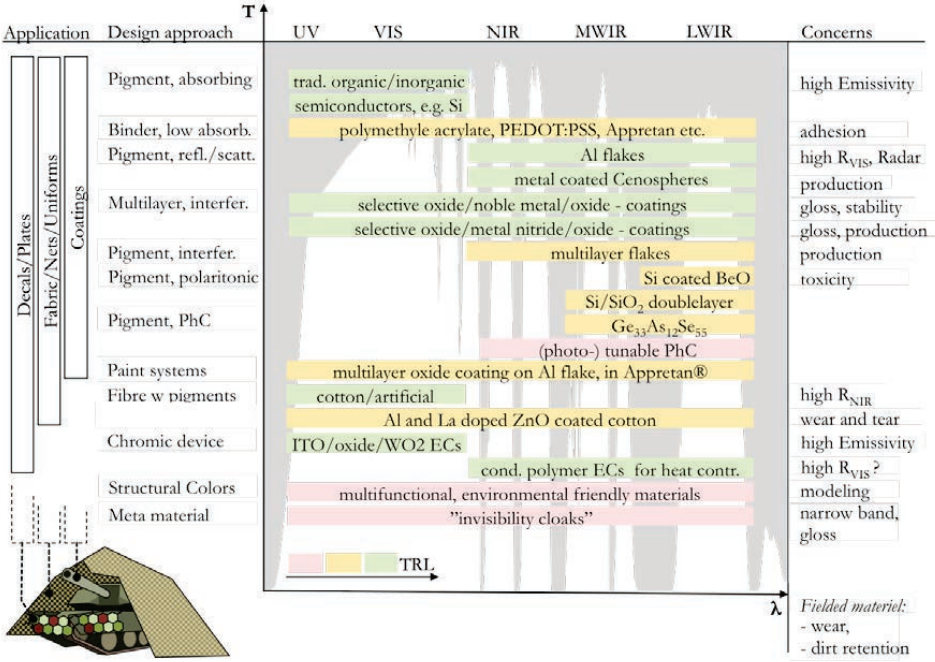

Figure 7-2. A diagram summarizing the results of the review of techniques and materials for spectral design in the Technology study. The bars on the left indicate potential applications for the respective spectral designs. The Design approach column indicates the category of spectral design approach. In the center examples of spectral designs at the forefront of research into the respective categories are presented. The color indicates Technical Readiness Level (TRL) and the width indicates the target wavelength band. The right column presents concerns identified related to the respective spectral designs.

interest. The technology has civilian applications. Hypothetically, the technique could be used to produce pixel-sized decals for military platforms, although, one foreseeable challenge is high gloss.

Currently there is great interest in biomimic materials and metamaterials. This research explores the potential of combining advanced materials with complex structures from nature. In biology, there are examples of interesting optical properties, such as age-resistant and environmentally friendly colors, originating from structures made of relatively simple materials. Developments in nano-technology production methods show great promise. Hypothetically, it will be possible to combine properties that satisfy military requirements for surfaces, other than the optical response, such as dirt resistance, thereby increasing the military utility of spectral design.

In the papers reviewed, there was no indication of any attempts to characterize all six of the desired characteristics of a surface identified in the previous tion. Often specular or integrated reflectance is the only characteristic mentioned.

7.1.4 Validity and reliability

None of the reports reviewed dealt with the entire set of technical parameters proposed. On the other hand, two of them, spectrally selective reflectance and emissivity, were discussed in many. This is not surprising, because survivability theory states that signature reduction features, such as spectral design, depend on the assessed threat (in our case the sensor threat types), and the most frequently used electro-optical sensors on the battlefield so far (eyes, imaging cameras, thermal sights etc.) detect reflected or emitted radiation. Consequently, we cannot be certain about having captured every type of technical parameter associated with signature management. The set will change over time and context. However, it seems safe to state that, in some situations, it is possible to find a set of technical parameters sufficient to coherently describe a desired optical signature. In some of these situations, it is also possible to obtain the desired characteristics using spectral design.

7.2 The Concept development study (Q2)

Q2: "How should military utility be defined in order to support decision-making?"

A proposed concept called *Military Utility* was developed using the concept analysis approach described in section 6.2.

7.2.1 A proposed concept called Military Utility

The proposed concept includes a three-level structure consisting of key features and their detailed components. When assessing military utility, an analyst must first determine the values of three situational variables that answer the questions; *what is the element of interest*, *to which military actor*, and, *in what context*? The situational variables were derived from a firm belief that the outcome of the assessment will be different, if assessing the military utility of an aircraft or an air defense capability; or if the assessment is carried out by the US Air Force or the Swedish Air Force; or if the primary use of an aircraft is to be, for example, air defense or ground attack in hostile territory.

At the basic concept level, the military utility of something, e.g. a technical system, is a compound measure of the *military effectiveness*, the assessed technical tem's *military suitability* for the military capability system, and the *affordability*. See Figure 7-3.

Military effectiveness is defined as a measure of the overall ability to accomplish a mission, when the Element of Interest (EoI) is used by representative personnel, in the planned or expected environment, for operational employment of the military force. *Military suitability* is to be understood as the degree to which an EoI can be satisfactorily taken into military use in a specified context, taking into consideration interaction with other elements of the capability system. Lastly, *affordability* is a measure of compliance with the maximum resources a military actor has allocated to the EoI, in a timeframe defined by the context. Therefore, for the concept to have its intended meaning, an object (the EoI) only has military utility, if it has the potential to be militarily effective in achieving the goals defined by the military actor and the context. The degree to which this potential can be developed is determined by how the EoI fits into the capability system of the actor. However, if the actor cannot afford to operate the capability system supported by the EoI, it has no military utility anyway.

Each dimension of military utility can in turn be operationalized as a compound of measures at an indicator level. The concept does not prescribe which indicators must be chosen; that is the decision of the analyst. Military effectiveness might be measured using indicators such as compliance to desired outcomes, desired schedules, target costs and acceptable risks. If the concept is to be developed into a useful quantitative framework for assessment of a specific technology, it is then necessary to identify quantitatively expressed links between technical parameters and indicators in the specific area of application.

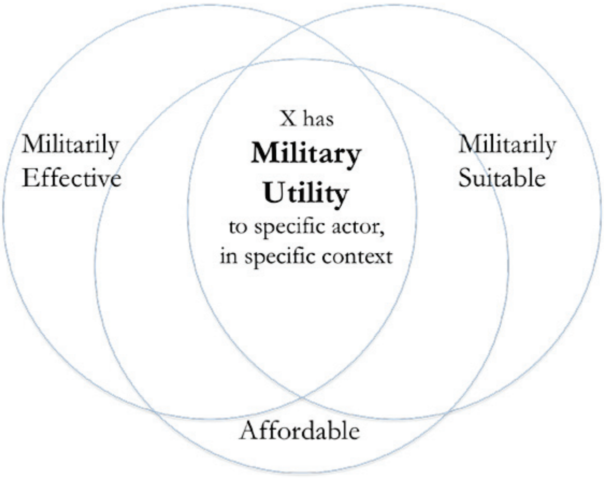

Figure 7-3 The military utility concept. Something has military utility to a specific actor in a specific context, if: it is militarily effective, and militarily suitable, and affordable, to that specific actor.

7.2.2 Validity and reliability

The purpose of the Concept development study was to identify those aspects that must be considered in order to support decision-making in the design of a military platform. A concept formation method was applied to strengthen validity, when compared with traditional concept analysis methods. One important advantage is that the concept development is based on the actual phenomenon of interest, as opposed to being a semantic investigation. Another major advantage is that the method chosen requires analysts to rigorously investigate and structure the constituent attributes in levels, dimensions and indicators, and then to explicitly define the relationships between them; see the resulting concept diagram (Paper III). It was then shown empirically that the concept was potentially useful in decision-making regarding the procurement of an armored vehicle. In conclusion, the proposed concept can serve as a hypothesis for answering the research sub-question.

Reflections on guidelines and discussions from the seminars are documented in Paper II. The empirical data used in the validating example of the procurement of an armored vehicle is publicly available.

7.3 The Modeling study (Q3)

Q3: "How can the military utility of spectral design in a Low Observable platform be assessed?"

The third sub-question was addressed using the military systems modeling and simulation method described in section 6.3. The Ladder model and the technical parameters from the Technology study, and the military utility concept from the Concept study, were used as input.

7.3.1 Assessment of the military utility of spectral design

In order to assure capture of the system nature of signatures in the system model, the Modeling study started by mapping influences between combat aircraft attributes. A text analysis of Ball's book on combat aircraft survivability (2003), and elaborating on surface properties, resulted in two diagrams.

The first diagram, Figure 7-4, describes the influences between kill chain probabilities and mission measures of effectiveness. By inspecting this diagram, an analyst can see, for example, that in order to account for the secondary effects of susceptibility reduction features on maneuverability, offensive capability must be included as a measure of effectiveness.

The second diagram, Figure 7-5, specifically focuses on factors influencing the probability of an aircraft being detected. Note the "surface electromagnetic response" factor included at the center of the second diagram. It can be seen that if the focus is on the impact of spectral design, a relevant model is required, which includes all identified influences from coating materials and structures to mission success, including possible secondary (undesirable) effects.

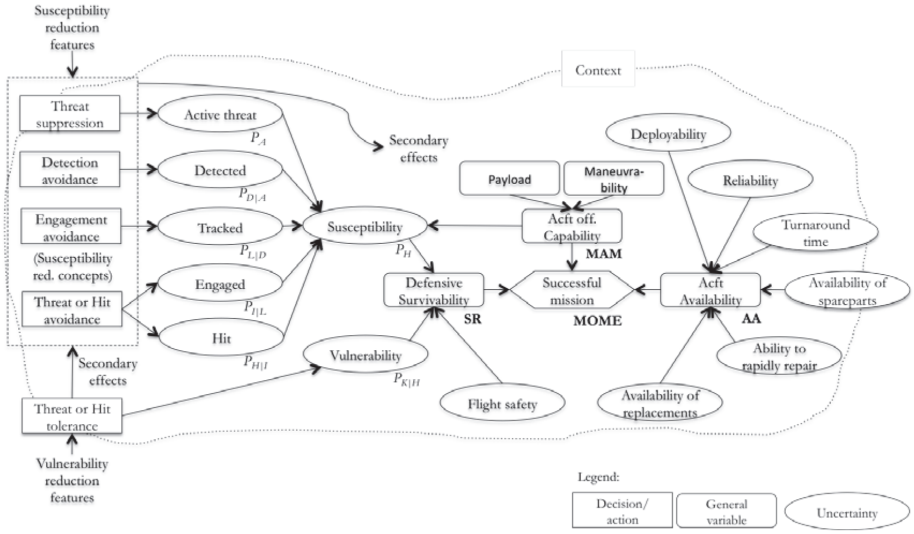

Figure 7-4 An influence diagram illustrating the links between combat aircraft survivability enhancement features and measures of mission effectiveness. The relevant measure is to the right and below each element.

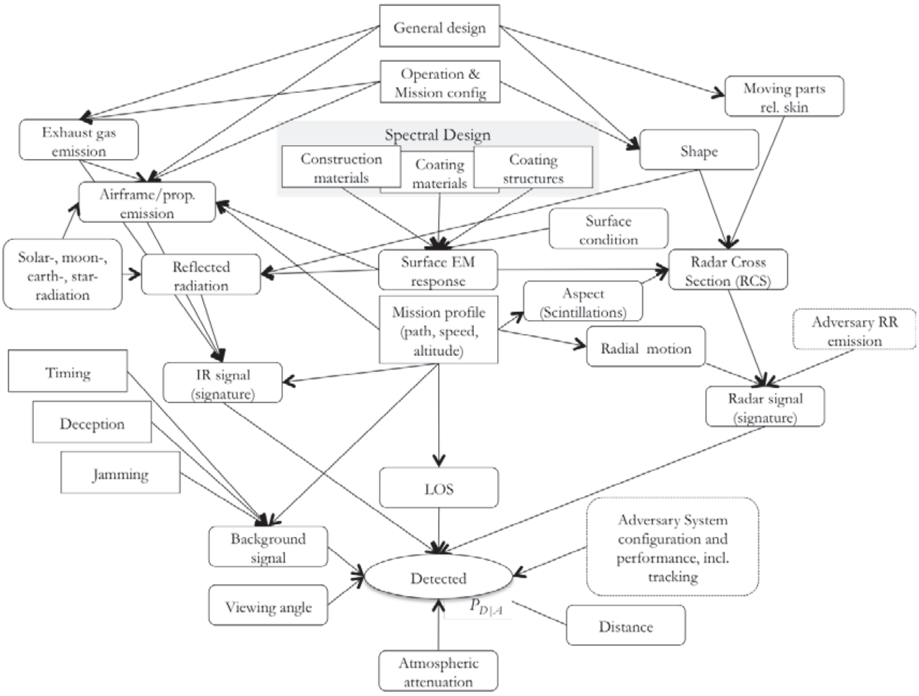

Figure 7-5 A diagram illustrating factors influencing the probability of detecting a combat aircraft when using both IR sensors and radar (RR).

The results in both Papers V and VI are based on the development and analysis of a common system model comprising an air to surface attack mission to neutralize a point target defended by surface-to-air missile (SAM) systems. The air defense in the model uses both radar and LWIR sensors for detection and tracking. The modeling activity used the Ladder model (Sect.7.1.1) as a template; see Figure 7-6.

After mapping the influences, the modeling was carried out in four phases, as described briefly earlier (Sect.6.3):

The first phase comprised defining a high-level mission model, based on a scenario with the potential to highlight signature impact. The mission model in this study had to include clearly defined objectives, threats, tactical mission profile options (e.g. paths, altitude, speed) and situational variables (e.g. summer, night). Mission MoEs were derived from the commander's mission and were quantitatively modeled using the probabilistic approach to survivability described earlier (Sect.3.4), thereby establishing an interface to lower level sub-models. Loss of aircraft was chosen as the primary measure of military effectiveness.

The second phase comprised defining key decision nodes for the mission model, and how to model them. In this study, operators were modeled to act according to simple doctrines. The pilots were modeled to follow pre-determined strike option plans until they could launch their weapons and maneuver. The air defense operators were modeled to fire one missile at each aircraft within range, 20 seconds after detection.

The third phase comprised defining the technical sub-models together to produce input to the top Mission model. See Figure 7-6. An important part of this phase, given the system nature of survivability enhancement features, is determining the fidelity of the sub-models. Models should be as simple as possible (Sect. 6.3), but they must include all relevant influences identified – otherwise possible secondary

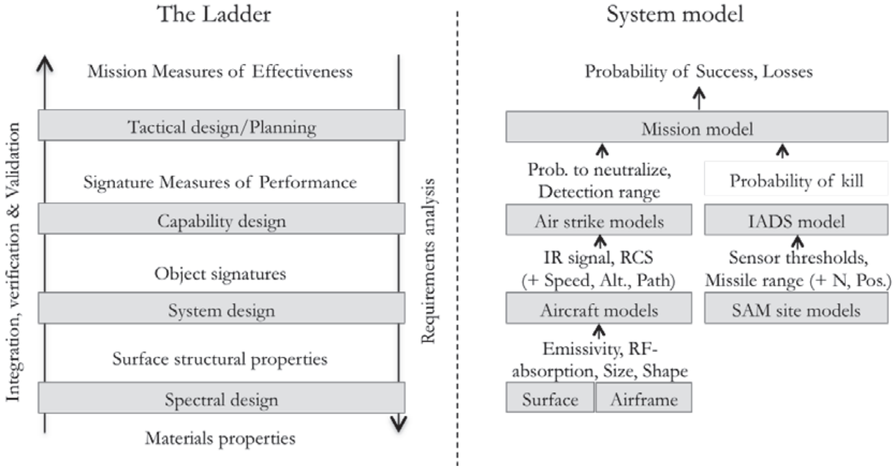

Figure 7-6 Application of the Ladder model in the system model used in Papers V and VI. Each system level in the ladder has corresponding sub-models and interlinking output/input parameters. (IADS – Integrated Air Defense System)

effects will not affect the mission MoEs. For example, in this Modeling study, increased aircraft speed should increase the IR signature, thereby increasing the probability of detection, but it should also decrease the probability of being hit by the missile. Technically, the sub-models were based on rather crude physical shapes and motion patterns, on some of the material optics phenomena described in chapter 5, and on the kill-chain probabilities and survivability measures described in chapter 3. The technical models are described in detail in Papers V and VI.

The fourth phase comprised creation of the models in a simulation environment, verifying the code and performing the analysis. In this Modeling study the Mission model, including sub-models, were created using Matlab™.

Paper V analyzes the balancing of efforts to reduce radar and LWIR signature. Therefore, the modeling activity includes both the IR and radar signatures. In Paper VI, the focus is on efforts to minimize LWIR signature using spectral design. Consequently, the effects of the IR signature model are described in more detail.

Paper V concludes that this modeling approach can be applied, during concept definition, to the problem of balancing radar and long wavelength infrared signature properties, within a relevant mission context. The results suggest that the methodology supports the quantitative evaluation of aircraft concepts. Paper VI concludes that the results support using the modeling approach described for assessing the military utility of spectral design. In some situations, such as assessing the military utility of tailored emissivity paint for aircraft surface coatings, it is sufficient to assess the military effectiveness dimension. It was shown that low emissive paint, on the front sector of an attack aircraft, in low altitude missions, has military utility.

However, the most important result is that the method seems to reduce the risk of sub-optimizations. In both cases it was shown how changes in technical or tactical variables might very well decrease a capability measure of effectiveness, for example, the detection range. However, if the reduction is not large enough, there is little or no change in the outcome measures of effectiveness at mission level. The military end result is thus unchanged, except perhaps when measured in development costs. In Paper VI, such a tipping point is identified. There is no detectable change in the expected loss of aircraft until the emissivity of the aircraft paint coating is reduced below a critical level. Then suddenly the loss is significantly reduced and, correspondingly, the military utility of the signature reduction effort is significantly increased.

7.3.2 Validity and reliability

Challenges to the validity of warfare modeling were discussed in chapter 3 and in section 6.3. Below these are discussed in relation to the Modeling study.

Using traditional cause-and-effect modeling, it is only possible to model certain aspects of the military system, due to its inherent complexity. In the context of this thesis, this means that we can only study the impact of changes in technical parameters in rather crude predetermined mission scenarios. However, as long as the behavior of the system can be mathematically modeled, and all stakeholders agree on system objectives, the modeling can still be considered relevant for decision-making in systems engineering. In practice, this means that thorough validation of the model is important (Sect.6.3.2). In this study the military system level model was validated via a seminar involving military subject matter experts. The modeling of more detailed weapon system levels was validated by comparisons with similar models in the literature. However, confidentiality surrounding evaluations of real military systems, such as the performance of weapons or sensors, makes validation of models difficult. The numerical results in this study rely, to a large extent, on one source for the performance of long wavelength infrared sensors in ground based air defense systems.

A multi-stage model like the Ladder model requires, at least, a good understanding and description of the outer attributes of the most detailed object modeled (the black box behavior) (Sect.6.3.2). In the context of the Modeling study this means understanding the most relevant aircraft surface measures of performance. These, including the mechanisms governing the low emissive properties of paint, were satisfactorily surveyed in the Technology study. Admittedly, however, the infrared signature model of the aircraft is too crude in terms of size and shape to say anything more than that the emissivity of the aircraft skin has a significant impact on military effectiveness in the situations simulated.

The mission system model in the Modeling study is completely deterministic. Hence, at some stage, we may have inappropriately replaced a stochastic variable input with its expected average (Sect.6.3.2). The static configuration of flight paths and positions of ground-based threats could possibly fall under that category. Arguably, however, given the simple infrared signature model of the aircraft, significant local variations dependent on aspect are unlikely.

The modeling at the mission system level is based on Ball's probabilistic survivability framework (Sect.3.4), which assumes independent events. This is not necessarily true in a duel between a unit of attacking aircraft and an integrated ground-based air defense system, which is why the model can produce misleading results (Sect.6.3.2). However, the setting here is simple. If detected, it is assumed that all aircraft in the unit are engaged simultaneously by single autonomous surface-to-air missile systems, firing only one missile at each aircraft. These assumptions are pessimistic, from an attacker's point of view, but produce a transparent result for a decision-maker.

Limiting the military system modeling to only one mission in a campaign will exclude the potential secondary effects on aircraft availability. For example, if new signature reduction efforts are introduced, there may be a negative impact on turn-around times, due to increased maintenance requirements. Thus, if implementing the Ladder model in a real development program, it is also important to model the campaign level. In this proof of concept study, demonstrating balance between survivability and offensive capability was sufficient (Sect.3.4.2).

Whilst acknowledging the possibility of the ostrich effect on this study (harmful omissions, see section 6.3.2), the risk is arguably reduced by the first step taken, i.e. firstly rigorously analyzing the influences of spectral design on other attributes of the platform - both desirable and undesirable (see the resulting influence diagrams Sect.7.3).

The modeling in the Modeling study is thoroughly described in Papers V and VI, and the computer code can be presented and demonstrated on request. The input parameter set is detailed in tables, and key sensor performance parameters are referenced to sources.

7.4 The Case study (Q4)

Q4: "How can the proposed model support decision-making in the development process of Low Observable platforms?"

The fourth research question was addressed using the case study research approach described in section 6.4. Two procurement programs, the SEP multirole armored vehicle and the Visby class corvette, were studied.

7.4.1 Lessons identified

Results indicate that it is possible to exploit a great deal of the potential of Low Observable technology in armored combat vehicles, without significant penalties to other attributes, or cost. However, it does require a systems approach to development and stealth must be established as a key architectural principle from the beginning of the program. Decision-making about design seems to be based on either: 1) heuristics, gathered from experience and skillfully applied by system architects or designers, 2) tests or measurements of prototypes, or, 3) modeling and simulation.

Paper IV concludes that the nature of signature attributes present a major challenge in terms of coherence and traceability between the military needs on the battlefield, and the signature requirements of the technical system. This calls for special competence and tailoring of the technical processes involving requirements analysis, systems architecture, and system design. A tailored workflow, from mission analysis to subsystem design, was derived from lessons identified. The activities in the workflow, including implied decision-making, are presented in Table 7-2.

The selection of scenarios is an essential input to the modeling activity. However, given the character of the implied decision-making, the type of modeling and simulation proposed in this thesis has the potential to support knowledge building throughout the rest of the workflow shown – ranging from choosing the most critical signature-dependent situation, to verifying system requirements.

Nevertheless, the study also indicates that there are still challenges in establishing coherence and traceability between military needs and lower system levels, at least on land and at sea. The following development is required:

- expansion of the system view to a mission system level,
- definition of measures of performance at all system levels, and
- linkable modeling and simulation tools that support analysis from top to bottom.

Table 7-2 A tailored workflow to support: requirements analysis, systems architecture, and system design, in the engineering of LO platforms (Paper IV). Typical decision-making included in each activity is presented explicitly.

Activity	Implied decision-making
Mission analysis. Use mission scenarios and probabilities of threat sensors as input to define key capability MoPs and signature critical situations	-Which scenarios, taken together, demonstrate planned use of the platform? -Which of these are the critical, signature-dependent, situations? -What are the most influential capability MoPs and what are their critical values?
Capability analysis. Use the output from Mission analysis to define signature requirements in dimensioning configurations	-What are the dimensioning sensor-target configurations, including situational parameters, given planned tactical use? -What are the critical values of the signature MoPs in these configurations?
System design and analysis. Use the output from Capability analysis to allocate subsystem design instructions and re-iterate, based on the resulting system signature response.	-Which is the optimal system design satisfying system requirements, including system signature requirements? -What are the preferred signature design instructions, given a system design?
Subsystem model design and IV&V (incl. spectral design)	-Which is the preferred sub-system design, given the signature design instructions?
System model IV&V	-Does the integrated design meet the system requirements?

7.4.2 Validity and reliability

When using the case study method some challenges require discussion, as pointed out in section 6.4.2.

There is often a risk of misleading generalizations. In this study, the risk was mitigated by filtering out potential lessons, using a framework based on best practice systems engineering, and by comparison with a second similar case.

Fuzzy boundaries pose another risk. Here the boundaries of the object of study were, intuitively, those of the development programs of the two cases studied. Only the time boundaries became an issue. The SEP case was terminated after the design phase. Hypothetically, this was a result of a poor development process, making SEP an inappropriate case. However, this hypothesis could be ruled out by comparing the consistent statements from respondents, i.e. from industry, the procurement agency and the customer.

Confidentiality can be a problem when accessing case settings. The cases were chosen because stealth was defined as a key architectural principle in both development programs, and because the resulting designs were considered well balanced. An additional case of successful stealth aircraft design in the study would have been desirable, but was assessed to be impossible because of limited access to data. In the cases studied there were some limitations regarding access to documents. However, this was compensated for with the necessary access to the key decision-makers involved.

The Case study approach is described in Papers III and IV. Referenced source documents are publicly available, but data was mainly collected from interviews. The risk of participant bias and error was reduced by making appointments well in advance, and by informing respondents about the purpose and theme of the inquiries when making appointments. Furthermore, the participants were given the opportunity to correct their statements by reading transcriptions of the interviews, and at a later stage, when reviewing the draft case study report. Researcher bias and errors were reduced by choosing respondents from all the actors involved, by establishing interview protocols in advance (based on best-practice systems engineering concepts), by making audio recordings of the interviews, and by sharing preliminary results with the respondents.

8

DISCUSSION AND CONCLUSIONS

In this final chapter, the results of the thesis are discussed and conclusions are drawn. Firstly, results from the four studies included in the thesis are synthesized in order to answer the overarching research question. Thereafter the limitations of the thesis study are discussed. Next, the more general, conceptual, aspects implied in the research question are addressed in a discussion of contributions to theory. Then, aspects related to the specific problem domain of designing Low Observable platforms are addressed in a discussion of contributions to practice. Finally, the last two sections present major conclusions and give guidelines for future research.

8.1 Synthesis

Security developments in Europe over the last decade have again increased interest in using advanced technology for military systems development, especially for the purposes of increasing the survivability of military personnel. However, in most European countries, the development of military capabilities is limited by strained budgets. The purpose of this thesis is to support decision-making by providing a developed approach to assessing the military utility of advances in technology. The specific aim is to propose methodological contributions to a framework for effective decision-making regarding the use of spectral design in the development of Low Observable platforms. The principal research objective is to answer the following research question:

> *"How can the military utility of spectral design be assessed in order to support decision-making in the development of balanced Low Observable platform design?"*
> (Sect.1.2)

A systems approach was chosen based on the possibility of modeling military situations as systems, and of recursively and coherently linking effects to adjustments made at successively more detailed system levels. The basic idea was to be able to observe measurable changes in the modeled military situation at the top system level when modifying spectral designs. "Because, given that we know how we would like to shape the military situation, and given that we can monitor changes due to spectral design, then arguably, it will be possible to assess the military utility of such adjustments" (Sect.1.3.2).

In the technology study (Sect.7.1/Paper I) the systems approach was manifested in the so-called Ladder model, making explicit the quantitative link between technical parameters of spectral design, and mission measures of military effectiveness; see Figure 7-1. A set of six technical parameters were identified and proposed as suitable to characterize the optical response of a surface obtained using spectral design, including, for example, low gloss and low emissivity. Consequently, these technical parameters satisfy the requirement for links between the spectral design level and the technical system level in the Ladder model.

In addition, the Technology study concluded that there are, for example, feasible paints and fabrics available for large parts of the optical spectrum, although there are challenges in designing an optical response to meet the anticipated multi-spectral sensor threat of the near future (Sect.7.1.3). Nevertheless, given the comprehensive research into advanced materials, chromic devices and advanced surface structures inspired by natural optical phenomena, the study shows there is potential in using spectral design technology.

The top end of the Ladder model indicates a measurable military utility (see Figure 7-1). Therefore, the aim of the Concept development study (Sect.7.2/Paper II) was to develop a useful concept for the military utility phenomenon in the context of developing a LO platform. Firstly, the study shows that military utility depends on three situational parameters of what, for whom, and in what context. These must be carefully defined before assessment. Next, it was shown that a military utility concept consisting of three dimensions (military effectiveness, military suitability, and affordability) satisfies these needs. In the military effectiveness dimension, compliance with the planned outcome of a military mission is measured, including boundary conditions such as: acceptable risks, costs and schedule. In the military suitability dimension, the degree of fit of the technical system, or technology, of interest is measured relative to the other components of a capability system. The affordability dimension provides a measure of whether ownership of the technical component assessed is within allocated monetary resources. The exact wording of the definitions can be found in the results section (Sect.7.2). For the concept to be useful in the context of this thesis, the indicators of the military utility dimensions (the military measures of effectiveness in Figure 7-1) have to be quantitative in order to provide a link to the lower system levels of the Ladder model. However, the operationalization of indicators is not prescribed by the concept. Instead, operationalization has to be part of the application of the concept to a problem.

In the Modeling study (Sect.7.3/ Papers V and VI) the Ladder model (including the military utility concept) was applied to the problem of quantitatively assessing the military utility of low emissive paint on aircraft, in the context of attacking a point target defended by ground based air defense. The purpose was to demonstrate the feasibility of the proposed model, and concept, in combination with MOR methods. At the mission system level, the Ladder model was implemented using a probabilistic framework for survivability assessments. This framework suggests using loss of aircraft as the military measure of effectiveness. At the spectral design level, surfaces were modeled as low gloss grey bodies, with emissivity as the technical parameter characterizing their properties. The modeling of intermediate models in the Ladder model and other details are described in Papers V and VI. The study results suggest that the approach demonstrated is useful for signature management decision-making during the concept phase of the development of a LO aircraft. The results show that evaluating signature reduction efforts at the military system level, with the aid of the military utility concept, helps to avoid sub-optimizations likely to happen otherwise. In summary, therefore, the results show that the modeling approach developed, including the Ladder model, the military utility concept, and the use of MOR methods, can provide an improved basis for decision-making.

The aim of the final study of the thesis, the Case study (Sect.7.4/Papers III and IV), was to investigate how decisions are made during the development of a LO platform, and how the proposed modeling approach can contribute. The results show that, in the two cases studied, the decision-making was based on a combination of heuristics, prototyping (both subsystems and full-scale), and modeling and simulation. A workflow for supporting requirements analysis, systems architecture, and system design emerged from the analysis. Within this workflow a number of decision-situations were identified, which are likely to benefit from improved modeling and simulation methods, and from expanding the system view to a mission system level. However, the analysis also shows that perhaps the greatest challenge to implementing the Ladder model is to identify and define suitable contrast measures for the inter-level link between the technical system level and the capability system level (See Figure 7-1), at least in the land and maritime arenas. If this challenge can be overcome in future development programs, the results indicate that the modeling approach proposed in this thesis will assist decision-making in signature management, and that it is likely to reduce the need for costly and time-consuming prototypes and tests.

8.2 Limitations

The limitations related to each study were discussed separately in the respective validity and reliability sections of the results chapter (Ch.7). However, there are a few limitations that need to be discussed regarding the overall generalizability of results.

The quantitative assessment in the Modeling study only covers the military effectiveness dimension of the military utility concept. This limitation is not a problem for the case demonstrated. It is reasonable to believe that low emissive paint will not have a significant impact on the military suitability or affordability dimensions. For example, no new facilities are required to implement the technology, the doctrines will remain the same, and the associated life cycle cost is, presumably, not significantly greater than that of traditional paint coatings. However, the case demonstrated has to be regarded as a special case of the more general assessment situation, where design choices will also affect cost, and induce change in other components of the capability system.

Furthermore, the results of the Modeling study support using the demonstrated approach in the concept phase, where the fidelity requirements of technical models are modest. During the development phase, models will have to be more detailed and, perhaps, there will also be implications arising from the need to support automated design space exploration.

The Case study shows that there is a need for a system perspective, and a viable framework for modeling and simulation, to support signature management during the development of platforms for the land and maritime arenas, as well as aerospace. However, the study also shows that difficulties in defining relevant contrast measures for some sensor-target configurations might prove to be an obstacle for implementation of the Ladder model, and thus the assessment approach demonstrated. In these cases, the model's value is not as a template for multi-stage modeling, but rather for highlighting the requirements analysis problem. In good systems engineering practice, subsystem requirements have to be consistent and coherent with the system requirement from which they originate.

In summary, there are limitations to the generalizability of the assessment approach demonstrated. Validity will benefit from future work replicating and expanding its use in problem domains requiring assessment in all dimensions of the military utility concept, into the development phase, and into arenas other than aerospace.

8.3 Contributions to theory

In the introduction, I stated that the background to the problem has a wider scope than that of assessing the utility of spectral design. I argued that it is but one example of applying the more generic question: “what is the military utility of this technology, or equipment?” (Sect.1.1). In the Concept study this phenomenon was framed in a statement derived from this military technology postulate : “the technology the military profession chooses, and how it uses that technology, affects the outcome on the battlefield and the sustainment of capabilities over time” (Paper III). Below I argue that the military utility concept (Sect.7.2), developed in the Concept study, contributes to the understanding of this phenomenon.

In comparison to existing related concepts (Sect.2.6), the military utility concept is original in that it has been developed specifically to support a systems approach to, and capability centric, analysis. This has resulted in a third dimension to the concept, compared to utility concepts built only on cost and operational effectiveness. The third dimension, military suitability, was included in order to make it explicit, from a military technology viewpoint, that a technical system only has utility if it is viewed as a component in a capability system.

The military utility concept should, by definition, be useful because it was developed from an identified need to support decision-making in five cases of generic use: technology forecast, defense planning, development, use, and lessons learned. However, the claim can be supported with arguments along two lines of reasoning. Besides quantitative analysis, the concept also supports qualitative analysis. When expressing the military utility of something, assessments are required in three dimensions, as stated above. In addition, the concept prescribes determining three situational variables of what, for whom, and in what context. This will undoubtedly help to frame the problem, focusing attention and, in turn, aiding discussions and qualitative assessments. These strengths can be illustrated by referring to part of the discussion about the importance of defining for whom a technical system is to have military utility: “Though the military utility of the F-117 was great to the coalition forces during the First Gulf War, it is safe to conclude that the military utility of the F-117 to the SwAF would be small” (Paper III & Ch.5.1.2). This statement is easily understood, if qualitatively analyzing the military suitability dimension of military utility. The F-117 simply does not fit into the framework of the Swedish capability for air-to-surface air operations. The compatibility between the aircraft and Swedish crews, weapons, logistics and doctrine can be assumed to be poor. On the other hand, in time, with a plan for training and possible technical modifications, the military suitability to SwAF capability, and thereby the military utility, could be enhanced. Of course, one could have similar discussions about the effects on military utility of varying the command level perspective, the system border of the assessed object, or the context, etc.

8.4 Contributions to practice

Unsurprisingly, given the context, I would argue that there are significant contributions to practice within the disciplines of systems engineering, especially survivability engineering, and military operations research. The other disciplines involved in the interdisciplinary approach (Sect.1.3), i.e. systems thinking and military science, were used to give the perspective and understanding of the problem domain.

The Ladder model (Sect.7.1.1) should be seen as a template for how to quantitatively link a set of technical parameters associated with spectral design (Sect.7.1.2) to measures of military effectiveness. Establishing such a link is not part of the military utility-concept itself, but an important step in its operationalization for assessments in the problem domain (Paper III & Ch. 5.3). The originality lies in applying a bottom-up systems perspective specifically to the spectral design technology, and in making the capability system level explicit. The bottom-up perspective focuses attention on the utility of making progress within the area of spectral design, as opposed to the current focus on reducing vulnerability or enhancing physical protection (Sect.3.5). Making the capability level explicit is necessary, if taking a system view on capability (Sect.2.1), and thereby acknowledging the risk of sub-optimizing capability by favoring technical solutions. Failure to address this risk is a criticism of other approaches within the survivability discipline. Making capability components explicit will likely also aid assessment of the military suitability dimension, because this requires analysis of the gap between the baseline status of capability components and the desired state, depicted in the military effectiveness dimension.

The review of related research (Sect.3.5) showed that, so far, the most progressive area for gauging survivability effectiveness is that of combat aircraft design. The focus, however, has been on reducing vulnerability, or on reducing susceptibility by reducing radar signature or by introducing active countermeasures. Hence, the contribution in this area is the introduction of a mission system model suitable for conceptual analysis of the impact of spectral design on the survivability of combat aircraft, more specifically of the duel between ground based air defense systems and attacking aircraft. Here, the mission system model is an application of the Ladder model and the probabilistic approach promoted by other academics. In addition, the case study of the development of Low Observable platforms revealed difficulties in decomposing needs into coherent, traceable, system requirements at the technical system level. Establishing corresponding mission system models for the land arena would help to mitigate these problems in the future.

Answering the research question also includes demonstrating a viable assessment method for balancing Low Observable military designs. The method adopted from Soban and Mavris for balancing radar and long wavelength infrared signatures in the design of attack aircraft (Paper V), and for optimizing the utility of spectral design (PaperVI), contribute in this respect. The method emerging in the Modeling study is useful in that, as part of an exploratory research project, it demonstrates the potential of developing the military utility concept into a framework for quantitatively assessing military utility. It is also useful in that it complements the Soban and Mavris probabilistic methodological framework regarding infrared signatures.

However, proposing a method for assessing the military utility of different designs is not enough to answer the research question. It is also necessary to identify where to apply the method in the development process, and to what ends, in order to end up with a well-balanced Low Observable platform design. The case study makes a significant contribution by identifying the key decision-making situations related to requirements analysis and design during the concept and development life-cycle phases (see Table 7-2). Using modeling and simulation to address the decision-making necessary at each system level, is most certainly useful. Applying a military utility perspective to the decision-making at each level would be original. As an example, the modeling study of low emissive coatings for attack aircraft (Paper VI) indicates how military utility-based decision-making could help to determine signature design instructions. One explicit result of the study was to show that the surface coating on the front aspect of an attack aircraft should be diffuse and have low emissivity throughout the long-wavelength infrared spectrum.

8.5 Conclusions

The aim of the research reported in this thesis was to propose methodological contributions to a framework for effective decision-making regarding spectral design in military signature management applications. The research is justified by several trends. There is extensive research, mainly civilian, into materials and techniques potentially suitable for spectral design. Meanwhile, there is also a growing interest in advanced technologies, and a need for enhanced survivability in military platforms, given the worsening security situation in Europe.

The research objective was addressed from a military system and capability centric perspective, using methods from several disciplines in the military sciences domain. The work was divided into four studies; a Technology study of spectral design, using a systematic review of literature; a Concept development study of military utility, using a concept formation method; a Modeling study to operationalize a link between spectral design and measures of military utility, using military operations research methods; and an exploratory Case study of the systems engineering of military Low Observable platform designs.

The main finding contributing to theory is a proposed concept, called Military Utility, which captures how to communicate the utility of technical systems, or technology, in a military context. It complements existing concepts in military sciences and systems engineering, specifically supporting a capability centric and systems approach to utility assessments, from a military actor's perspective.

The first finding contributing to survivability engineering practice is a proposed model, called the Ladder model, which supports the quantitative assessment of the military utility of spectral design. The novelty lies in it presenting a bottom up systems perspective for using spectral design to reduce susceptibility to threats, and in explicitly including a capability system level to reduce the risk of sub-optimization. It is anticipated that this will aid engineers in requirements analysis and design, because it makes explicit the need for the coherent and traceable allocation of quantitatively expressed requirements at every system level, from the military mission system level to technical sub system levels.

In addition, the Ladder model is expected to be useful to academics studying military technology, as it is an example of how to operationalize the military effectiveness dimension of the military utility concept.

The applied Ladder model is also a contribution to practice, when quantitatively assessing the military effectiveness of spectrally designing Low Observable attack aircraft. This application of the Ladder model will help to assess the utility of progress in spectral design, when compared to the current focus on active counter measures and reducing vulnerability.

The adapted method used for quantitatively assessing the military effectiveness of spectral design in the development of Low Observable attack aircraft, is another contribution to practice. Implementation of the method, using the Ladder model, complements a probabilistic framework, first developed and promoted by academics in the combat aircraft survivability engineering community, especially in terms of infrared signature analysis. In this thesis, it was used to expose a possible pivot point where further efforts to reduce radar signature were no longer worthwhile, because of the probability of detection by infrared sensors; it was also used to demonstrate the importance of including earthshine in assessments of infrared signatures.

Lastly, the set of lessons identified regarding successful requirements analysis and design, in Low Observable platform development programs, is a contribution to the systems engineering discipline. Guidelines from earlier research in combat aircraft survivability engineering have been corroborated for use in the development of ground combat vehicles and naval vessels. A tailored generic workflow to support requirements analysis and design was identified, explicitly identifying decision-situations potentially aided by modeling and simulations – and thus by employing the methodology proposed above.

To summarize, the overall result of the work presented in this thesis is the integration of related work in military sciences, systems engineering and material optics to support decision-making regarding the use of spectral design technology in the signature engineering of Low Observable military platforms. The resulting major methodological contributions comprise:

- a proposed concept called Military Utility,
- the Ladder model – a template for operationalizing the military effectiveness dimension of the proposed concept regarding spectral design in signature management applications,
- an applied Ladder model for analyzing the military utility of spectral designs in Low Observable attack aircraft,
- an adapted methodology to conduct the analysis,
- a workflow, identified from relevant development programs, with decision-situations that can benefit from the adapted methodology.

8.6 Future research

The study of the use of spectral design in signature management applications in this thesis can be considered an example of an assessment of the Military Utility of a technology when applied to a military platform. In order to further validate the proposed Military Utility concept, and to develop an assessment theory, there is a need to study its use in addressing the wide palette of problems defining the phenomenon (See Concept study). Below I present four directions for research, which I find particularly interesting.

The object of assessment in the applied examples is *one* technology in combat aircraft. There are other technologies, and it seems that there has been less study of the assessment of signature management applications for land combat vehicles. The Case study has shown that the combat vehicles case would be very interesting since the background is very different, and perhaps more complex, when compared with that of the airspace theater. In addition, dirt and wear are important issues in the land theater (Technology study). In accordance with these results, the current multilateral project in the NATO science and technology organization called *Assessment Methods for Camouflage in Operational Context* (RTO 2015), has also identified ground combat vehicles as a case of interest to all participants. The project acknowledges that the military operational context currently plays a minor role in the evaluation and design of camouflage systems, although in military practice, it is deemed crucial in assessing the performance of these systems. The aim of the project is, therefore, to investigate and to recommend techniques for incorporating the operational context in camouflage assessment and requirement analysis. Within the framework of Swedish participation, I would advocate using and evaluating the Ladder-model. Furthermore, it would be interesting to see if academics in other military science disciplines would also find the Military Utility concept useful. The definition of the concept does not limit its use to technology. Following on from the capability system view advocated in this study, capability components, such as doctrine or organization, would be equally relevant candidates for assessment.

The time perspective in the applied examples relates to decision-situations during the development of a military platform (See Modeling study). The Military Utility concept has recently been introduced into the Swedish Armed Forces process for technology forecasting. The next step is to evaluate its contribution. At the other end of the time scale, I plan to study the use of the concept for assessments in the operation planning process. The first step will be to identify relevant situations in the planning process that would benefit from an improved basis for decisions.

The dimensionality is another aspect of Military Utility assessments. In the applied examples (Modeling study) we found that when studying the impact of low emissive paint on attack aircraft, it is only necessary to assess the Military Effectiveness dimension. Because we assessed that the technology did not significantly affect either the Military Suitability or the Affordability dimensions, when compared with paints currently used; however, this must be considered a special case. It is important, therefore, to study when, and how, measures of all three dimensions should be compounded into a measure of Military Utility. This issue was identified but not fully investigated in the Concept study. In addition, of the three dimensions, I found that the Military Suitability dimension is the least studied. Therefore, it would be particularly interesting to study assessments of the military utility of alternatives with variations in Military Suitability.

The methodology in the applied examples is quantitative, based on a probabilistic framework for survivability assessments. This kind of approach is continuously developing, for example, in the fields of Design Space Exploration and Multidisciplinary Design Optimization (Modeling study). However, the Military Utility concept does not stipulate which methods to use for assessments (Concept study). Thus, in decision-situations other than those studied in this thesis – for example, if a situation is too complex to model quantitatively, or if there is insufficient time or resources for modeling – related work indicates that it is beneficial to use qualitative methods, or combinations. Therefore, I would welcome academics, who favor different methodologies and methods, adopting the proposed concept to conduct assessments in their respective fields. Theory building in military technology will benefit greatly.

In summary, there is still a lot of work to be done, not only to investigate and evaluate use of the Military Utility concept in general, but also to assess the use of spectral design in signature management application. In addition, there are other technologies and there are other perspectives. The work presented in this thesis presents one stepping-stone on a path towards a theory for better assessments of the utility of military technology.

REFERENCES

Abrahamsson, M., 2002. Uncertainty in Quantitative Risk Analysis – Characterisation and Methods of Treatment.

AcqNotes.com, 2016. JCIDS Process - Military Utility Assessment (MUA). Available at: http://www.acqnotes.com/acqnote/acquisitions/military-utility-assessment-mua [Accessed December 6, 2016].

Aliev, A.E. et al., 2006. Chalcogenide inverted opal photonic crystal as infrared pigments. *International Journal of Nanoscience*, 5(1), pp.157–172.

Andersson, K., 1993. *Preparation and Characterisation of Sputtered Titanium- and Zirconium Nitride Optical Films*. Uppsala. Available at: http://fhs.diva-portal.org/smash/record.jsf?pid=diva2%253A708500&dswid=7896.

Andersson, K.E., Veszelei, M. & Roos, A., 1994. Zirconium nitride based transparent heat mirror coatings —preparation and characterisation. *Solar Energy Materials and Solar Cells*, 32(2), pp.199–212. Available at: http://www.sciencedirect.com/science/article/pii/0927024894903042 [Accessed January 23, 2014].

Andersson, K.E., Wahlström, M.K. & Roos, A., 1992. High stability titanium nitride based solar control films. *Thin Solid Films*, 214(2), pp.213–218. Available at: http://www.sciencedirect.com/science/article/pii/0040609092907724 [Accessed January 23, 2014].

Anteroinen, J., 2013. *Enhancing the development of Military Capabilities by a Systems Approach*. National Defence University, Helsinki. Available at: http://www.doria.fi.

Arwin, H., 2014. *Thin Film Optics and Polarized Light* Aureus., Linköping: University of Linköping.

AUS MOD, 2014. Defence Capability Development Handbook. , pp.1–115.

Axberg, S. et al., 2013. Textbook in Military-Technology, vol. 9: Theory and Methods (Swedish).

Ball, R.E., 2003. *The Fundamentals of Aircraft Combat Survivability Analysis and Design* 2nd ed., Reston, VA: AIAA Education.

Ball, R.E. & Calvano, C.N., 1994. Establishing the Fundamentals of a Surface Ship survivability Design Discipline. *Naval Engineers Journal*, 106(1), pp.71–74.

Bergström, D., Sjöqvist, L. & Gustafsson, D., 2012. *Passive and active spectropolarimetric imaging for target detection - a literature review study*,

Bertalanffy, L. von, 1968. *General system theory: foundations, development, applications*, New York: George Braziller.

Bohman, L., 2003. *Handbook on signature management technology for ground (swedish)*, FOI.

Bohman, L., 2012. *Sensorer mot markmål*, Linköping. Available at: http://www.foi.se/report?rNo=FOI-R--3476--SE.

Born, M. & Wolf, E., 1970. *Principles of Optics* 4th ed., London: Pergamon Press Ltd. Available at: https://archive.org/stream/PrinciplesOfOptics/BornWolf-PrinciplesOfOptics#page/n29/mode/2up.

Bracken, J., Kress, M. & Rosenthal, R.E., 1995. *Warfare Modeling* J. Bracken, M. Kress, & R. E. Rosenthal, eds., John Wiley & Sons, Inc.

Burgess, M. & Svetoslav, G., 2015. Survivability for deployable protected land vehicles : concepts , models and applications. *Journal of Battlefield Technology*, 18(2), pp.7–13.

Chen, P.-Y. & Alù, A., 2011. Mantle cloaking using thin patterned metasurfaces. *Physical Review B*, 84(20), p.205110. Available at: http://link.aps.org/doi/10.1103/PhysRevB.84.205110 [Accessed March 6, 2014].

Cho, P. et al., 2015. Maintenance and Flight Scheduling of Low Observable Aircraft Philip. *Naval Research Logistics*, 62(February 2015), pp.60–80.

Churchman, C.W., 1968. *The systems approach*, New York: Delacorte Press.

Cilliers, P., 1998. *Complexity and Postmodernism - Understanding complex systems* 1st ed., London and New York: Routledge.

Conley, H.P., 1988. *A History of Camouflage: Concealment and Deception*, Available at: http://www.dtic.mil/dtic/tr/fulltext/u2/a216593.pdf.

DCDC, 2007. Joint Doctrine Publication 3-80 . 1 Opsec , Deception and Psyops.

DCDC, 2014. UK Defence Doctrine. *Joint Doctrine Publication 0-01*, Novnber, pp.1–83. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/389755/20141208-JDP_0_01_Ed_5_UK_Defence_Doctrine.pdf.

Denscombe, M., 2014. *The Good Research Guide* 5th ed., Maidenhead, UK: Open University Press, McGraw-Hill Education.

DoD, 2008. Directive 7045.20 Capability Portfolio Management. , (7045).

DoD, 2012. Glossary of Defense Acquisition Acronyms and Terms. Available at: https://dap.dau.mil/glossary/Pages/Default.aspx.

DOD, 2010. *Department of Defense Dictionary of Military and Associated Terms*, US Department of Defense. Available at: http://www.dtic.mil/doctrine/new_pubs/jp1_02.pdf.

Driggers, Ronald G.; Friedman, Melvin H.; Nichols, J.M., 2012. Introduction to Infrared and Electrooptical systems.

Driggers, R.G., Friedman, M.H. & M., N.J., 2012. *Introduction to Infrared and Electrooptical systems* 2nd ed., Artech House.

Eisner, H., 2008. *Essentials of Project and Systems Engineering Management*, Hoboken, NJ, USA: John Wiley & Sons, Inc.

Emmeche, C., Køppe, S. & Stjernfelt, F., 1997. Explaining Emergence : Towards an Ontology of Levels. *Journal for General Philosophy of Science*, 28(1), pp.83–119.

Fielding, J.P. & Nilubol, O., 2004. Integration of survivability assessment into combat aircraft design for operational effectiveness. In *24th International Congress of the Aeronautical sciences*.

Fitzsimmons, M., 2007. Whither Capabilities-based Planning? *JFQ*, (44), pp.101–105.

Flood, R.L. & Carson, E.R., 1993. *Dealing with complexity* 2nd ed., New York: Plenum press.

Friedman, G. & Sage, A.P., 2004. Case studies of systems engineering and management in systems acquisition. *Systems Engineering*, 7(1), pp.84–97.

Fuller, J.F.C., *The Foundations of the Science of War*,

GAO, 1997. *Operation Desert Storm: Evaluation of the Air Campaign*, Available at: http://www.gao.gov/products/NSIAD-97-134.

Goertz, G., 2006. *Social Science Concepts - A User´s Guide*, Princeton University Press.

Goertz, G.M., 2012. Concepts and measurement: Ontology and epistemology in Social Science Information. , 51, pp.205–215.

Goh, W.J., 2014. *Survivability design of ground systems for area defense operation in an urban scenario*. Naval Post graduate School, CA, US.

Granqvist, C.G. et al., 2009. Progress in chromogenics: New results for electrochromic and thermochromic materials and devices. *Solar Energy Materials and Solar Cells*, 93(12), pp.2032–2039. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0927024809000798 [Accessed February 28, 2014].

Guzie, G.L., 2004. *Integrated Survivability Assessment, ARL-TR-3186*, White Sands Missile Range.

Hallberg, T. et al., 2005. Scientific report Development of low-emissive camouflage paint : Final report Development of low-emissive camouflage paint : Final report. , (February). Available at: http://cdn.shopify.com/s/files/1/0235/5803/files/CamoPaint_1.pdf.

Hallberg, T. et al., 2014. *Spectral and polarimetric signatures for passive EO-sensors (in Swedish), FOI-D--0611--SE*, Linköping.

Hartcup, G., 1979. *Camouflage - The history of Concealment & Deception in War*, Barnsley: Pen & Sword Books Ltd.

Holm, G., 2007. *Systems modeling and simulation (in Swedish)*, Stockholm: The Swedish Defence Research Agency (FOI).

INCOSE, 2015. *Systems Engineering Handbook* 4th ed. D. D. Walden et al., eds., John Wiley & Sons.

Ingelstam, L., 2012. *System - att tänka över samhälle och teknik*, Eskilstuna: The Swedish Energy Agency.

Jackson, M.C., 1995. Beyond the Fads. *Systems Research*, 12(1), pp.25–42.

Jackson, M.C., 2003. *Systems Thinking, Creative Holism for Managers*, Chichester, England: John Wiley & Sons Ltd.

Jacobs, P.A., 2006. *Thermal Infrared Characterization of Ground Targets and Backgrounds* 2nd ed., SPIE.

Jaiswal, N.K., 1997. *Military Operations Research: Quantitative Decision Making*, Kluwer Academic Publishers.

Jenn, D.C., 2005. *Radar and Laser Cross Section Engineering* 2nd ed., Virginia: AIAA Education.

John, S., 1987. Strong Localization of Photons in Certain Disordered Dielectric Superlattices. *Physical Review Letters*, 58(23), pp.2486–2489.

Johnson, J., 1958. Analysis of image forming systems. *Image Intensifier Symposium, AD 220160*, pp.244–273.

Kariis, H. et al., 2013. *Maskeringsfärg, markarenan. Tekniskt underlag, internationella signaturer, FOI-R--3669--SE*, Linköping, Sweden. Available at: http://www.foi.se/rapport?rNo=FOI-R--3669--SE [Accessed January 27, 2014].

Kim, K.S. & Lee, J.H., 2012. Simplified vulnerability assessment procedure for a warship based on the vulnerable area approach. *Journal of Mechanical Science and Technology*, 26(7), pp.2171–2181.

Larson, E. V., 1996. *Casualties and consensus: the historical role of casualties in domestic support for U.S. military operations*, Santa Monica, CA: RAND.

Lawson, H., 2010. *A Journey Through the Systems Landscape*, College Publications.

Lewis, T.P., Fulk, D.A. & Castro, G., 2007. Analysis Support for Acquisition: Part 1: Analysis of Alternatives. In A. G. Loerch & L. B. Rainey, eds. *Methods for conducting military operational analysis*. MORS, pp. 147–196.

Liwång, H., 2015. *Risk-based ship security analysis – a decision-support approach*,

Loerch, A.G. & Rainey, L.B., 2007. *Methods for Conducting Military Operational Analysis*, Lynch, D., 2004. *Introduction to RF Stealth*, SciTech Publishing Inc.

Mahulikar, S.P., Potnuru, S.K. & Arvind Rao, G., 2009. Study of sunshine, skyshine, and earthshine for aircraft infrared detection. *Journal of Optics A: Pure and Applied Optics*, 11(4), p.45703. Available at: http://stacks.iop.org/1464-4258/11/i=4/a=045703?key=crossref.2fd77bd37121f8a3560b2f927c99c45f.

McLean, I. & McMillan, A., 2014. Utility - Oxford Reference. *The Concise Oxford Dictionary of Politics (3 ed.)*. Available at: http://www.oxfordreference.com/view/10.1093/acref/9780199207800.001.0001/acref-9780199207800-e-1429?rskey=uk32Cp&result=1 [Accessed June 19, 2014].

Merriam-Webster, 2016a. Capability. *Merriam-Webster Dictionary*. Available at: http://www.merriam-webster.com/dictionary/capability [Accessed June 2, 2016].

Merriam-Webster, 2016b. Engineering. *Merriam-Webster Dictionary*.

Merriam-Webster, 2016c. Technology. *Merriam-Webster Dictionary*.

Morse, P.M. & Kimball, G.E., 1951. *Methods of Operations Research*, Cambridge, MA: M.I.T. Press.

NATO, 2015. *AAP-06 NATO Glossary of Terms and Definitions* Edition 20.,

NATO, 2013. Allied joint doctrine for operational-level planning.

OD, 2014. utility: definition of utility in Oxford dictionary (British & World English). *Oxford Dictionaries Online*. Available at: http://www.oxforddictionaries.com/definition/english/utility?q=Utility [Accessed June 19, 2014].

Prather, D.W. et al., 2009. *Photonic Crystals: Theory, Applications, and Fabrication*, Hoboken, NJ, USA: Wiley.

Quade, E.S. & Boucher, W.I. (eds), 1968. *Systems Analysis and Policy Planning: Applications in Defence*, Santa Monica, CA: the RAND Corporation.

Richards, M.G. et al., 2009. Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration. *Journal of Spacecraft and Rockets*, 46(5), pp.1049–1064.

Richards, M.G. et al., 2008. Systems Architecting for Survivability : Limitations of Existing Methods for Aerospace Systems. In *6th Conference on Systems Engineering Research*. Los Angeles, CA., pp. 1–12.

RTO, 2015. Assessment Methods for Camouflage in Operational Context (SCI-287). Available at: https://www.cso.nato.int/ACTIVITY_META.asp?ACT=7562.

Rubežien, V., Baltušnikait, J. & Padleckien, I., 2009. Development of Visible and Near Infrared Camouflage Textile Materials. *MATERIALS SCIENCE (MEDŽIAGOTYRA)*, 15(2), pp.1–5.

Saville, P., 2005. Review of Radar Absorbing Materials. , (January), p.62. Available at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA436262.

SEBoK, 2016. Life Cycle Cost. *Guide to the Systems Engineering Body of Knowledge, v. 1.6*. Available at: http://sebokwiki.org/wiki/Life_Cycle_Cost_(LCC)_(glossary) [Accessed June 15, 2016].

Sigalas, M.M. et al., 1994. Electromagnetic-wave propagation through dispersive and absorptive photonic-band-gap materials. *Physical Review B*, 49(16).

Sivertun, Å., 2012. Militärgeografi och GIS – delar av militärteknik. *Kungl Krigsvetenskapsakademiens Handlingar och Tidskrift(ISSN 0023-5369)*, (1), pp.108–120.

Skolnik, M.I., 2001. *Introduction to Radar Systems* 3rd ed., New York: McGraw-Hill.

Soban, D. & Mavris, D., 2000a. Formulation of a Methodology for the Probabilistic Assessment of System Effectiveness. In *AIAA Strategic and Tactical Missile System s Conference*. Monterey, CA: AIAA, pp. 1–12.

Soban, D. & Mavris, D., 2000b. Methodology for Assessing Survivability Tradeoffs in the Preliminary Design Process.

Soban, D.S., 2001. *A Methodology for the Probabilistic Assessment of System Effectiveness as Applied to Aircraft Survivability and Susceptibility*.

Soban, D.S. & Mavris, D.N., 2013. Assessing the Impact of Technology on Aircraft Systems Using Technology Impact Forecasting. *Journal of Aircraft*, 50(5), pp.1380–1393. Available at: http://arc.aiaa.org/doi/abs/10.2514/1.C031871.

Soban, D.S. & Mavris, D.N., 2001. Use of probabilistics in campaign analysis. *SAE Technical Papers*, (SAE World Aviation Congress-2001 Aerospace Congress). Available at: http://prx.library.gatech.edu/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-84877556735&site=eds-live&scope=site.

Stensson, P., 2015. Capability in Practice and Tactical Superiority. *The Journal of the JAPCC*, (21), pp.50–56. Available at: http://www.airpower.maxwell.af.mil/airchronicles/apj/apj95/spr95_files/bash.htm.

Stensson, P., 2014. *The Quest for Edge Awareness - Lessons not yet learned*,

Sun, J., Bhushan, B. & Tong, J., 2013. Structural coloration in nature. *RSC Advances*, 3(35), p.14862. Available at: http://xlink.rsc.org/?DOI=c3ra41096j [Accessed May 14, 2014].

SwAF, 2011. *Swedish Armed Forces development plan (in Swedish), HKV 23 320:52470, Annex 1.4*, Stockholm.

Thokala, P., 2009. *Life cycle cost modelling as an aircraft design decision support tool.* UNIVERSITY OF SOUTHAMPTON. Available at: http://eprints.soton.ac.uk/72021/.

Thokala, P., Scanlan, J. & Chipperfield, A., 2012. Framework for Aircraft Cost Optimization Using Multidisciplinary Analysis. *Journal of Aircraft*, 49(2), pp.367–374. Available at: http://arc.aiaa.org/doi/10.2514/1.C000187 [Accessed October 25, 2016].

Veszelei, M. et al., 1994. Optical constants and Drude analysis of sputtered zirconium nitride films. *Applied optics*, 33(10), pp.1993–2001. Available at: http://ao.osa.org/abstract.cfm?URI=ao-33-10-1993 [Accessed January 23, 2014].

Veszelei, M., Andersson, K.E. & Roos, A., 1993. Optical characterization of sputtered semitransparent zirconium nitride films. *Optical Materials*, 2(4), pp.257–266. Available at: http://www.sciencedirect.com/science/article/pii/092534679390022S [Accessed January 23, 2014].

Wake, L.V. & Brady, R.F., 1993. *Formulating Infrared Coatings for Defence Applications*, Available at: http://www.dtic.mil/dtic/tr/fulltext/u2/a267555.pdf.

Washburn, A. & Kress, M., 2009. *Combat modeling*, Dordrecht Heidelberg London New York: Springer.

Wasson, C.S., 2006. System Acceptability. In *System Analysis, Design, and Development - Concepts, Principles, and Practices*. John Wiley & Sons.

White, J.R., 2012. Aircraft Infrared Principles, Signatures, Threats, and Countermeasures. , (September).

Yablonovitch, E., 1987. Inhibited Spontaneous Emission in Solid-State Physics and Electronics. *Physical Review Letters*, 58(20), pp.2059–2062.

Yin, R.K., 2013. *Case Study Research - Design and Methods* 5th ed., Sage.

Yue, Y. & Henshaw, M., 2009. An Holistic View of UK Military Capability Development. *Defense & Security Analysis*, 25(1), pp.53–67.

Zdansky, E., 2012. *Ground winter signatures, an inventory, FOI-R--3509--SE*, Linköping, Sweden. Available at: http://www.foi.se/rapport?rNo=FOI-R--3509--SE [Accessed January 27, 2014].

ORIGINAL PUBLICATIONS

PAPER I

2014 SPIE. Republished, with permission, from:

Kent E Andersson and Christina Åkerlind,
A review of materials for spectral design coatings in
signature management applications,
Proc. SPIE Vol. 9253, 2014
https://doi.org/10.1117/12.2067167

Invited Paper

A review of materials for spectral design coatings in signature management applications

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ABSTRACT

The current focus in Swedish policy towards national security and high-end technical systems, together with a rapid development in multispectral sensor technology, adds to the utility of developing advanced materials for spectral design in signature management applications. A literature study was performed probing research databases for advancements. Qualitative text analysis was performed using a six-indicator instrument: spectrally selective reflectance; low gloss; low degree of polarization; low infrared emissivity; non-destructive properties in radar and in general controllability of optical properties. Trends are identified and the most interesting materials and coating designs are presented with relevant performance metrics. They are sorted into categories in the order of increasing complexity: pigments and paints, one-dimensional structures, multidimensional structures (including photonic crystals), and lastly biomimic and metamaterials. The military utility of the coatings is assessed qualitatively. The need for developing a framework for assessing the military utility of incrementally increasing the performance of spectrally selective coatings is identified.

Keywords: Spectral Design, Signature Management, Camouflage, Military Utility, Military-Technology, Coating

1. INTRODUCTION

In Swedish defense policy[1] focus has again widened from the focus in recent years on force protection in asymmetric expeditionary scenarios, to include national security. Military capabilities are assessed to be evolving towards high-end technology and a need for more competent personnel - at the cost of volume. In turn, fewer and more expensive platforms mean an increased interest in effect, of course, but also mobility. Mobility is often achieved by decreasing weight at the expense of less armor and the decreasing force protection capability is in turn compensated for with active Electronic Warfare systems and camouflage and deception means – i.e. systems for *Signature Management*. In parallel there is rapid development in multispectral sensor technology and a proliferation among non-state actors of advanced optronic, infrared and microwave sensors - increasing the threat to Swedish Armed Forces in international operations.[2] Both factors add to the utility of developing new more effective solutions for signature management. The need to camouflage soldiers is high in any event, and the requirement to conduct both expeditionary missions and be prepared for national protection scenarios drives the need for adaptive signatures of platforms and hence the need for Signature Management Technology (SMT).

Any property, or a combination of properties, of an object, that makes it distinguishable from its immediate background by a sensor defines the object signature.[3] However, this study is limited to the signature originating from electromagnetic interaction with the surface of an object. In addition, now that the need for SMT increasingly includes the infrared spectrum, there is a great demand for solutions meeting the requirements from visible through to long wavelength thermal infrared regions simultaneously. Furthermore, the need to adapt the signature to the full range of missions, in

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Optics and Photonics for Counterterrorism, Crime Fighting, and Defence X; and Optical Materials and Biomaterials in Security and Defence Systems Technology XI, edited by Douglas Burgess, Roberto Zamboni, et al., Proc. of SPIE Vol. 9253, 92530Y · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2067167

international as well as national scenarios, also increases the benefit of controllable signatures. The ability to actively control – multispectrally – the signature of an object, such as a combat vehicle, is thus sought after, but very limited.

Spectral design is the ability to create a desired spectral optical response from a surface in favor of the application of interest by choosing suitable materials and structures. The technique is used in several military applications: e.g. the optical filter on head-up displays, laser protective coatings on optics and heat radiation control. When using spectral design for SMT purposes the objective is to tune the spectral appearance of an object in support of military tactics. In some contexts a military object should be seen, e.g. for show of force or for deception. The most challenging case, however, is camouflage, i.e. trying to minimize the contrast between an object and its immediate background in those parts of the spectrum where the threat sensors are sensitive. Thus, the military effectiveness of SMT is related to the threat sensor capability and is often measured in *distance to detection* or *time before detection*. Meanwhile, emission in the remainder of the spectrum should, if possible, be optimized for emission of the excessive heat.[4]

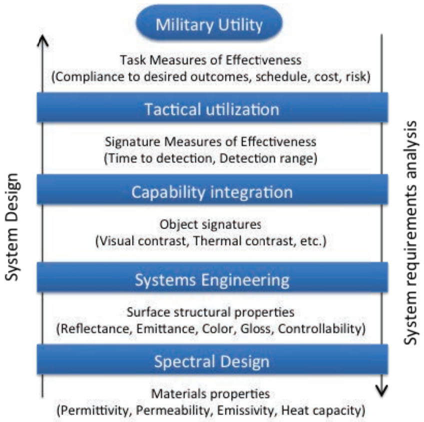

Figure 1. The illustration is a model of the spectral design leg of a signature management process seen as a balancing of needs and design choices in several activities at different system levels. When designing a capability, spectral design utilizes materials with favorable properties to obtain desired structural properties of surfaces in a technical system. System engineering activities balance surface properties with other design measures to obtain a desired object signature. When the object has been integrated into a capability, with proper techniques and procedures for its use, desired signature measures of effectiveness could be achieved. Ultimately proper tactical utilization of the system's capability gives effective support to accomplish the mission militarily. Only then does spectral design have military utility. When analyzing system requirements, the process is traversed in the other direction.

However, the signature of an object in a real environment is complex. Apart from the surface, reflectance and specular properties, it also depends on several factors such as the size of the object, the wavelength of the incident light, its polarization, and also on shadows and atmospheric phenomena. In order to design the signature and possible controllability, with the aid of Systems Engineering, the requirements process has to start with the object in its operational environment. The aim is to give the system designers the freedom to optimize the signature by balancing construction methods with chosen surface properties.[3] Here one must also balance signature management with other protection measures, such as physical and electronic warfare protection.[5] Finally, for a signature management system to have real military value you must know your signature; you must have a tactical concept for how to use it and the ability to adapt it rapidly to the tactical situation. Thus the process of designing a system with signature management capability, starting from a spectral design activity, is a complex one and is captured in Figure 1. Turning the process around, the figure also illustrates the equally complex process of formulating relevant requirements for spectral design and material properties.

Research into materials with the potential to be used in spectral design for SMT applications in the optical and thermal spectra is extensive. Apart from the military applications, it covers smart textiles, solar energy, “cool roofs”, decorative coatings, heat control of satellites etc. By exploiting these advances in the future, it may be possible to use spectral design to satisfy the new survivability requirements of signature management.

The work presented in this paper is a first effort in adding a military-technological perspective to spectral design for signature management, i.e. to assess the military utility. The aim is to review what types of materials and coating techniques are available for spectral design purposes and to get a rough idea what their utility is for SMT. Firstly, there is an introduction of terminology used and the desired characteristics of a spectral design coating. In order to limit and to focus the survey the use case is multispectral optical camouflage, i.e. reducing the contrast with the background. In the next section of the paper results are presented and discussed. Finally a summary of results, conclusions and a discussion on future work are presented.

1.1 Terminology and Physical quantities

Electromagnetic radiation (light) of some wavelength, λ, incident on an optically thin coating (thin film) is reflected, absorbed or transmitted, hence $I(\lambda)=R(\lambda)+A(\lambda)+T(\lambda)=100\%$, where $I(\lambda)$ is the intensity of the incident light , $R(\lambda)$ is the *reflectance*, $A(\lambda)$ is the *absorptance* and $T(\lambda)$ is the *transmittance*. If Maxwell´s equations are used to solve the boundary problem of a propagating wave at the surface between two media the Fresnel reflection coefficients are obtained,

$$r_p = \frac{N_1\cos(\theta_i) - N_0\cos(\theta_t)}{N_1\cos(\theta_i) + N_0\cos(\theta_t)}\,,\ r_s = \frac{N_0\cos(\theta_i) - N_1\cos(\theta_t)}{N_0\cos(\theta_i) + N_1\cos(\theta_t)} \text{ and } R(\lambda)=\boldsymbol{r}\cdot\boldsymbol{r}^* \tag{1}$$

where r_p is the reflection coefficient for light polarized parallel and r_s for light polarized perpendicular to the plane of incidence, respectively. These expressions show the relationship between the observable reflectance of a surface and optical properties, since $N_1 = n_1+ik_1$ is the complex refractive index of the coating material and N_0 is that of the ambient air. In a *dielectric* (non-absorbing) material the refractive index is real valued. θ_i is the angle of incidence to the surface normal and θ_t is the angle to the normal for refracted, transmitted, light.

Light reflected from a smooth surface, like a mirror, is *specular*, i.e. the angle of reflection is the same as the angle of incidence. Light reflected from a rough surface is *diffuse*, i.e. scattered in all directions. In SMT context the former surface is denoted *glossy* and the latter as *low gloss*.

If the x- and y- components of the electric field vector of a light wave propagating in z-direction are completely correlated the light is said to be totally *polarized*. If there is no correlation the light is said to be *unpolarized*, like from the sun or ordinary lamps.[6] Polarization features arise from the geometrical orientation, shape, shading and roughness of an object surface. In general, man-made objects with smooth surfaces have more defined polarization signatures than natural objects and tend to take on a polarized component in reflected or emitted radiation.[7] The ratio between the intensity of polarized light and the total intensity of light irradiated from a surface is denoted the *Degree of Polarization* (DoP).[6]

The radiaton emitted from a perfect blackbody, i.e. a surface emitting maximum possible energy, depends on wavelength and the absolute surface temperature T of an object. It is expressed through Planck´s radiation law as the spectral radiant exitance, $E_{bb}(\lambda,T)$, through

$$E_{bb}(\lambda,T) = \frac{c_1}{\lambda^5\left(e^{\frac{c_2}{\lambda T}} - 1\right)} \quad (\mathrm{Wm^{-2}\mu m^{-1}}) \tag{2}$$

where $c_{1\ \mathrm{and}}\ c_2$ are radiation constants, $c_1 = 3{,}7418 \times 10^8\ \mathrm{Wm^{-2}\mu m^4}$ and $c_2 = 1{,}4388 \times 10^4\ \mu\mathrm{m\,K}$. In practice most surfaces are not black and hence are called *gray bodies*.[8] The *Emittance* of a surface is obtained by integrating over all wavelengths for a specific temperature. The ratio between a surface gray body emittance and that of a blackbody is denoted *Emissivity*, ε. Hence, by designing the surface emissivity it is possible to tune an objects *apparent temperature* to that of the background.

1.2 Desired characteristics for coatings in multispectral low signature applications

From the definition of signature we find that it is partly defined by the sensitivity spectrum of the threat sensor. One justification for the research is, however, that sensors are becoming increasingly multispectral and hence we will not limit our interest to particular parts of the electromagnetic spectrum from the sensor sensitivity point of view. The aim is to design coatings that control emissions resulting from a combination of incident solar radiation and thermal self-emitted radiation. We will, however, assume that the sensors are used at such a distance that the attenuation and scattering of electromagnetic radiation from the object, due to interaction with molecules or aerosols in the atmosphere, greatly affect the detected intensity in some parts of the spectrum. From this point of view it is useful to discuss the optical properties of spectrally selective coatings in four wavelength regions; the UV-VIS-NIR region 0.2-2.5µm, the MWIR-region 3-5µm, the LWIR 8-14µm and the radar region >1mm.[8,9] The situation is illustrated in Figure 2 below.

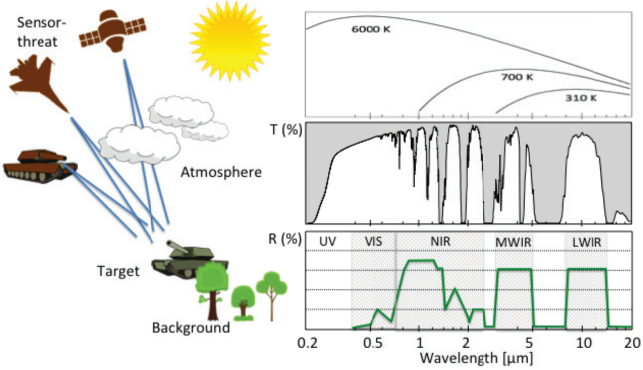

Figure 2. The picture to the left illustrates a typical detection/camouflage scenario. The right upper diagram shows the blackbody radiation spectra of the illuminating sun, the target exhaust and a soldier respectively. The middle diagram shows the transmittance spectra of the atmosphere. The atmospheric “windows” identified for detection; VIS, NIR, MWIR and LWIR are indicated in the lower diagram together with the “ideal” emission spectra of a coating used to camouflage a ground target in the situation depicted.

In the UV-VIS-NIR region the electromagnetic radiation from an object is dominated by reflected light from the sun, the moon, the stars or from an artificial light source. In this interval it is, therefore, relevant to study the materials reflective properties. Now, the sensors in UV-VIS-NIR are sensitive to spectral variations in the detected radiation, e.g. the human eye or any imaging device such as a camera. Therefore, low signature requires the reflectance of an object surface to be spectrally adapted to that of the object background. Our first characteristic of a potentially good coating for signature management purposes is, therefore, *spectrally selective reflectance*, close to that of the background. This usually means R_{VIS} <15%, $R_{NIR(green)}$: 45-60%, $R_{NIR(brown)}$: 10-25% and $R_{NIR(black)}$: 5-10% in accordance with earlier studies.[10–12] The background response indicated in Figure 2 is chlorophyll-like in VIS-NIR.

There are, however, a further two parameters to take into account in the UV-VIS-NIR region. A glossy surface reveals an object regardless of spectral adaptability. Hence a second required characteristic is *low gloss*.[3(p83)]

Furthermore, there are reports of development in Spectropolarimetric imaging. These sensors are sensitive to the polarization state of light irradiated from a surface, in addition to spectral intensity, and show potential for more robust detection of objects in a complex and cluttered environment.[7] *Low degree of polarization* is, therefore, proposed as a third characteristic.

In the MWIR or LWIR regions the electromagnetic radiation from an object is dominated by its own thermal radiation, which is why it is relevant to study material emissivity in this part of the spectrum. The emissivity of naturally occurring backgrounds, such as vegetation, rock or sand is almost always higher than man-made objects, especially those made of metal. However, since the objects we would like to camouflage are often hotter than their surroundings, this is usually a good thing. The apparent thermal contrast with the background stays small. *Low infrared emissivity* is, therefore, considered to be a fourth characteristic of low signature materials in this study. This value can easily be increased as needed and in this work an emissivity of about 0.4-0.6 is considered to be acceptable, in accordance with, for example, Hallberg et al.[10(p7)]

In the radar wavelength region a target is detected by illuminating the object and detecting the reflected energy. A signature management coating for optical wavelengths must therefore not interfere with the targets spectral design for radar wavelengths.[13] In most applications this means the reflectance of the coating should be very low. This can be achieved by making the coating very thin and transmissive, deposited on top of a radar absorbing coating, or by using a material with high absorption. In some use cases, however, the radar reflectance should instead be high, e.g. when deposited on the cockpit glass dome of a combat aircraft.[†] Our fifth indicator of a low signature coating material relates to the radar spectrum and, due to the contradicting requirements of different applications, the indicator is formulated as *non-destructive properties.*

From the arguments above we find that, in order to be really useful, the signature system of a mobile military object has to be adaptable to environment, background, weather, threat level and mission. One way of meeting these demands is to use exchangeable skins, camouflage nets, uniforms etc. If, however, the need to change signature is within the framework of a mission, the situation requires the surface coating to have adjustable optical properties. Hence, our sixth characteristic of a coating for signature management purposes is *controllability* at optical wavelengths. Hitherto sensors have not been very selective, spectrally, in the thermal infrared part of the spectra, but there is a development towards multiband detectors.

2. METHOD AND LITERATURE

The survey was conducted as a literature search followed by a qualitative assessment of utility, using the six characteristics of a coating for multispectral optical SMT identified above as indicators. The databases *Web of Science*, *Scopus*, *CSA* and *SPIE* were chosen and probed for articles.[‡] Articles were excluded if their focus was clearly on other phenomena, properties or applications than those of interest to this study, or if the article focused on measurement techniques. In a first iteration the exclusion criteria were applied to titles and in a second to abstracts. Publically available research reports with experimental data from the Swedish Defence Research Agency, FOI, are considered of

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[†] If the glass dome were to transmit radar wavelengths the inside of the cockpit would make an effective radar reflector. A thin metallic film on the glass surface reflects radar waves in all directions but transmits visible light.

[‡] Modifications of the following search string was used: (*review* OR *characterisation* OR *measurement**) AND (*reflect** OR *"low emissive*"* OR *dielectric* OR *diffuse* OR *lambertian* OR *"low gloss"* OR *infrared* OR *IR* OR *TIR* OR *optical* OR *tunable* OR *adapt**) AND (*chromogenic** OR *"thermo chromic"* OR *"electro chromic"* OR *multilayer* OR *metamaterial** OR *pigment** OR *polymer** OR *"nano composite*"* OR *tailor**) AND (*surface** OR *coating** OR *material** OR *structure**) AND (*BRDF* OR *scatterometry* OR *camouflage* OR *"signature management"*).

scientific quality and are used if relevant. Review articles, written by established researchers in the respective fields studied, were used to narrow the scope of the survey back in time.

3. RESULTS AND DISCUSSION

Designs for spectrally selective coatings can be divided into two categories, paints and pigments or periodic surface structures.[14(p18)] The latter are further divided into subcategories in order of increasing complexity: one-dimensional structures, multidimensional structures (including photonic crystals), and lastly biomimic and metamaterials.

3.1 Paints and pigments

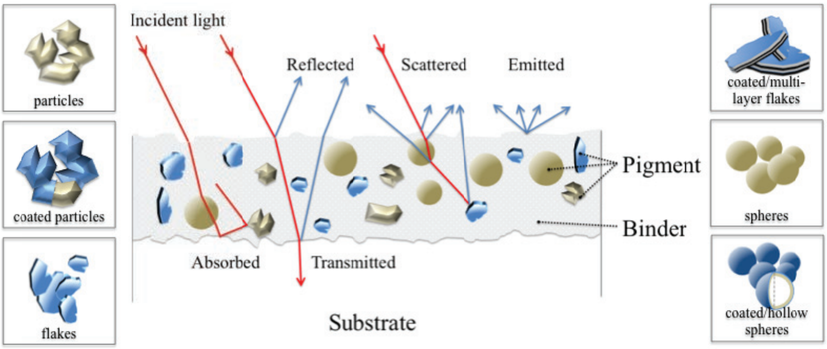

Figure 3. In the middle there is an illustration of a typical paint coating system and possible interactions with light. The paint consists of a mixture of pigments in a binder applied to a substrate. To the left and right pigments of different complexity are depicted.

As an introduction[15] to paint coating systems, they generally consist of pigments and a binder on a substrate, see Figure 3, and the *pigment material*, *the particle size*, *the particle shape* and *the paint binder* are all important parameters when designing its spectral properties. Apart from absorption within the coating and reflection at the boundaries, the particle size and shape affect the optical response of a material through backscattering, a phenomenon commonly used in spectral design of VIS-NIR spectrally selective coatings. The emission from the surface due to backscattering will increase if the ratio between the refractive index of the particles and of the binder increases. Consequently, in order to be able to adjust the paint properties with a suitable mix of pigments, binders should also exhibit as low absorption as possible throughout the region of interest. Of course the binder must also provide adhesion to the substrate (not a requirement in temporary paints), protect the pigments and preserve their infrared properties.

In 1993 Wake and Brady summarized development in VIS-NIR spectral design coatings and addressed some of the challenges of extending spectral requirements to the Thermal IR region (TIR).[15] They stated that the traditional organic and inorganic pigments used to damp reflectance in VIS cannot be used, since they also absorb TIR and thus cause high emissivity. From extensive experiments they learnt that exploiting scattering from large pigment particles is restricted in TIR. The size needed would risk making a coating "visibly coarse and would affect color uniformity, dirt retention, and other important performance properties"[15,16] A possible approach, Wake & Brady conclude, is to use metal flake pigments, e.g. aluminum, which provide strong reflection across the visible and infrared spectrum. Flaked metal pigments are chosen over particle shaped ones since they maintain high reflectivity when compounded in a film, due to their relatively large flat surfaces.

Hallberg et al. pick up on this line of study comparing different types of pigment for low emissive applications[10]. They study highly reflective Al, Ag and Cu flake pigments, uncoated or coated with dielectrics. However, since these materials also are highly reflective in VIS, they conclude that, unfortunately, these types of pigments reduce the camouflage performance in the visible part of the spectrum. An anti-reflectance treated $TiO_2/Au/TiO_2$ flake pigment was also produced using magnetron sputtering and dividing the thin film into flakes when removed from the substrate. A paint meet transmittance requirements in VIS, but not low emittance requirements. Hallberg et al. conclude that among pure metal pigments, only Al, in combination with polymer-based binders, gives acceptably low emissivity. They report that the most probable explanation is that Al naturally forms a stable oxide protecting it from deteriorating chemical reactions with the binder. Furthermore, the level of emissivity can be adjusted easily by tuning the Al flake density in the paint. A semiconductor like Si is heavily absorbent of wavelengths shorter than the bandgap wavelength, for Si this is below 1.1μm. Hence, it looks black in VIS and can be used to lower reflectivity.

A study of the use of metal-coated cenospheres as pigments in low emissive paints was conducted by Hedborg Karlsson & Hallberg et al.[10,17,18] A cenosphere is an inert and hollow sphere consisting of silicon dioxide and aluminum oxide. Coated spheres showed much the same properties as the respective metal powder in both VIS and IR, but when mixed with a binder the absorption in LWIR was much too high. One hypothesis was that the spheres fell to the bottom of the paint.[§] The need for a new binder or a more inert metal coating was identified. The conductivity of the Al-coated cenospheres was, however, found to be lower than that of corresponding metal pigments, which is why the authors expect the radar transmittance to be better. Metal flakes have a tendency to agglomerate and thus cause high reflectivity in RR.[**]

A large portion of the hits from the database search for developments in recent years in pigments with NIR-reflecting properties concern the roofing industry and originate from an interest in producing “cool roofs” for energy saving purposes. Researchers report coatings with pigments yielding different colors while still exhibiting NIR-reflectance in the 70-90% range.[19–24] The substrates are generally clay and the coatings are applied through engobing.

In the military sector there is great interest in lowering the signature of soldiers in the VIS-NIR wavelength region where night vision goggles are becoming a high volume threat.[2,25–32] The blending of artificial and natural fibers in fabric for modern uniforms normally gives NIR-reflectance that is too high when compared to natural background,[33] which is why new pigments are being developed for lowering NIR-reflectivity, such as NIR-absorbing Vat dyes.[34] Washing, though, seems to deteriorate performance if using textile printing techniques and paste with low emissive pigments. Incorporating pigments in the polymer fiber at the fiber forming process, however, seems to be feasible since this can be combined with textile printing with reactive dyes for VIS-NIR performance.

Mao et al. recently presented emissivity as low as 0.63 in coated cotton fabric using pigments of Al and La doped ZnO.[35] In another report Mao et al. show a lowering of the cotton fabric emissivity using a coating with W-doped VO_2 pigments. They were also able to show that this kind of fabric changed emissivity spontaneously with changes of ambient temperature.[36] Mao et al. suggest using both coatings on uniforms for infrared camouflage. No other indicator characteristics than LWIR emissivity is reported. There are no comments on degradation due to wear and tear. Pigments with chromogenic properties would be of interest for the desired controllability aspect of surfaces. There are also reports on TC-pigments being characterized.[36,37] This development is of interest in spectral design for thermal control purposes, especially on simple lightweight systems like uniforms.

Wake and Brady reported on the impact of binders in paint coating systems in 1993 and suggest selecting pigments with refractive indices and particle size and shape that scatter light effectively in bands where resins absorb.[15] Resins and binders with weak absorption in parts of TIR of interest have been studied by several researchers: e.g. polyvinylidene

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[§] Personal comm. with Thomas Hallberg 12-08-2014

[**] Ibid

fluoride[38]; dimethyl silicone resins[39]; inorganic silicate oligomers-form polymers[40]; polyurethanes, vinyl polymers, silicone polymers, epoxy resins, polyethylene and chlorinated polyolefine[41].

There are also a few studies that have reported on complete paint coating systems for optically multispectral SMT. These results can serve as a snapshot of current developments. The reported performance of these coatings, filtered using the six-indicator instrument, is presented in table 1. Note that the pigments used are based on Al flakes. Hallberg et al. comment on the binder that "except for the IR reflective pigment and the binder, the paint should include many other ingredients or additives which will improve various properties of the paint, such as: solvent (water), thickener, coalescent, dispersing agent, antifoaming agent, extender, anticorrosion agent, and different kinds of color pigments for the visual camouflage" and that these additives seem to increase the emissivity of a paint by about 10%.[10] Hedborg Karlsson et al. point out that the infrared reflectance is higher for the paint than for its individual components. [42] The authors also considered the adhesion of their paint to be insufficient. The best combination of visible and TIR properties is reported by Shen et al. using a relatively complex Al based flake pigment. They are coated with SiO_2 in order to prevent them oxidizing, which would otherwise increase the pigment emissivity. The high visible reflectivity of Al/SiO_2 is reduced by depositing metal oxides, ferro-cyanide and pure metal on the surface. None of the studies, however, reports on all the characteristics considered of interest for spectral design coatings in this review.

Table 1. The three best performing paints identified in the survey compared to desired characteristics.

Coating syst.	*RVIS-NIR*	*Gloss*	*DoP*	*Emissivity*	*RR*	*Controllability*
Desired:	R_{VIS} <15, $R_{NIR(g.)}$ 45-60, $R_{NIR(br.)}$ 10-25, $R_{NIR(bl.)}$ 5-10%	Low	Low	0.4-0.6	Non destruct. (low R_{RR})	Switchable in near real time
18 µm Al, flake, in water solvable polymethyle acrylate, (Hallberg et al. 2005)[10]	"Green"	N.R.	N.R.	E_{MWIR} 0.4 E_{LWIR} 0.5	$T_{RR(X)}$ >70%	In design phase
10-20 Al, flake, in PEDOT:PSS, (Hedborg Karlsson et al. 2007)[42]	R_{NIR} 50-70%	N.R.	N.R.	0.2-0.3	N.R.	In design phase
$Al/SiO_2/Fe_2O_3/FeO$ $/Fe_4[Fe(CN)_6]_3/Cr_2O_3/Cr$, coated flake, in Appretan® N96101, (Shen et al. 2012) [43]	R_{VIS} <15, $R_{NIR(g.)}$ 55% (0.38~1.2µm)	N.R.	N.R.	E_{LWIR} 0.51-0.55	N.R.	In design phase

N.R. = Not reported

Summing up, the paint coating system remains an important area for research. There is currently an interest in multispectral aspects, such as: advanced pigments for low emissivity and selective properties in VIS-NIR, binders with little absorption in MWIR and LWIR and printing techniques for textiles.

3.2 One-dimensional structures

Moving from paints with pigments to coatings with layers of deposited optical films, we find other techniques and applications. Results from research in solar energy applications are assessed to be of particular interest since many of the challenges in techniques and processing are the same as in signature management, and even some of the desired characteristics in coatings are similar.

C.G. Granqvist sorts spectrally selective coatings into four categories: *Low heat transfer* (high $T/A_{VIS+NIR}$, high R_{TIR}); *Solar control* (high T_{VIS}, high $R_{NIR+TIR}$); *Smart Windows* (Adaptable R/T) and *Passive cooling* (Low R_{TIR}).[44] From the respective design criteria we find the second and third categories of primary interest in this study.

Multilayer interference coatings for solar control are traditionally based on thin semi-transparent noble metal films deposited on glass substrates, embedded between oxide films of high refractive indices for antireflection and atmospheric protection purposes.[45] Durability is known to be a problem. Exchanging the metal film for metal nitrides, such as TiN or ZrN, is an option studied by Andersson et al. A R_{VIS} of <20%, a R_{NIR} 20-70% was reported.[46,47] From reported data the emissivity is assessed to be in the 0.2-0.4 range. The films are specular and the polarization and radar-transmission are not known. Hallberg et al. have, however, demonstrated a possible method of exploiting the properties of multilayer coatings in signature management applications, despite the gloss, by removing the coating from the substrate and breaking it up into pigments.[10] However, the high R_{NIR} of the Au-pigment could not be achieved in the resulting paint. Nevertheless, pending the reasons for insufficient performance in the paint formulated by Hallberg et al. it would be interesting to investigate other highly IR-reflective, more stable, multilayer coatings used as pigments.

Efforts to achieve adaptable signatures in near real time make electro-chromic (EC) switching especially interesting since this phenomenon makes the optical performance of a surface controllable by using an electric signal. TC-coatings are undoubtedly of interest for spectral design purposes in heat control. Chemical switching[48] and other switching phenomena could of course add to the knowledge of switching mechanisms for controllability, but have to be omitted from this survey because of a lack of space. In a paper on recent advances in chromogenics in 2009[49] Granqvist et al report on EC-coatings for fenestration applications with considerable controllable transmittance intervals. They present a short overview of designing EC devices for fenestration purposes, consolidated in Table 2 below. Their latest results concern a polyester (PET) foil device, indicated in bold. The substrates were sputter coated and the final device was 0.4mm thick and flexible. The mid-luminous transmittance, ΔT, is reported to be 55% with maximum transmittance around 70%, and the time from colored to bleached state is about 30s. For this paper it is interesting to note that R_{VIS} switches between 8 and approximately 15%. R_{NIR} is 30% at its maximum at around 2μm. In a later review[50] Granqvist reports on different EC-designs commercially available, with pros and cons, indicating that EC-switching technology has become mature for solar energy applications. A few years earlier some challenges in producing high quality devices on a large scale were reported.[49]

Table 2. An overview of designs for EC fenestration devices, based on advances reported by Granqvist et al 2009 (Their own latest device in bold).

Layer #	Function	Alternatives for fenestration[49]
1	Substrate	**Flexible Polyester (PET) foil,** Glass
2	Transparent conductor, electrode	**In_2O_3:Sn (i.e. ITO)**, heavily doped oxide semiconductors such as ZnO:Al, ZnO:Ga, or SnO_2:F. And possibly Metal-based coatings, carbon nanotubes or graphene
3	Ion Storage layer/EC	"Many", but IrO_2 and **NiO** are of recent interest. IrO2 is expensive but has good EC-properties after dilution with cheaper Ta_2O_5. NiO-based films mixed with wide band gap oxides, such as MgO or Al_2O_3, is an option.
4	Ion conducting electrolyte	"Many", including polymers with ion conduction due to added salts, ionic liquids, and hydrous oxides exhibiting proton conduction
5	Electro Chromic layer (EC)	**WO_3**
6	Transparent conductor, electrode	See layer 2
7	Substrate	See layer 1

Chandrasekhar et al.[51–53], and others[54], have presented different EC-devices with performance of interest to signature management in IR and for heat control of spacecraft. Using various parameters Chandrasekhar et al. demonstrate how their EC-devices can be tailored for optimized performance in specifically the MWIR and LWIR windows.[51] "This is seen in practical Conducting Polymer devices in the form of thin (<0.5 mm), flexible, entirely solid-state, variable area

($1cm^2$ to $1m^2$) flat panels. Typical properties include: very high reflectance variation; switching times <2 s."[55] The MWIR emissivity can be varied between approximately 0.55 and 0.8 and the LWIR emissivity can be varied between approximately 0.3 and 0.85.

The reflectance phenomena exploited in the materials presented so far have originated from boundaries. There are, however, some materials with lattice resonances, phonons, in the infrared part of the spectrum caused by light interacting with ion-pair dipoles. These quasi-particles are called *Polaritons* to separate them from ordinary lattice vibrations and hence the materials are called polar materials. To conclude, this is a bulk phenomenon and the optical consequence is an interval of high reflectance. In the literature this interval is known as the *Reststrahlen band* or the *Polaritonic bandgap*[56]. Sigalas et al. studied GaAs, but there are many materials exhibiting reststrahlen bands (see, for example, the Handbook of Optics [57]), though not that many in that part of IR of interest.

Beryllium Oxide (BeO) and Boron Nitride (BN) are two examples. They have reststrahlen bands resulting in high reflectance in the 9.5-15µm and the 8-9.5µm regions respectively. Ribbing showed in 1993 that a 2.5µm layer of BeO on BN could result in a coating with low emissivity, lower than 0.2 on average, covering the width of the LWIR atmospheric window[58]. Later the use of BeO in radar domes was suggested.[59] This use would exploit the low emissivity, the off-band high emissivity and the excellent heat conducting properties – to reduce the probability of detection from IR sensors – combined with the electrical insulating properties allowing radar transmittance. The reflectance is diffuse and in the 80% range.[59] Since the safe deposition of a thin film of BeO on a substrate "is not a trivial problem"[58], Ribbing et al. also suggest an alternative solution. A 0.83µm thin layer of Silicon is reported as being deposited on BeO in order to maximize the reflectivity on the short wavelength side of the low emissivity band. The resulting emittance is reported to be 0.1.[59]

Högström et al.[60,61] have also studied the coexistence of polaritonic and structure bandgaps in a multi-layer Si/SiO_2 one-dimensional photonic crystal produced using Chemical Vapor Deposition. Silicon was used as a high index dielectric and SiO_2 was used as a low index dielectric. In addition SiO_2 has a reststrahlen band in the 8-9.3µm wavelength range. It was shown that the two bandgap phenomena can be combined and that the polaritonic gap can either be strengthened or made to vanish by choice of periodic structure.[47] It is even possible to combine the two materials in a coating design to give low emittance in both atmospheric windows, 0.24 in MWIR and 0.38 in TIR, exploiting the structure gap for the former and the polaritonic gap for the latter.[58] In between the windows the emissivity is mostly above 0.7. The polaritonic gap reflectance is reported to be robust, while the structure gap reflectance is sensitive to angle of incidence. The structure reflectance moves to shorter wavelengths and the polaritonic reflectance widens with angle of incidence.[62]

Lately rather complex structured bandgap materials have been reported. Zhao et al. report on the possible performance of a one-dimensional, two defect modes, photonic crystal based on principles of Distributed Bragg Reflector microcavity[††]. The structure was modeled with the MWIR and LWIR-transparent materials, PbTe and Na_3AlF_6, as high refractive index and low refractive index materials respectively. This way it is possible to obtain a photon inhibiting, highly reflective, band cross the 1-20µm spectrum. At the same time, at 1.06µm and 10.6µm, the two microcavities cause spectral transmittance greater than 96%, i.e. at military laser wavelengths. The authors conclude that this performance will satisfy laser and infrared stealth in NIR, MWIR and LWIR.[63] The material is far from being put to use, but the results show the potential in this line of development.

Ribbing, however, explains that some promising results have been accomplished using photonic crystal as a component in a Multi-Spectral Camouflage Coating (MSCC) for ground applications as well as for aircraft applications[‡‡]. Nordin

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[††] Defects in the periodic structure designed to be resonators at a very specific wavelength

[‡‡] Personal communication, Professor Carl-Gustaf Ribbing, June 2014

reported on this at a Swedish seminar on signature management in 2012.[64§§] MSCC is a 2mm thick rubber-like decal in three layers, supplied by the meter. The bottom layer is for radar absorption, the middle layer is for IR and the topmost layer is for VIS and NIR. Decals of the MSCC are cut from the roll and glued directly to the surface of the platform. The presentation did not include performance details other than that the IR layer design is based on photonic crystal and that it has proved to be transparent for radar wavelengths. Results from characterization would be interesting.

Summing up, one-dimensional structures, i.e. multilayer coatings, have at least three directions of development. Multilayer interference coatings are used to tailor bands of maximum reflectance or transmittance, and hence is one approach to better low emissive pigments. Another direction of development is so called bandgap materials, either natural polaritonic materials, or (periodic) structured bandgap materials. Their advantage is having bands of reflectance without being electrically conductive. However, it is still not clear how to apply them in a coating system. If applied as a decal they risk having a strongly angular dependent reflectance. A third direction of development is flexible and controllable electro-chromic devices utilizing conducting polymers, potentially applied as decals on military platforms. One-dimensional structures, however, run the risk of being glossy.

3.3 Multidimensional structures

In 1987 Yablonovitch and John published papers on how to control electromagnetic wave propagation in man-made periodic structures of dielectric media, later called Photonic Crystals (PhC). It was shown that, under certain structural symmetry conditions and a large enough ratio between refractive indices of the constituent dielectric materials, an energy band gap appears. The term (optical) band gap is used in analogy with electronic band gaps.[65,66] There may be gaps in the energy band structure of the crystal, meaning that electrons are prevented from propagating with certain energies in certain directions. If the lattice potential is strong enough, the gap can extend to cover all possible propagation directions, resulting in a *complete band gap*. The optical analogue is the PhC, in which the atoms or molecules are replaced by macroscopic media with differing dielectric constants, and the periodic potential is replaced by a periodic dielectric function. If the dielectric constants of the materials in the crystal are sufficiently different, and if the absorption of light by the materials is minimal, then the refractions and reflections of light from all of the various interfaces can produce many of the same phenomena for photons (light modes) that the atomic potential produces for electrons.[67] The optical consequences are suppression of emission in the crystal and total reflectance of light in a wavelength region determined by the lattice constant of the structure and with a broadening corresponding to the band gap. One might also note that the preconditions for constructive interference in multilayer interference coatings and reflectance bands from photonic crystals show strong analogy. This would be why interference coatings are sometimes also called one-dimensional photonic crystals or structured band gap materials. Thus, a naïve approach to the theory of 3D photonic crystals would be to view them as a “3D interference” phenomenon. To conclude, the potential in 3D photonic crystals for spectral design is twofold. Firstly, to limit the angular dependence of emission, and secondly, the possibility of tailoring the spectral width and position of reflectance and transmittance bands using easy-to-come-by-and-process materials simply by tuning structure and symmetry.

PhCs discussed at the beginning of the section are compounds of dielectrics. As early as 1996, though, Sigalas et al. pointed out features using metals. The materials would be much smaller in size and weight than the all dielectric photonic band gap materials, but would be absorbent.[68] There is a continued interest in metallic PhCs and some reported applications in spectral design.[69,70]

During the last half of the 1990s the manufacture and characterization of 3D PhCs developed from being possible at millimeter wavelengths to NIR.[71–73] In 2006 Aliev et al. reported the successful fabrication of large surface areas of 3D PhCs optimized for high reflectivity in the MWIR and LWIR bands. The process involved self-assembling large SiO_2

[§§] http://www.yki.se/en/media/news/Sidor/090831.aspx, 20/08/2014 spheres, of 0.8 – 4.5μm diameters, followed by melt infiltration with chalcogenide glass $Ge_{33}As_{12}Se_{55}$ and removal of the SiO_2 spheres by chemical etching.[74] The title of the paper indicates fabrication of pigments, but this part of the process is not described. Characterization of a paint coating system with this kind of synthetic pigment would be very interesting, but to our knowledge nothing has been reported.

Today, when doing literature search for PhCs, there is a vast amount of matching and very recent references, most with applications such as PhC-fibers, optical waveguides, components in efficient lasers and other. There are, however, a few authors reporting research into multispectral SMT. Albertoni et al. simulate a set of PhC structures and show the possibility of managing the flow of LWIR light around a target and how to control it in order to make a thermal photonic camouflage device. "The PhC is able to collect thermal light from the environment and transport it virtually on every point of the devices". The authors state that these devices can be designed to change the reflection angle in order to camouflage the spatial signature of the target.[75,76] Kadiyala et al. demonstrate, through optical modeling of polymerized colloidal crystalline array (PCCA) structures, a novel concept that has the potential to enable the use of tunable 3D photonic crystals for adaptive camouflage. The phenomenon used for tuning is photo-responsive isomerization. The wavelength shift reported using a diamond lattice structure of spheres surrounded with azobenzene polymer is only a few nanometers. The authors state, however, that they will continue to optimize the model by varying different lattice parameters and material properties and that "the ultimate result of all such optimizations is to achieve an all angle adaptive camouflage coating".[77]

To summarize, there is extensive research on photonic crystals and the research for spectral design purposes could benefit. 3D PhC pigments have been realized using seemingly cost effective fabrication techniques, but the application in paint coating systems remains to be seen. There are results reported indicating that continued research on PhCs turns into research on Metamaterials (see next section) and advanced management of light rays.

3.4 Biomimic and Metamaterials

Environmental friendly non-fading brilliant colors seen on the feathers of some birds, and on the wings of butterflies, are due to structures and are thus called *Structural Colors*. The phenomenon was first observed and described by Hooke in "Micrographia" in 1665.[78] There has been a vast number of studies since on the optical properties of multilayers in fish scales, on photonic structures in butterfly wings and on the iridescence from golden beetles etc., describing the structural colors, the photonic crystals and other optical surface properties in nature.[79–86]

Structural coloration is based on the reflection of light while pigment coloration is a result of absorption. Structural colors can be both iridescent, when the color changes with viewing angle (interference or diffraction phenomena), and non-iridescent, when the color originates from scattering and structural irregularities. Sun et.al. have produced an excellent review of the different kinds of colors structures, and have also described attempts at mimicking.[87] The coloration of mimicked structures will, as in the natural case, arise through common physical mechanisms such as thin film or multilayer interference, diffraction gratings, scattering (coherent and incoherent) and photonic crystals etc., depending on the composition of the building blocks.

Biomimetics, introduced by Schmitt in 1957[88], is the art of mimicking structures, found in nature, to improve functionality in artificial devices and to find inspiration for novel applications.[89,90] One example is butterfly wings. They have been used as a template for preparing replicas in the form of large area periodic ZrO_2 structures for potential applications and integration in optical technology**.**[91] Another example is the reflective scales on the wings of the butterfly *Argyrophorus argenteus*, which have broadband reflecting properties. Scaled-up replicas with thicknesses < 1μm have been manufactured and investigated using microwaves.[92] It has been suggested that the structures of cicada wings have a camouflage-like anti-reflection function[93] and inorganic replicas of these structures, for use in solar cell applications, are now emerging.[94]

Tailored reflectance is desirable in SMT. Fractals as a concept was first introduced by Mandelbrot in the 1970s.[95] A fractal is a fragmented geometric shape that is self-similar, i.e. when several parts shaped alike are put together, the new larger shape, looks like one of the smaller shapes. Fractal structures often have properties between random and ordered structures and can be of interest in obtaining broadband reflectance. Examples of structures closely resembling fractal structures are found in nature, these could include mountain ranges, river networks, coastlines, snowflakes, blood vessel systems and broccoli.

Polarization is another important characteristic in SMT. Polarization is in fact important for the sight of birds and insects; the dung beetle needs to sense polarization for orientation,[96] and there have been some studies of reflected light from the cuticles of beetles.[97–99] Polarization properties vary between: specular reflection, polarizing light circularly, strong scattering of linear polarized light, preserving polarization and having depolarizing properties.[99] Attempts to mimic polarization effects have also been exemplified by Sun et.al.[87]

Controllability is yet another example of desirable features in SMT and several examples of dynamic colors exist in nature, for example in insects or squids. A color change can be caused by a variation in the photonic structure, in the angle of incident light, in index of refraction contrast, or other environmental stimuli such as humidity or temperature. Attempts to mimic are exemplified by Sun et.al.[87]

In biology structures with double functionalities are common. One example is the combination of an optical characteristic and water repelling function, such as the anti-reflective eyes of a moth. Inspired by this, Askar et.al have shown how the hydrophobicity of a substrate surface can be enhanced and self-cleaning AR coatings developed, using structures of nanopillars with high aspect ratio properties. These coatings can be useful in improving conversion efficiency and reducing glare in optical devices.[100]

In biology simple materials are used. The most abundant and complex structures found in nature, chitin, cellulose and chlorophyll, are built from combinations of carbon, oxygen and hydrogen. The microstructure of chitin, for example, is, however, the origin for iridescent colors of butterflies and insects, which in turn have inspired the development of future photonic structure materials.[10194102] In the laboratory environment, on the other hand, very complex materials are created, but often in very simple structures. Nevertheless, with the development in nanotechnology and manufacturing, and with inspiration from nature, future combinations of complex materials and advanced structures are assessed to have great potential – for example, in spectral design for SMT.

Two examples are chosen to show the potential in nano-composites for camouflage. Chun et al. deposit a nanocomposite coating of Ni-P-CB on an ABS plastic matrix and show that it has low infrared emissivity.[103] Wang shows how improved microwave absorption in a wide band, combined with low infrared emissivity, can be achieved by incorporating TiO_2 or Al_2O_3 into an ordered mesoporous structure of carbon. Besides good impedance matching, the large surface area and tunable pore-size make it an interesting material for a vast range of applications. Wang et al. suggest using it for simultaneous microwave absorption and infrared camouflage.[104,105]

Metamaterials are often described as artificial structures appearing as a material at some frequency range, with properties that cannot be found in nature. The properties of metamaterials are gained from the structure instead of the material. Applications range from perfect or super-focusing lenses, antennas, all-optical memories and gradient-index materials to “invisibility” cloaking. Even though total invisibility is impossible, the reduction of both optical and acoustic visibility is important in general terms for signature reduction. However, today, optical metamaterials at visible wavelengths are extremely thin and rather glossy, which means the synthesis is rather challenging.[106]

To some extent military signature management and space applications are alike; functionality is needed in a harsh environment. Venancio et.al, have presented an excellent list of classification of metamaterial with promising properties for space applications, from surfaces with anti-reflection to absorbent properties, sub-diffraction imaging properties and materials with polarization control functions and lastly, spectral properties for filtering and for dichroic properties. They suggest further studies on following functionalities and metamaterials for space application: An absorber for stray-light baffling using low-density arrays of long nanotubes and polarization scrambling using either 1D meander structure or double mesh structures.[107]

An important part of research, in order to understand and concretize future advanced structures, such as multispectral camouflage, is modeling and simulation. A few examples of theoretical modeling of metamaterials deal with anti-reflection properties[108], modification of radiation characteristics[75], tunable photonic bandgaps for electromagnetic invisibility cloaks[76] and high-absorption surfaces[109]. Thanks to improvements in micro and nano-technology some are even experimentally verified. Realization of large surface area lithographic methods, for example micro contact printing or nano-imprint, is enabled through the use of realistic geometrics for the structures, such as metallic cross grating or perforated plates.[108] Chen has produced an excellent overview and has also theoretically and practically studied the feasibility and implementation of mantle cloaks for 1-3D objects.[110] He found them beneficial for invisibility and camouflage applications because they reduce the overall visibility.

Today limited bandwidth, losses and imperfections severely limit current metamaterial cloaks. A low profile of an ultra-thin mantle cloak improves bandwidth limitations; however, little or nothing is said about the robustness to losses. Often theoretical simulations show promising results that are difficult to realize due to imperfections.

To summarize, functionality in nature is, to a large extent, based on complex structures and a lot can be mimicked to find new and effective or multifunctional design solutions, not least in spectral design. There is potential in being able to combine the complex structures of nature with the complex materials of material science. Great challenges remain to overcome problems regarding bandwidth and losses at short frequencies.

A final note, the categorization of materials and structure concepts used in this paper is not perfect, as there are materials and structures that might fit into several categories. There are trends also in materials and structures research it seems.

4. SUMMARY AND CONCLUSIONS

An overview of materials, surface structures and coating principles of potential interest for signature management applications using spectral design is presented. In order to limit the scope of the survey, the desired properties used as indicators were derived from optical multispectral camouflage, i.e. applications requiring low contrast with the background. The major trends and areas of development are covered, but a systematic review proved to be too ambitious for the space available in this paper, and some potentially interesting research areas, like for instance graphene or mimicking shape shifting surfaces from biology, have been left out.

The results are structured in order of increasing complexity, where challenges within one order of complexity could be regarded a driving force within the next. The starting point is developments in paint coating systems. It is regarded as the basic, traditional, technology for signature management since it is relatively easy to apply, protective properties can be built in and it is fairly cheap. The challenge is to combine pigments and binders in a system where the properties of the components create a synergetic optical response throughout the spectrum from VIS to TIR. Pigments and binders used for a narrower spectrum are absorbent (emissive) in thermal infrared and hence cannot meet an optically multispectral threat. The best coatings found are based on coated flake pigments of aluminum. Adhesion, high reflectivity in the visible spectrum and a tendency to form electrically conductive coatings, which disturb the radar signature, are remaining challenges.

Here multilayered structures are regarded as the second order of complexity. Breaking metal based multilayers into pigments is one approach to tailoring the reflectivity, but no paint coating system reported yet meets the potential of the respective components. Another approach is using non-conducting bandgap materials in layers, either naturally polaritonic materials, structured bandgap materials (also called one-dimensional photonic crystals) or a combination thereof. Using multi-layered structures it is possible to create electro-chromic coatings, making the transmittance controllable to a certain extent across interesting optical wavelengths. This latter technique is assessed to have potential through the use of suitably pixel-sized decals on military platforms, maybe in combination with other coating systems. One foreseeable challenge is gloss.

The optical response of any one-dimensional structure is, however, bound to be dependent on the angle of incidence of irradiating light, which is why there is great interest in the development of structured bandgap materials in three dimensions, so called 3D photonic crystals. The advantage expected is not being dependent on rare properties of specific materials, but instead being able to tailor reflectance bands by tuning the size of a periodic structure, using suitable materials easier to obtain or process. Photonic crystals for infrared wavelengths have been reported, but there are no reports yet, to our knowledge, on the characterization of a coating system for signature management.

Our fourth order of complexity is biomimic and metamaterials. To learn more about the properties of complex structures many researchers are now turning to biology. In biology there are examples of interesting optical properties, such as age-resistant and environmentally friendly colors, originating from complex structures made out of relatively simple materials. Laboratories report advanced material combinations, albeit in relatively simple structures. Consequently, there is potential in combining advanced materials with complex structures from nature, and developments in nano-technology show great promise. Hopefully it will be possible to combine properties and satisfy military requirements for surfaces other than the optical response, such as dirt resistance, thereby increasing the military utility of spectral design.

None of the reports found have studied all six of the desired characteristics of a multispectral optical coating for signature management. Gloss is sometimes mentioned indirectly, but without being quantified. Often only the specular or integrated reflectance is reported. In research on biomimetics and metamaterials there are reports on polarization properties, but only, it seems, because the application is related to antennas. Characterization of optical coatings in the radar wavelength range was only found in one report. Either, there is still a lack of interest in studying multispectral properties, or the correct nomenclature was not used when probing for results, or these areas are classified. There is, however, a great interest in low emissive coatings in the civilian energy sector or, militarily, for heat control or space applications. Most coatings are assessed only to have controllability when designed, and could be used for static signature systems. Controllability for near real-time applications may be obtained using electro-chromic devices based on conducting polymers, or further in the future using tunable 3D photonic crystal.

In summary there are no ready-made solutions to optically multispectral, spectral design coatings for signature management. There are, however, promising ideas about how to move forward, which is why spectral design is assessed to have continued great potential. The utility of spectral design is also assessed to benefit from research into other applications and from commercial interest in nano-technology, boosted, for example, by the electronics, construction and energy industries.

5. FUTURE WORK

Based on the conclusions of the results reported, there is obviously great interest in continuing research into advanced materials and structures, and their characterization. There are, however, few results reported on applied spectral design coatings for signature management. It would be interesting, from a military utility point of view, to learn more about how the different approaches to spectral design could be combined in applied coatings – and what properties these structures could have. A first step must be learning more about how to model the optical behavior of such a compound coating system, with multiple materials in complex structures – both in order to be able to design usable coatings meeting functional requirements, and to put relevant functional requirements on spectral design.

This also highlights a second research area of great interest. What are the requirements of military coatings applied to platforms, uniforms or other systems? Without specific requirements the true military utility of spectral design, the performance achieved by coatings, and related research, cannot be assessed. Therefore, in order to spend limited military R&D funding more effectively, and to meet more quickly the survivability requirements of signature management systems from an increased threat, there is a need to study the balancing process depicted in the introduction. There is a need to understand or develop the process of how to assess the military utility of advances in spectral design, and in the other direction, how to get from desired military utility to the relevant requirements of spectral design. The work presented here forms one end of the process and recent work[111] on the concept of military utility forms the other. Using this concept the military utility of signature management applied to a system, e.g. a combat vehicle, is considered to be a compound measurement of its military effectiveness, its suitability to the military capability system concerned, and its affordability.

6. AKNOWLEDGEMENTS

This work was financially supported by the Swedish National Defence College and the Swedish Armed Forces. The authors would also like to thank Dr Hans Kariis, Dr Steven Savage, Dr Thomas Hallberg, Professor C-G Ribbing (emeritus), Professor Gunnar Hult and the signature materials project group at the Swedish Defence Research Agency for valuable input.

REFERENCES

All FOI-reports are available at http://www.foi.se/en/Search/

[1] Swedish Department of Defence, "Försvaret av Sverige Starkare försvar för en osäker tid", 151 (2014). www.regeringen.se/content/1/c6/24/04/14/263c8454.pdf. (24 August 2014)

[2] Bohman, L., "Sensorer mot markmål", FOI-R--3476--SE, Linköping, 67 (2012)

[3] Bohman, L. (ed), [Handbook on signature management technology for ground], FOI, (2003).

[4] Kariis, H, Björkert, S, Forssell, G, et al. "Styrbara signaturmaterial - möjligheter och forskningsbehov", FOI-R--1412--SE , 34 (2004).

[5] Olsson, Ö., Karlsson, L., Lindwall, P., Dickman, O., Grop, A., "A Systems Approach to Stealth on Ground ; SAT/Mark Technology Demonstrator", SPIE Proc. 4718, 1–11 (2002).

[6] Arwin, H., [Thin Film Optics and Polarized Light], University of Linköping, Linköping, 372 (2014)

[7] Bergström, D, Sjöqvist, L, Gustafsson, D., "Passive and active spectropolarimetric imaging for target detection - a literature review study", FOI, 139 (2012).

[8] Jacobs, P. A., [Thermal Infrared Characterization of Ground Targets and Backgrounds], SPIE, 184 (2006).

[9] Driggers, R. G., Friedman, M. H., Nichols, J. M., [Introduction to Infrared and Electrooptical systems], Artech House, Boston & London, 583 (2012).

[10] Hallberg, T., Niinimäki-heikkilä, T., Hedborg-Karlsson, E., Salonen, P. S., Nilsson, C., Jänis, A. "Development of low-emissive camouflage paint : Final report Development of low-emissive camouflage paint : Final report", FOI, (2005)

[11] Rubežien, V., Baltušnikait, J., Padleckien, I., "Development of Visible and Near Infrared Camouflage Textile Materials", Materials Science (Medžiagotyra), 15(2), 1–5, (2009).

[12] Rubeziene, V., Padleckiene, I., Baltusnikaite, J., Varnaite, S., "Evaluation of Camouflage Effectiveness of Printed Fabrics in Visible and Near Infrared Radiation Spectral Ranges", Mater Sci., 14(4), 361–365, (2008).

[13] Åkerlind, C., Jänis, A., Kariis, H., Arwin, H., Järrendahl, K., "Spectroscopic ellipsometry and vector network analysis for determination of the electromagnetic response in two wavelength regions", Phys Status Solidi., 5(5), 1089–1092 (2008).

[14] Kariis, H., Andersson, Å., Hallberg, T. Pohl, A., Savage, S., "Signaturanpassning, soldat - utvecklingen inom signaturmaterial 2012", FOI-R--3558--SE (2013).

[15] Wake, L.V., Brady, R.F., "Formulating Infrared Coatings for Defence Applications", DSTO Report (1993). www.dtic.mil/dtic/tr/fulltext/u2/a267555.pdf

[16] Sward, G. G., Jacobsen, A. E., "Paint Testing Manual", 13th ed., A. Soc. Test. Mater., Philadelphia, PA (1972).

[17] Hedborg Karlsson, E., Hallberg, T., "Optiska egenskaper hos metallbelagda cenosfärer", FOI-R--0878--SE (2003).

[18] Hedborg Karlsson, E., Nilsson, C., Hallberg, T., Kariis, H., "Technical report Pigments with Potential for Adaptable Optical Properties", FOI-R--1256--SE (2004).

[19] Thongkanluang, T., Limsuwan, P., Rakkwamsuk, P., "Preparation and Application of High Near-Infrared Reflective Green Pigment for Ceramic Tile Roofs", Int J Appl Ceram Technol., 8(6), 1451–1458 (2011).

[20] Sarasamma Vishnu, V., Lakshmipathi Reddy, M., "Near-infrared reflecting inorganic pigments based on molybdenum and praseodymium doped yttrium cerate: Synthesis, characterization and optical properties", Sol Energy Mater Sol Cells, 95(9), 2685–2692 (2011).

[21] Wang, J-L., Li, Y-Q., Byon, Y-J., Mei, S-G., Zhang, G-L., "Synthesis and characterization of NiTiO3 yellow nano pigment with high solar radiation reflection efficiency", Powder Technol. 235, 303–306 (2013).

[22] Ferrari, C., Libbra, A., Mucio, A., Siligardi, C., "Design of ceramic tiles with high solar reflectance through the development of a functional engobe", 39, 9583–9590 (2013).

[23] Anon, "Huntsman launches infrared reflecting pigments", Addit Polym., 7, 2–3 (2012).

[24] Jose, S., Reddy, M. L., "Lanthanum–strontium copper silicates as intense blue inorganic pigments with high near-infrared reflectance. Dye Pigment", Dyes and Pigments, 98(3), 540–546 (2013).

[25] Ramsley, A.O., Bushnell, W.B., "Development of the U.S. woodland battle dress uniform", US Army Natick/TR-81/008, (1981).

[26] Baltušnikait, J., Padleckien, I., "Development of Visible and Near Infrared Camouflage Textile Materials", Materials Science (Medžiagotyra), 15(2), 1–5 (2009).

[27] Gupta, K. K., Nishkam, A., Kasturiya, N., "Camouflage in the Non-visible Region", Journal of Industrial Textiles, 31(1), 27-42 (2001).

[28] Clarkson, G. M., "Camouflage fabric", US Patent no 5798304, (1998).

[29] Coleman, R. A., "Application of Infrared Absorbers to Nylon 6,6", US Army Natick Laboratories TR-75-19 (1974).

[30] Holcombe, J.D., Nandi, M. K., "Infrared Suppressive Material", US Patent no 20070009679 (2007).

[31] Sioen, J.J., Wille, J., "Infrared Shielding and Radar Attenuating Textile Material", European Pat. EP 1 703 247 A1, 1–13 (2006).

[32] Frankel, K., Sousa, S., Cowan, R., King, M., Concealment Of The Warfighter’s Equipment Through Enhanced Polymer Technology", U.S. Army Natick Soldier Center Natick (2004). http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA433437

[33] Kariis, H., Andersson, Å., Hallberg, T., Pohl, A., Savage, S., "Signaturanpassning soldat. Utvecklingen inom signaturmaterial 2012", FOI-R--3558--SE (2013).

[34] Zhang, H., Zhang, J. C., "Near-infrared green camouflage of cotton fabrics using vat dyes", J Text. Inst., 99(1), 83–88 (2008).

[35] Mao, Z., Yu, X., Zhang, L., Zhong, Y., Xu, H., "Novel infrared stealth property of cotton fabrics coated with nano ZnO: (Al, La) particles", Vacuum, 104, 111–115 (2014).

[36] Mao, Z., Wang, W., Liu, Y., Zhang, L., Xu, H., Zhong, Y., "Infrared stealth property based on semiconductor (M) -to-metallic (R) phase transition characteristics of W-doped VO 2 thin films coated on cotton fabrics", Vacuum, 558, 208–214 (2014).

[37] Qian, G., Wang, Z.Y., "Near-Infrared Thermochromic Diazapentalene Dyes", Advanced Materials, 1582–1588 (2012).

[38] McCann, "No Title", Surf Coatings Aust. 27(8), (1990).

[39] Mar, H. Y. B., Zimmer, P. B., "Low infrared emissivity paints comprising an Oxime cured Silicone binder", US Patent 4131593, 2–5 (1978).

[40] Brady, R. F. "The Chemistry Of Film-Forming Resins", J Prot Coatings Linings, 4(7) (1987).

[41] Lee, H-S., Staaf, Ö., Ghaem, H., "IR-properties of some binders for the coatings industry", FOA-R--00-01576-615 (2000).

[42] Hedborg Karlsson, E., Kariis, H., Andersson, Å., Åkerlind, C., "Ny typ av lågemissiv kamouflagefärg - slutrapport", FOI-R--2316--SE (2007).

[43] Shen, F.C., Feng, X. X., Ma, T., Zhang, J. C., Zhang, H., Gao, P. G., "Study on the Low-Emissive Camouflage Pigment", Adv Mater Res., 624, 303–306 (2012).

[44] Granqvist, C. G., "Solar Energy Material", Appl Phys. 52, 83–93 (1991).

[45] Fan, J. C. C., Bachner, F. J., Fole, G. H., Zavracky, P. M., "Transparent heat-mirror films of TiO2/Ag/TiO2 for solar energy collection and radiation insulation", Appl Phys Lett., 25(12), 693 (1974).

[46] Andersson, K. E., Veszelei, M., Roos, A., "Zirconium nitride based transparent heat mirror coatings —preparation and characterisation", "Sol Energy Mater Sol Cells, 32(2), 199–212 (1994).

[47] Andersson, K. E., Wahlström, M. K., Roos, A., "High stability titanium nitride based solar control films", Thin Solid Films, 214(2):213–218 (1992).

[48] Åkerlind, C., Arwin, H., Jakobsson, F. L. E., Kariis, H., Järrendahl, K., "Optical properties and switching of a Rose Bengal derivative: A spectroscopic ellipsometry study", Thin Solid Films 519, 3582–3586 (2011).

[49] Granqvist, C. G., Lansåker, P. C., Mlyuka, N. R., Niklasson, G., Avendaño, E., "Progress in chromogenics: New results for electrochromic and thermochromic materials and devices", Sol Energy Mater Sol Cells, 93(12), 2032–2039 (2009).

[50] Granqvist, C. G., "Solar Energy Materials & Solar Cells Oxide electrochromics : An introduction to devices and materials", 99, 1–13 (2012).

[51] Chandrasekhar, P., Zay, B. J., Mcqueeney, T., Birur, G. C., Sitaram, V., "Physical , chemical , theoretical aspects of conducting polymer electrochromics in the visible , IR and microwave regions", Synth Met., 155, 623–627 (2005).

[52] Chandrasekhar, Zay, McQueeney, et al., "Conducting Polymer (CP) infrared electrochromics in spacecraft thermal control and military applications", Synth Met., 136, 23–24 (2003).

[53] Chandrasekhar, P., Zay, B., Ross, D., "Far-IR-through-visible electrochromics based on conducting polymers for spacecraft thermal control and military uses …", In: Chromogenic Phenomena in Polymers, American Chemical Society, 66–79 (2005).

[54] Franke, E., Neumann, H., Schubert, M., Trimble, C. L., Yan, L., Woollam, J. A., "Low-orbit-environment protective coating for all-solid-state electrochromic surface heat radiation control devices", Surf Coatings Technol., 151-152, 285–288, (2002).

[55] Chandrasekhar, P., Zay, B. J., Birur, G. C., et al., "Large, Switchable Electrochromism in the Visible Through Far-Infrared in Conducting Polymer Devices", Adv Funct Mater., 12(2):95–103 (2002).

[56] Sigalas, M. M., Soukoulis, C., Chan, T., Ho, K. M., "Electromagnetic-wave propagation through dispersive and absorptive photonic-band-gap materials", Phys Rev B., 49(16) (1994).

[57] Dobrowolski, J., Driscoll, W., Vaughan S., [Coatings and Filters Handb Opt.], ch. 8 sect. 99 (1978).

[58] Ribbing, C. G., "Reststrahlen material bilayers: an option for tailoring in the infrared", Appl Opt., 32(28), 5531–4 (1993).

[59] Ribbing, C. G., Staaf, Ö., Andersson, S. K., "Beryllium oxide - a material for selective supression of thermal emission from domes", SPIE Proc. 2286, 510–520 (1995)

[60] Högström, H., Ribbing, C. G., "Polaritonic and photonic gaps in SiO2/Si and SiO2/air periodic structures", Photonics and Nanostructures - Fundam Appl., 2(1), 23–32 (2004).

[61] Högström, H., Forssell, G., Ribbing, C. G., "Realization of selective low emittance in both thermal atmospheric windows", Opt Eng., 44(2) (2005).

[62] Högström, H., Ribbing, C. G., "On the angular dependence of gaps in 1-D Si/SiO2 periodic structures", Opt Commun. 271(1), 148–153 (2007).

[63] Zhao, X., Zhao, Q., Zhang, Q., Wang, L., "Numerical study on laser and infrared compatible stealth by forming “hole-digging spectrum” of doped photonic crystal", Proc. of SPIE., Vol 7847 (2010).

[64] Nordin P., "MSCC, vägen framåt", Symposium i signaturanpassningsteknik, September 4-5, (2012).

[65] Yablonovitch, E., "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", Physical review letters., 58(20), 2059–2062 (1987).

[66] John, S., "Strong Localization of Photons in Certain Disordered Dielectric Superlattices", Phys Rev Lett., 58(23), 2486–2489 (1987).

[67] Joannopoulos, J. D., Johnson, S. G., Winn, J. N., Meade, R. D., "Photonic Crystals", 2nd ed. Princeton University Press (2008).

[68] Sigalas, M. M., Chan, C. T., Ho, K. M., Soukoulis, C. M., "Metallic photonic band-gap materials", Phys Rev B., 52(16) (1995).

[69] Fleming, J. G., Lin, S. Y., El-Kady, I., Biswas, R., Ho, K. M., "All-metallic three-dimensional photonic crystals with a large infrared bandgap", Nature, 417, 52–55 (2002).

[70] Gao, H-C., Dai, S-T., "A novel material with low infrared target features", 27(4), 671–4 (2007). http://europepmc.org/abstract/MED/17608172

[71] Soukoulis, C. M., "Photonic Band Gap Materials: The “Semiconductors” of the future?", Phys Scr. T66, 146–150 (1996).

[72] Lin, S., Fleming, J., Hetherington, D., et al., "A three-dimensional photonic crystal operating at infrared wavelengths", Nature, 394(6690), 251–253 (1998).

[73] Noda, S., "Full Three-Dimensional Photonic Bandgap Crystals at Near-Infrared Wavelengths", Scienc, 289(5479), 604–606 (2000).

[74] Aliev, A. E., Zakhidov, A. A., Baughman R. H., Yablonovitch, E., "Chalcogenide Inverted Opal Photonic Crystal as Infrared Pigments", Int J Nanosci., 5(1), 157–172 (2006).

[75] Albertoni, A., Perfetto, S., "Mid wave and long wave infrared metamaterials and nano-materials design with Finite Element and Finite Difference Time Domain models for target camouflage", SPIE Proc. 7834, (2010).

[76] Albertoni, A., "Long wave infrared metamaterials and nano-materials design, simulation, and laboratory test for target camouflage in the defence application", SPIE Proc. 8185 (2011).

[77] Kadiyala. A., Dawson, J. M., Hornak, L. A., "Modeling of a 3-D Tunable Photonic Crystal for Camouflage Coating", SPIE Proc. 7781 (2010)

[78] Hooke, R., [Micrographia: or, Some physiological descriptions of minute bodies made by magnifying glasses], London, J. Martyn and J. Allestry (1665).

[79] Berthier, S., Charron, E., Boulenguez, J., "Morphological structure and optical properties of the wings of Morphidae", Insect Sci., 13(2), 145–158 (2006).

[80] Seago, A. E., Brady, P., Vigneron, J-P., Schultz, T. D., "Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles (Coleoptera",. J R Soc Interface, 6 suppl 2, 165-84(2009)

[81] Vukusic, P., Sambles, J. R., "Photonic structures in biology", Nature, 424(6950), 852–5, (2003).

[82] Bradley, D., Heilman, B. D., Miaoulis, L. N., "Insect thin films as solar collectors", Appl Opt. 33(28), 6642–7 (1994).

[83] Parker, A. R., Mckenzie, D. R., Large, M. D. J., "Multilayer reflectors in animals using green and gold beetles as contrasting examples", J Exp Biol., 201(9), 1307–1313 (1998).

[84] Vigneron, J., Pasteels, J., Windsor, D., et al., "Switchable reflector in the Panamanian tortoise beetle Charidotella egregia (Chrysomelidae: Cassidinae)", Phys Rev E., 76(3) (2007).

[85] Goldstein, D. H., "Polarization properties of Scarabaeidae", Appl Opt., 45(30), 7944 (2006).

[86] Arwin, H., "Application of ellipsometry techniques to biological materials", Thin Solid Films., 519(9), 2589–2592 (2011).

[87] Sun. J., Bhushan, B., Tong, J., "Structural coloration in nature", RSC Adv., 3(35), 14862 (2013).

[88] Yu, K., Fan, T., Lou, S., Zhang, D., "Biomimetic optical materials: Integration of nature's design for manipulation of light", R Soc Chem Adv., 3, (2013).

[89] Bhushan B., "Biomimetics: lessons from nature--an overview", Philos Trans A Math Phys Eng Sci., 367(1893), 1445–86 (2009).

[90] Bar-Cohen, Y., "Biomimetics: Biologically Inspired Technologies", CRC Press, Boca Raton (2005).

[91] Chen, Y., Gu, J., Zhu, S., Fan, T., Zhang, D., Guo, Q., "Iridescent large-area ZrO[sub 2] photonic crystals using butterfly as templates", Appl Phys Lett., 94(5), (2009).

[92] Vukusic, P., Kelly, R., Hooper, I., "A biological sub-micron thickness optical broadband reflector characterized using both light and microwaves", J R Soc Interface, 6, 193–201 (2009).

[93] Watson, G. S., Blach, J. A., "Characterisation of cuticular nanostructures on surfaces of insects by atomic force microscopy: mining evolution for smart structures". SPIE's International Symposium on Smart Materials., 378–385 (2002).

[94] Stoddart, P. R., Cadusch, P. J., Boyce, T. M., Erasmus, R. M., Comins, J. D., "Optical properties of chitin: surface-enhanced Raman scattering substrates based on antireflection structures on cicada wings", Nanotechnology, 17(3), 680–686 (2006).

[95] Mandelbrot, B., "Fractals : a geometry of nature : fractal goemetry is the key to understanding chaos. It is also the geometry of mountains, clouds and galaxies", New Sci., 127(1734), 38–43 (1990).

[96] Goldstein, D., Goldstein, D. H., "Polarized Light, Revised and Expanded", Marcel Dekker (2003).

[97] Åkerlind, C., Arwin, H., Hallberg, T., Kariis, H., Landin, J., Järrendahl, K., "Scattering and Depolarization Properties of Natural Structures - Optical Studies of the Beetle Cyphochilus insulanus", American Vacuum Society 58th Conference, Nashville. American Vacuum Society (2011).

[98] Arwin, H., Berlind, T., Johs, B., Järrendahl, K., "Cuticle structure of the scarab beetle Cetonia aurata analyzed by regression analysis of Mueller-matrix ellipsometric data", Opt Express, 21(19), 22645–56 (2013).

[99] Hodgkinson, I., Lowrey, S., Bourke, L., Parker, A., McCall, M. W., "Mueller-matrix characterization of beetle cuticle: polarized and unpolarized reflections from representative architectures", Appl Opt., 49(24), 4558–67 (2010).

[100] Askar, K., Phillips, B. M., Fang, Y., et al., "Self-assembled self-cleaning broadband anti-reflection coatings", Colloids Surfaces A Physicochem Eng Asp., 439, 84–100 (2013).

[101] Parker, A. R., Hegedus, Z., "Diffractive optics in spiders", J Opt A Pure Appl Opt., 5(4), 111–116 (2003).

[102] McPhedran, R., Nicorovici, N., McKenzie, D., et al., "Structural colours through photonic crystals", Phys B Condens Matter, 338(1-4), 182–185 (2003).

[103] Chun, W., Liu, X., Xuan-jun, W., "A novel low infrared emissivity material by Ni-P-CB electroless nanocomposite", Adv Mater Res., 79-82 (2009).

[104] Wang, T., He, J., Zhou, J., et al., "Microwave absorption properties and infrared emissivities of ordered mesoporous C–TiO2 nanocomposites with crystalline framework", J Solid State Chem., 183(12), 2797–2804 (2010).

[105] Wang, T., He, J., Zhou, J., et al., "Electromagnetic wave absorption and infrared camouflage of ordered mesoporous carbon–alumina nanocomposites", Microporous Mesoporous Mater., 134(1-3), 58–64 (2010).

[106] Hapgood, F., "Metamaterial revolution: The new science of making anything disappear", Discov. Mag., (2009).

[107] Gaspar Venancio, L. M., Hannemann, S., Lubkowski, G., et al., "Metamaterials for optical and photonic applications for space: preliminary results", SPIE Optical Engineering + Applications. International Society for Optics and Photonics (2011)

[108] Brückner, J., Le, J., Escoubas, L., et al., "Metamaterials for visible and near infrared antireflective properties and large surface elaboration", SPIE Proc. 8619, 1–16 (2013)

[109] Peters, D. W., Davids, P., Wendt, J. R., Cruz-Cabrera, A., Kemme, S., Samora, S., "Metamaterial-inspired high-absorption surfaces for thermal infrared applications", SPIE Proc. 7609 (2010).

[110] Chen, P-Y., Alù, A., "Mantle cloaking using thin patterned metasurfaces", Phys Rev B., 84(20) (2011).

[111] Andersson, K. E., Bang, M., Marcus, C., et al., "Military Utility, a proposed concept to support decision-making", In manuscript, (2014).

PAPER II

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Kent Andersson, Martin Bang, Carina Marcus, Björn Persson,
Peter Sturesson, Eva Jensen and Gunnar Hult,
Military Utility, a proposed concept to support decision-making,
Technology in society, Vol. 43, November 2015, p 23-32
http://dx.doi.org/10.1016/j.techsoc.2015.07.001

Technology in Society 43 (2015) 23–32

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Military utility: A proposed concept to support decision-making

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form
3 July 2015
Accepted 11 July 2015
Available online 31 July 2015

Keywords:
Military
Decision-making
Concept analysis
Operational research
Systems engineering

ABSTRACT

A concept called Military Utility is proposed for the study of the use of technology in military operations. The proposed concept includes a three-level structure representing key features and their detailed components. On basic level the Military Utility of a technical system, to a military actor, in a specific context, is a compound measure of the military effectiveness, of the assessed technical system's suitability to the military capability system and of the affordability. The concept is derived through conceptual analysis and is based on related concepts used in social sciences, the military domain and Systems Engineering. It is argued that the concept has qualitative explanatory powers and can support military decision-making regarding technology in forecasts, defense planning, development, utilization and the lessons learned process. The suggested concept is expected to contribute to the development of the science of Military-Technology and to be found useful to actors related to defense.

1. Introduction

> *For Clausewitz, in his masterly analysis of the mental and physical spheres of war, neglected the material–man's tools. If he thereby ensured to his work an enduring permanence, he also, if unwittingly, ensured permanent injury to subsequent generations who allowed themselves to forget that the spirit cannot win battles when the body has been killed through failure to provide it with up-to-date weapons* [1,p.158].

New requirements and challenges are born from strained military budgets and a rapidly changing world, as well as from the fact that the time when the military industry was in the forefront of technological development has passed in most areas. In Sweden, and probably in most other democratic states, the question of how limited resources should be put to best use is more relevant than ever before. In general, a military system is complex and already its early life cycle stages, from R&D to initial operation, span over several years and often a decade. After that a typical platform on land, at sea or in the air has an operational lifetime of perhaps thirty years or more. Hence, decisions today may influence warfighting capacity for decades.

Our first case of a decision situation is *the technology forecast*. Even before the technical system is born as a concept, armed forces have to make decisions about what technologies to invest their limited R&D budget in. This means there is a need to forecast and predict the utility of technologies as part of a potential technical system in some far away uncertain future.

The second case is *defense planning*. In short to midterm defense planning, i.e. the next ten-year period, decision makers are faced with the question of when and with what technical systems to replace those currently in operation, while keeping within budget restraints. Furthermore it has to be done taking requirements from interdependent capabilities and foreseen doctrinal, tactical and organizational development into account—optimizing the whole capability system.

The third case is *development*. Once in the concept, development and production life cycle stages of a technical system, the question of how to build a technical system of maximum utility to the customer, the armed forces, within a limited time frame and budget, is addressed using requirement management within the systems engineering process.

The fourth case is *use*. In the utilization and support stage of a materiel system, military commanders and their staffs plan the best use of their limited resources in order to maximize the probability

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http://dx.doi.org/10.1016/j.techsoc.2015.07.001
0160-791X/

of mission success. Concretely, during planning, a staff is typically required to assess what capability systems, i.e. units and technology, the opponent is likely to use based on their strengths and vulnerabilities. Assessing own strengths and weaknesses in the situation the staff is likewise asked to recommend the best use of own available capabilities, not least based on expected technical performance.

The fifth case regards *lessons learned.* This is the long-term review of systems and capabilities throughout all stages from technology forecast, development, defense planning and use. The lessons learned process must be executed in close collaboration with the system stakeholder in order to be accurate in validation of system performance and capability but also to be accurate in the time domain helping decision makers get near-real time information regarding the utility development of the system-in-focus.

In light of the above illustrated incentives for competence in decision making, *Military-technology* is developing as an academic subject at the Swedish National Defence University, SEDU, defined as:

> “Military- Technology is the science which describes and explains how technology influences military activity at all levels and how the profession of an officer affects and is affected by technology” [2].

It seems, though, that in every project similar analytic constructs have to be defined over and over with moderate adjustments to application. And evidently there are similarities between central questions in all the presented use cases from decision situations above. But, is it then possible to form a common theory, to support decision-making regarding use of technology in military affairs, from R&D investments to military operational planning? A more complete Military Technology conceptual apparatus would make it easier to relate to theories across academia, e.g. to economics or management sciences. It would certainly aid effective communication across disciplines within the defense community, i.e. between actors within military research agencies, the armed forces, procurement agencies and industry.

With this paper we intend to propose a concept with potential for both qualitative and quantitative analysis to support decision-making in military technology. The concept is named *Military Utility*. The starting point is a presentation of the postulates of Military Technology and the theory of concept analysis. After that an applied method for concept analysis is presented followed by a description of the resulting concept. The center of gravity is the following discussion on the concept dimensions and indicators. The paper ends with an example, final conclusions and proposed future work.

2. Military-technology

The technology the military profession chooses, and how it uses that technology, will affect the outcome on the battlefield and the sustainment of capabilities over time. This phenomenon is at the centre of interest here. Our viewpoint originates from postulates in military-technology [3]: the character of war change in pace with the development of technology, technology has influence on all military command levels, and a lack of understanding of technology causes diminishing military opportunities. Consequently, for an analyst in military-technology it is essential to understand what is important to the military decision-maker—i.e. what constitutes military utility?

In an article on the military-technological perspective on Geographical Information Systems, Åke Sivertun finds that maximizing military utility, (translated from Swedish “Militär nytta”) of the technology, is the core question. He stipulates a definition of the concept—how to in an effective way and at a minimum cost, in human life as well as materiel, reach the military mission objectives [4]. This definition is here regarded as a first iteration of the concept.

Military-technology is cross-disciplinary covering engineering as well as both natural and social sciences. The terminology used originates from these and the aim is to propose a concept in harmony with the use of related concepts within these disciplines. Coming from a Systems Engineering tradition viewing problem phenomena as *Systems* is fundamental. A System should be understood as “an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements” [5]. In the military domain, *Capability* is a key concept. Our understanding of capability is that it is being able to do something and being able to do it well [3]. With *Military capability* an actor can solve military tasks and thereby achieve desired effects. Using a systemic approach military capability can be viewed as a system composed of interacting elements, as thoroughly discussed by Jukka Anteroinen [6]. We can choose to sort these elements into categories of Personnel, Organization, Methods and Technology (POMT) or into Doctrine, Organization, Training, Personnel, Materiel, Facilities, Leadership and Interoperability (DOTPMLFI), as in NATO publications. Regardless of categorization we realize that any component in a system, e.g. the technology element, has dependencies to other elements. Hence, a component has military utility only if it is viewed as a contributing element in a *Capability system*.

The prefix *Technical* system is used to label the technical element in an operational military capability system when it is beneficial to view the element in itself as a system. In this paper the object for the assessment is an element in the capability system and it is labeled the *Element of Interest (EoI)*, following the Systems Engineering tradition.

3. Concepts development and concept analysis

The above identified need for a concept is based on the view of them fulfilling several important functions within the scientific community. Frankfort-Nachmias and Nachmias states that a concept: provides a common language; provides a perspective to understand the phenomena; allows classification and categorization of different phenomena and; finally, it is the fundamental building block of theories [7,p.28]. Goertz submits that concepts are essential theories about ontology [8,p.5]. Govanni Sartori even claims that “*concepts are not only elements of a theoretical system but equally tools for fact-gathering, data containers*” [9]. A conclusion is that how a concept is designed constitutes not only the building blocks of theories, but also affects how the phenomena are measured and examined. Concept analysis is a process where the characteristics as well as the relations to other relevant concepts are made clear. It can be argued that in fields directly connected to a profession the need of concept analysis increases. A comparison can be made to nursing science where concepts analysis has a given role and where several methods have been developed [10].

There is a lack of lexical definition of the phenomena indicating that the concept is underdeveloped. Two approaches can be used in support of concept development. One is traditional Concept Analysis where the aim is to capture how the concept is used. The other approach is to focus on the phenomena, developing the concept, sometimes referred to as Concept Formation. Which approach is used is primarily dependent on the purpose of the concept in question. The difference between developing a concept for broader usage, through concept analysis, and providing a stipulative definition of a word is minimal according to Goertz [8,p.3].

There is a fundamental difference in views on concepts, and how to measure them. Goertz and Mahoney conclude that quantitative scholars primarily "*use indicators and the aggregation of the indicators that are causes or cause the concepts*" [11] to construct the concept in question. Qualitative scholars on the other hand use a semantic process identifying the attributes that constitutes the concept. Goertz and Mahoney argue that which approach to use depends on whether reliability or validity is central for the research in question. Since, in most cases, we cannot choose one over the other, we need a method to build concepts that both capture a specific phenomenon and allow measurement with a level of reliability permitting a systematic comparative and causal analysis [11].

Since this study aims to find a concept aiding communication in the discourse of military technology and supporting evaluation of artifacts we find Goertz's ontological, causal and realist approach to concept analysis beneficial. Goertz's view of concept analysis has been used in several different papers, e.g. Belich (2011) [12] and in Rapkin and Braaten (2009) [13]. How to operationalize the concept in a framework for evaluation of any given EoI is left for future work.

Goertz advocates structuring concepts in multiple levels, or at minimum three levels, much like Sartori's "ladder" [9]. Below the *basic level*, i.e. the *concept* labelling the phenomena, a *secondary level* consisting of the concept *dimensions* is formed. When for example Arat, in 1991, states that democracy consists of 'participation', 'competitiveness' and 'coerciveness' he defines the constitutive three dimensions of the concept democracy at the secondary level. The next level down Goertz calls the *indicator*- or the *data level*. The intention of this level is to operationalize, i.e. to identify specific measures of how to decide whether a studied phenomenon falls under the concept, or to what degree. For the concept to be complete it has to describe how to combine indicators to form the secondary level dimensions and how to combine secondary level dimensions to get the basic level concept. Goertz concludes that "the basic and secondary levels are really the theory of the concept, while the indicator level is the connection to measures and data collection" [8,pp.5–10].

Several guidelines exist on how to conduct Concept Analysis [14]. The methods, however, take on the form of checklists rather than a structured and stringent research method usually required for reliability within academic work. The subsequent concept analysis was conducted roughly according to the guidelines provided by Goertz [8,Ch.2]. Goertz's guidelines have similarities to Sartori's ten rules for concepts analysis as well as to part of Walker's and Avant's method [10].

At the basic level the negative pole of the concept is analysed and it is also determined whether the concept as such is to be considered dichotomous or continuous. At the secondary level, the dimensions are listed and all necessary conditions are explicitly given. At the indicator level the theoretical relationship between the basic and the secondary level are clarified. According to Goertz's guidelines the causal relationship between the different levels should be examined at the indicator level. In our work generic indicators are suggested. But since the identification of detailed indicators is closely connected to constructing a more formal theory or framework this level will be further investigated in future research, for example theory building case studies.

In accordance with Sartori's eighth rule a search for related concepts was performed in the fields of War Studies and Systems Engineering (SE). The rule states that when selecting the term that designates the concept, it needs to be related to and controlled against the "semantic field to which the terms belong" [9]. For this text the tentative concepts were identified using an initial common requirement from the cases used in the introduction: a measure of the concept should support an Armed Forces's decision about which candidate for an EoI to choose, seen as a component in a capability system, while balancing desired effect against limited resources.

The analysis evolved in a series of seminars held at the SNDU Division of Military Technology during an extended period of time.

4. The concept of military utility

The concept analysis resulted in a proposed concept labeled "Military Utility"; where the conceptual definition is captured in a Goertz-diagram, see Fig. 1.

An assessment of Military Utility requires knowledge of three situational variables: the Element of Interest, the Military Actor and a specified Context. The Military Actor being any part of a military organization having military capabilities and organizational objectives.

Military Utility consists of three dimensions: *Military Effectiveness*, *Military Suitability* and *Affordability*. These are not substitutable. That is, for an Element of Interest to have Military Utility to a Military Actor it has to be effective, suitable *and* affordable to that Military Actor in a specified Context.

Military Effectiveness is a measure of the overall ability to accomplish a mission when the EoI is used by representative personnel in the environment planned or expected for operational employment of the military force. Military Effectiveness is operationalized using measures of the degree to which the mission objectives are, or can be expected to be, fulfilled. There are four substitutable indicators at this level, mirroring different characters of objectives: Compliance to *desired outcomes*, *schedule*, *cost* and *risk*. Desired outcomes constitute the purpose of the mission. Schedule, cost and risk objectives are boundary conditions.

Military Suitability is the degree to which an EoI can be satisfactorily placed in military use in a specified context with consideration to interaction with other elements of the capability system. Military Suitability in turn is operationalized using measures of the degree to which the EoI fits together with other elements of the resulting capability. In the model above, indicators corresponding to TEPIDOIL (Training, Equipment, Personnel, Infrastructure, Concepts and Doctrine, Organization, Information and Logistics) illustrate possible elements on this level. The indicators are chosen from an analysis of the situational variables.

Affordability is a measure of compliance to the maximum resources a military actor has allocated to the EoI in a time frame defined by the context. Affordability is operationalized using LCC (Life Cycle Cost), TOC (Total Life Cycle Cost) or other measures of ownership cost and allocated resources in the budget.

5. Dimensions and indicators

The Military Utility concept should support a stakeholder's decision-making concerning the use of technology in military activities. The concept is hence typically to be used to answer generic questions like: *Is there Military Utility in this emerging technology?* Or—*What is the Military Utility of system X compared to system Y?* Or—*How should this technical system be used to maximize Military Utility?* In this section a discussion on the constituent parts of the concept, i.e. the dimensions and indicators, is presented capturing the most important argumentation from the concept development seminars. The starting point is, however, the top most level and a discussion on the input to an assessment, the situational variables.

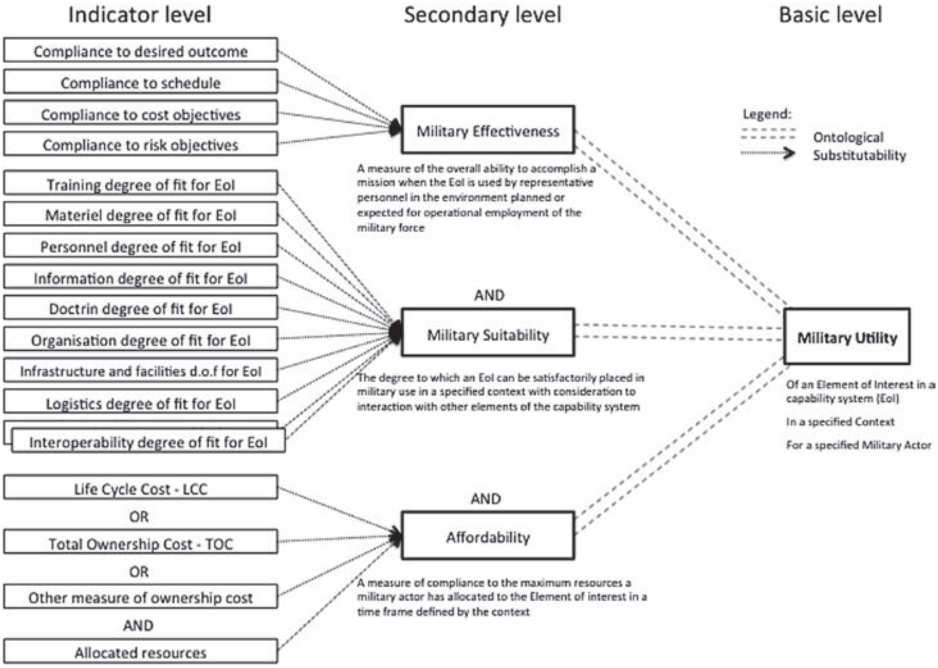

Fig. 1. The resulting Military utility concept modeled in a Goertz-diagram.

5.1. Military utility—Basic level

‘Utility’ was considered a plausible best fit to the proposed concept, since it is used throughout the three domains covered by military-technology with a general sense of supporting decisions. According to the Oxford Dictionary, Utility means “the state of being useful, profitable, or beneficial” [15]. The word has, according to the Oxford Political Dictionary, transformed from a general sense of Usefulness and has today a more specific meaning when used in social science [16]. Its primary meaning in economics is the cognitive process that leads to a decision to choose one thing over another. In the military domain, according to the American Glossary of Defense Acquisition Acronyms & Terms, Utility is defined as “The state or quality of being useful militarily or operationally. Designed for or possessing a number of useful or practical purposes rather than a single, specialized one.” [17] This definition indicates that the multipurpose aspect is essential. However, this does not always have to be true in our intended application, at least not when the artifact or technical system is analyzed within a given environment. If, on the other hand, the purpose or the context in which the artifact is going to be used is unknown, the multipurpose criterion becomes more relevant. In the Systems Engineering (SE) domain the closest fit is a definition of Operational Utility, “the degree to which the system in focus enables users to accomplish organizational missions and achieve stated goals and objectives, while posing no unacceptable safety, environment or health hazards or risks to its operators or public” [18,p.50]. There is however a need to develop the limited resources dimension and to specify the concept from a specifically military organizational viewpoint.

There are other related concepts plausible for the basic level. ‘Value’, used in SE or ‘Value Engineering’ [5,p.36], has a focus on a supplier—customer relation and is therefore not suitable. The concept is also too intertwined with monetary profit [19] to be used as is. SE concepts like ‘Operational Effectiveness’ [17] or ‘Cost Effectiveness’ [18] were discarded because they are considered special cases of Military Utility. ‘System Acceptability’ [18] was discarded since it is considered to be defined from a supplier's perspective.

Faced with a problem concerning military utility we argue that an analyst first has to find the answers to three questions: What is the System of Interest?; Who is the military actor using it?; and in what context is it used? These are referred to as the three situational variables.

5.1.1. What is the Element of Interest?

From a military-technology viewpoint an assessed object has military utility only if it is viewed as a contributing component in a capability system. Consequently, if we want to assess the utility of a technical system we will have to analyze the effects produced by the whole capability system, i.e. when asked what the military utility is of this or that artifact an analyst always has to ask—as an element of what capability system?

If we use a field artillery unit as a system example, the resulting military utility of one unit is dependent on the capability system that it is a part of. The technical specification is one factor as well as the military context. Field artillery is a highly demanding weapon system regarding ammunition and intelligence. To obtain military utility during a battle the artillery gun needs a functional logistic system as well as a functional communication system between the target acquisition system and the fire unit (e.g. an artillery observation team). The artillery gun does not exist in a vacuum and therefore its utility cannot be assessed as a single unit. The ability of the crew to operate the gun, the ability to receive and understand information regarding the location of the target, the ability to maintain ammunition and spare parts during combat are all needed to receive any utility.

Another consequence of the system approach is that the component of military technological interest is not always the technical element itself but an element interacting with the technical element, e.g. the doctrine or the organization. This is for instance the case when developing and evaluating new ways of how to use existing materiel resources. An analyst typically compares the effect delivered by alternative systems as a whole but keeps the technical system unchanged and alternates the doctrine or the tactical procedures.

A technology, on the other hand, underpins system performance but cannot really be viewed as a system element in itself. Therefore, in order to forecast the military utility of a technology, using the proposed definition, an analyst has to first apply the technology to a technical system, which then in turn is viewed as an element in a capability system. A challenge is that the same technology could appear in multiple technical systems. Furthermore, the more generic the technology is, e.g. miniaturization of electronics, the more difficult it will become for an analyst to assess the military utility with any precision. Such an assessment is probably done supporting decision-makers on strategic level, where the technology can be seen having influence on a wide range of systems.

5.1.2. Who is the military actor using the EoI?

The prefix “Military” is used to signal the use of the concept to support military decision-makers—having military capabilities, goals and objectives. As a consequence the military utility of a technical system is not the same for all user organizations, since they have neither the same capability systems to integrate the EoI into, nor the same goals or objectives.

As an example, only a few of the richest nations in the world can afford to have specially designed aircrafts for all types of missions. For example, the US stealth aircraft F-117 Nighthawk proved to be valuable to the coalition forces during the First Gulf War in 1990–1991 [20,21]. It had a modest payload capacity and a limited maneuverability but was designed for low probability of intercept (LPI). The F-117 was used for Suppression of Enemy Air Defenses and Command and Control facilities. The Swedish Armed Forces on the other hand, prioritizing the defense of Swedish territory, has chosen the JAS39 Gripen multipurpose aircraft. It is designed to balance the requirements from air defense, air to ground as well as reconnaissance missions. In order to fulfill those requirements the LPI concept has to be balanced as well. Hence, though the military utility of the F-117 was great to the coalition forces during the First Gulf War it is safe to conclude that the military utility of the F-117 to the SwAF would be small. It is only rational to have highly specialized military means if you have the overall capacity to shape the battlefield in favor of that capability.

A military organization is hierarchical and composed of units at different levels,[1] with different tasks and objectives. In our proposed definition of the concept it is for example possible to find that the military utility of a EoI is great at the tactical level while at the same time small at the operational or strategic levels. One example is assessing the military utility of a patrol vehicle in an expeditionary mission. A tracked and armored personnel vehicle is perhaps the first choice of the land component commander whereas transportability and maintainability weigh in favor of a soft skin wheeled vehicle at an operational or strategic level. Hence, if the military utility concept were only to be used at the highest organizational level it would not be useful for supporting assessments and discussions within the military organization. Consequently, the military technology analyst has to identify not only the military organization, but also to what service, unit or task force within that organization the EoI should be of use. At higher command levels the Military Utility at lower command levels will have to be included, though, making this a more complex assessment. It should be possible to add an attribute to the concept to mark this distinction, e.g. military *warfighting* utility, military *tactical* utility, military *operational* utility, military *strategic* utility etc.

Finally, the proposed concept is designed from a military actor point of view. Thus, it can be used by the Armed Forces to support decision-making within their organization, but also to understand the capabilities of other military actors. This point of view also makes it useful to other actors supporting military organizations, since when discussing military utility there is no question of who the stakeholders are. When used by, for example, procurement agencies or the industry, the concept should be understood as being their assessment of the utility from a specific military actor's point of view.

5.1.3. In what context is the EoI used?

From the discussion of the ”for what?” and ”for whom?” aspects of Military Utility it is already clear that an analyst needs to understand a military actor's purpose for using the EoI and the status of the surrounding capability system to make an assessment. A military purpose is typically composed of military objectives stated within a mission planned for a specific operational environment. Hence, in order to assess the military utility of an EoI, within a capability system, an analyst has to account for all (or the most important) situational variables that influence the military actor's ability to be successful in the specific context, such as opposing forces' capabilities, climate, terrain, international law etc., i.e. the assessed Military Utility of an EoI only has meaning if related to the planned use—either expressed as requirements on the EoI planned contribution to military capabilities or within a planned mission.

5.1.4. Concept level measurement considerations

Bernoulli assumed already in the 18th century through the St Petersburg paradox that maximizing an individual's income is not the same as maximizing the utility (Bernoulli 1738) [22]. The utility one person can have of a specified amount of money is consequently not the same as that of the next person. If using the taxonomy proposed by Stevens [23] on types of scales, i.e. the nominal, the ordinal, the interval, or the ratio scale, Bernoulli thereby also showed that utility cannot be measured on a ratio or interval scale.

Neither can the Military Utility be a linearly proportional product of the number of EoI units available to a military actor, e.g. two JAS39 Gripens do not double the amount of military utility compared to one. The system in which the specific EoI exist offers constraints as well as possibilities. In economics this is called the law of diminishing marginal utility (also known as Gossen's first law) [24]. This demonstrates that the military utility curve has a roof where no more utility can be gained from the system without external changes. When some kind of cost dimension is included, there is a tipping point regarding the maximum utility gained from X number of units. The example of the field artillery can be used again. The military utility of artillery is related to the combined armed forces. Having two artillery battalions when there is only one company of infantry in the operation area is not a maximum use of resources, and therefore the military utility of the artillery is limited. Military Utility consequently needs to be in relation to something, another alternative or a minimum status quo.

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[1] Top down the levels in a military command hierarchy are usually referred to as: the strategic, the military-strategic, the operative, the tactical and the war-fighting levels.

When making choices, ranking one option over another, it is often desirable to compile the result of the evaluation process into one number, a scalar assessment. It seems reasonable to say that if having technical system ‘A’ available in a given context, as compared to having technical system ‘B’, yields a slightly better chance of achieving stated goals (assuming they come to the same cost). System A has arguably greater Military Utility than system B in this context and hence a continuous scale can be applied to the concept. Correspondingly, in a scenario where two alternatives yield the same probability of success but one comes at a lesser cost—that alternative has the greater military utility. Examining the scale further we find that an alternative EoI that yields no better probability of achieving the organizational goals than status quo, nor at a lower cost, should be considered ‘useless’. And since there are probably even worse choices a decision-maker can make there is evidently a negative pole to military utility, i.e. ‘inutility’ or even ‘harm’.

5.2. Military Utility—Secondary level

5.2.1. Military effectiveness dimension

The first dimension of a utility concept has to account for the purpose of using the assessed EoI at all, i.e. the military mission. Hence, it is only meaningful to discuss military utility if the capability, to which the EoI contributes, has any potential of being effective in a given context.

In the SE and Military Domain *Operational Effectiveness* is a “Measure of the overall ability of a system to accomplish a mission when used by representative personnel in the environment planned or expected for operational employment of the system considering organization, doctrine, tactics, supportability, survivability, vulnerability, and threat” [17,18]. Wasson explains this concept as the requirement of a system to be able to support missions “to a level of performance that makes it operationally effective in terms of accomplishing organizational goals and objectives, namely outcomes, cost, schedule, and risk” [18]. That is, achieving an effect is usually not enough for a system to be operationally effective, the effect must be delivered at the right time and at the right cost and at acceptable level of risk.

The Prefix “Operational” signals that the measure is assessed when the EoI is used operationally in the context for which it was intended, not to be confused with operations performed at a joint command level. As stated earlier the military utility of an EoI has to be assessed separately at different command levels. This logic still holds if using Effectiveness at the secondary level, since an EoI can have different effects on the different objectives at different command levels. The prefix is however changed to ‘Military' Effectiveness, to make it clear that this dimension is assessed from a military perspective as well as to broaden the scope of use to any command level.

The definition of operational effectiveness is assessed assuming the best possible fit of the EoI into the capability system, using trained and experienced personnel, applying the capability according to the doctrine and the plan etc. As a consequence the Military Effectiveness dimension mirrors the full potential of the EoI. Hence, a possible mismatch between the EoI and interacting elements of the capability has to be accounted for in another dimension (See Suitability). Another consequence is that there is an implied best possible doctrine supporting the plan. Hence, when assessing an entirely new technology or revolutionary technical system an analyst first has to assume a new tentative doctrine bringing out the potential in the EoI.

Furthermore, since the concept is aimed to be open to operationalization, it is not beneficial in the definition to specify all factors that possibly affect Military Effectiveness. Consequently consideration of “organization, doctrine, tactics …” etc. has to be done at lower levels of the concept model. In summary *the Military Effectiveness dimension is a measure of the overall ability to accomplish a mission when the EoI is used by representative personnel in the environment planned or expected for operational employment of the military force*.

5.2.2. Military suitability dimension

The second dimension of Military Utility produces the means to analyze the relation between the EoI and the other elements of the capability system.

In the SE and Military Domain *Operational Suitability* is “The degree to which a system can be satisfactorily placed in field use with consideration to reliability, availability, compatibility, transportability, interoperability, wartime usage rates, maintainability, safety, human factors, habitability, manpower supportability, logistics supportability, documentation, environmental effects and training requirements” [17,18]. In consequence Operational Suitability answers the question of how well suited a system is to a specific application for a particular user in a given operating environment. Thus, it can be used to characterize how well the EoI fits within this user's existing capability system, or how well it fits after development. The Prefix “Operational” is exchanged with ‘Military’ with the same logic as above.

Some degree of Military Suitability is necessary for an EoI to have any Military Utility. An EoI with low suitability to the other components in the Armed Forces capability system would arguably be of little use, e.g. there is no trained personnel to use the system, the Command and Control system is not compatible, there is no doctrine for how to utilize possible benefits, there are no facilities to maintain the EoI etc. If, on the other hand, a perfect suitability is assumed the capability system can benefit from the full potential of the EoI. Analyzing the Suitability dimension of an EoI is thus beneficial when answering questions like—how should a unit be organized for the organization to get the most out of this EoI? Or—how should the tactics be developed for the organization to benefit the most from this EoI? Or—what changes are necessary in order to maintain the capability if buying this new system? etc. In other words, the Military Suitability dimension is important for understanding the system effects of replacing technical systems.

If the military utility concept is used to study military adversaries, the suitability dimension is often very informative. If a military actor understands under what circumstances the adversary has best possible suitability of his weapon systems, efforts should of course be made to shape the battlefield in a less favorable direction.

Opposite to the definition of ‘Operational Suitability’ above, the definition of Military Suitability should be kept generic allowing modifications on the indicator level. Though the list of affecting factors in Operational Suitability is extensive it is probably not exhaustive. For instance, it should very well be possible to add suitability from national or international law to the list. Instead the following definition is chosen: *Military Suitability is the degree to which an EoI can be satisfactorily placed in military use in a specified context with consideration to interaction with other elements of the capability system.*

5.2.3. Affordability dimension

The third dimension of the Military Utility concept accounts for the consequences of having limited funding.

For SE and the Military Domain DoD defines Affordability as “ 1. A determination that the Life Cycle Cost (LCC) of an acquisition program is in consonance with the long-range investment and force structure plans of the DoD or individual DoD components. 2. Conducting a program at a cost constrained by the maximum resources the DoD or DoD component can allocate to that capability" [17].

'Affordability' is hence more suitable than 'Cost' to represent the limited resources dimension of the concept, since it has a positive direction, like effectiveness and suitability.

As an illustration, assume that a military actor tries to find the solution with maximum military utility. An analysis of the problem, e.g. a military mission, will then result in requirements of desired effects delivered by the solution. But for that solution to be possible the military actor needs to be able to afford it—otherwise no effect will be delivered. Hence the solution delivering the most possible of the desired effect, while still being affordable to the military actor, has the greatest military utility.

In use cases where the Military Utility of an EoI is assessed supporting a specific military operation the affordability dimension is omitted. The rationale is that a military actor does not plan for using an EoI if it is not available. Any limitations in resources affecting the use of the EoI are instead accounted for in the mission cost objectives as indicators of the military effectiveness dimension.

The DoD definition, transformed into a measure, yields the definition for Affordability used in the proposed concept. *A measure of compliance to the maximum resources a military actor has allocated to the system of interest in a time frame defined by the context.* The last additional condition makes it possible to use the concept in other time frames than the system lifecycle.

5.3. Operationalization—Indicator level

The operationalization of the dimensions of military utility is the bridge between the conceptual-theoretical and the empirical-observational level. What can be measured and how? During concept development the ambition was to find generic clusters of indicators, rather than indicators themselves. The indicators finally chosen for an assessment will be dependent on use case and context.

5.3.1. Indicators to military effectiveness

Leaning on existing definitions the effectiveness of a capability relates to the ability to reach desired effects stated in objectives for "outcomes, cost, schedule, and risk" [18].

The Oxford Dictionary defines *Effect* as: "A change which is a result or consequence of an action or other cause" [25], i.e. there are potentially both positive and negative consequences of an effect, pending on viewpoint. From a military perspective US DoD states that Effect is: " 1. The physical or behavioral state of a system that results from an action, a set of actions, or another effect. 2. The result, outcome, or consequence of an action. 3. A change to a condition, behavior, or degree of freedom." [26].

Here it is interpreted as if the outcome objectives constitute *all desired effects* for which the EoI is to be assessed. This can be exemplified using the aircraft decision situation again. Military-Technology analysts in the SwAF were probably once in the late 1970s faced with a question similar to—What combat aircraft system should the SwAF choose for the next 30–40 years, within a given budget? They came up with a recommendation to buy 200+ JAS 39 multirole aircrafts. This seems rational since this aircraft type is effective in all types of combat air operations needed to defend Swedish territory: counter air, air strike or reconnaissance—probably weighted in that order. If the F-117 ever was on the table, it was probably found very effective for nightly air strikes but not very effective for anything else.

The former reasoning is logical if the assessment of military utility is done at the military-strategic command level. Acquisition of complex, expensive, military technical systems is however often decided at a strategic level viewing the EoI as a component in the 'security policy system', achieving more abstract effect objectives. Similarly, the greatest military effectiveness of nuclear weapons might not be in the warfighting capacity, but rather for achieving a deterring effect.

The interpretation of the cost, schedule and risk objectives is that they constitute the boundary conditions for using the EoI in the utilization stage of the specified context. There is a limit to acceptable additional costs for using the EoI in the operation, there is a schedule for when the outcome-objectives have to be achieved to reach a desired end-state, and there is a limit to acceptable risk for undesired effects.

The planned ownership cost of a technical system is included in the affordability dimension. All other limiting resources for using the capability have to be accounted for in the effectiveness dimension, and they have to be defined as cost objectives. Some examples could be: in this operation the daily consumption of diesel for this capability A must not exceed 10 tons; or there are only one hundred troops available for this capability B, or the number of spare parts of type X is limited to Y, etc.

Any effect not contributing to achieving the mission objectives may add to undesired effects, e.g. a risk of a sensor system revealing its own position, a risk of a weapon system with low precision resulting in collateral damage, or a safety risk to personnel operating the EoI. The risk of undesired effects hence has to be accounted for in mission risk objectives. This is the boundary condition that, for example, limits the use of weapons delivering more effect than needed.

The most straightforward way to make a compound quantitative measure of Military Effectiveness is to transform all indicators into probabilities of achieving the respective objectives, multiply them with weights and sum up. The operation is allowed since Military Utility can only be assessed on an ordinal, i.e. a rank order, scale. This is however one of those things easier said than done and there are a multitude of textbooks in the field of operational research describing general cases and how to tackle the problem [27,28].

In the scope of this paper it is sufficient to state that there are typically four types of substitutable indicators contributing to Military Effectiveness: *Compliance to desired outcomes*, *Compliance to Cost*, *Compliance to Schedule* and *Compliance to Risk*. If they are not relevant to the assessment at hand they do not all have to be represented in the compound measure (meaning that they are assessed to be the same for all alternatives).

5.3.2. Indicators to military suitability

According to Wasson Measures of Suitability (MoS) are "Objective performance measures derived from subjective user criteria for assessing a system's operational suitability to the organizational and mission applications" [18]. When used within the Systems Engineering domain these measures quantify issues like supportability, human interface compatibility, maintainability etc., in order to answer questions of how well the technical EoI fits into the user's organization, mission applications and operating environment.

As Anteroinen states in *Enhancing the Development of Military Capabilities by a Systems Approach* USA, UK, Australia, Finland and NATO among other military actors "view capability as a system of interlocking and interdependent components" [6]. They do, however, choose to categorize their system elements differently from each other. USA uses DOTMLPF: Doctrin, Organisation, Training, Materiel, Leadership and Education, Personnel and Facilities. NATO uses DOTMLPF with an additional I for Interoperability. UK uses TEPIDOIL: Training, Equipment, Personnel, Infrastructure, Concepts and Doctrine, Organisation, Information and Logistics, Etc. The Swedish Armed Forces have chosen the British view for assessing technical systems [29]. Evidently, there are different ways of how to view capabilities and hence the concept should not dictate which architecture to use and thereby what indicators of military suitability to include.

For the continued discussion the TEPIDOIL architecture for capabilities is adopted. The Doctrine measure should then quantify how well the EoI is supported by the Doctrine and the tactical and technical procedures (TTPs), the Organizational measure should quantify to what degree the military force is organized to make the most of the EoI etc. etc. If, for example, the British army had made a correct analysis of the Military Utility of the battle tank before they used it for the first time in World War I perhaps the outcome would have been another [30]. The initial success when the tanks broke through German lines could not be exploited since there was no doctrine developed for how to combine them with infantry, i.e. the Doctrine Measure of Military Suitability was close to nil.

To conclude, a compound measure of Military Suitability is suggested in percent of maximum expected Military Effectiveness. If zero, the EoI has no Military Utility, since no capability is developed, due to no doctrine, no training of operating personnel and/or no logistics etc. If the compound measure on the other hand is 100%, the full potential of the EoI is developed. The compound measure is in turn a function of indicators quantifying the EoI fit with other elements of the capability. A product of the constituent indicators, individually expressed in percent, meets our need of a function, but is not the only way to calculate a scalar assessment.

5.3.3. Indicators of affordability

In a study of concepts for future military technical systems it is nowadays more or less mandatory to take into account the system's life cycle cost to the owner. “Life cycle cost (LCC) represents all the costs that will be borne during the life of a System (Main System and Support System) to acquire, operate, support it and eventually dispose of it. The list of costs items to be considered in a project is defined and organized in a Life Cycle Cost Breakdown Structure (LCCBS) also referred to as a cost breakdown structure (CBS)” [31]. The Swedish CBS is described in a handbook on technical systems in SwAF [29].

There are other measures of ownership cost than LCC. Total Ownership Cost (TOC) adds indirect, fixed, linked costs to LCC, e.g. like common support equipment, common facilities, personnel required for unit command, administration, supervision, etc. NATO concludes that TOC is a better measure for budgeting purposes, determining the use of services between systems, for optimization purposes and for financial analysis [31].

In conclusion, measures for ownership cost are very well examined and if having a budget of reference and an estimated ownership cost it should be rather straightforward to obtain a measure for Affordability. The Affordability must, ultimately, be weighed together with the Military Effectiveness and Military Suitability in order to form a balanced measure of Military Utility.

5.3.4. Measurement considerations

However, though the concept allows a scalar assessment this is not necessarily the best way to present an assessment of military utility. The compounding process would assumedly involve assigning weighting factors to dimensions on the secondary level and then summing globally to get the result. The advantage is that it is easy to rank the different options - on the other hand, the disadvantage is that information from the different dimensions is lost. The opposite of the scalar assessment is the matrix assessment, where e.g. the dimensions of the secondary level (Military Effectiveness, Military Suitability and Affordability) are presented in a matrix. Alternatively, as long as the dimensions of Military Utility are positive numbers, they could be presented in a polar diagram. Or the elements of the matrix need not even be numbers. In fact they might as well be colors representing how well a certain requirement is fulfilled in some situation. Expressing assessments in scalars has advantages, e.g. when doing multiple simulations or doing some sensitivity analysis of the results. But an analyst has to keep in mind that humans are never unbiased, why the quality of the decision does not necessarily improve with a seemingly neutral scalar assessment. In fact, in a decision process the most important thing is often that the assessment is transparent to the decision-maker. Military utility is a subjective measurement and the need for an assessment can only be seen from a decision maker's perspective. Finding a transparent framework for doing the assessment is, however, not in the scope of this paper. It is enough to state that the concept in itself allows scalar assessment but is not limited to such a measure.

5.3.5. The new Swedish Armored Wheeled Vehicle (AWV) decision situation

But is there an example from reality indicating a need of the military utility concept, and perhaps illustrating the possibility to measure? As it turns out procurement is a grateful example of the sought for decision situation, since Swedish law require a documented unclassified model for evaluating tenders. In 2009, in the example chosen, the Swedish procurement agency, FMV, issued a Request For Quotation (RFQ) [32] for the acquisition of new armored wheeled vehicles.

In their defense planning process the Swedish armed forces, SwAF, had identified a need to replace their armored wheeled vehicles in two infantry battalions, in total 226 vehicles. There was also a requirement for delivery in time to reach initial operating condition for the first battalion in December 2014. The RFQ had one annex stating operational conditions and constraints, including organization of a mechanized infantry battalion, how it operates, expected enemy and typical missions [32,Pt.C.4].

A decision-maker, using the military utility concept as a guideline, has thereby defined the situational variables; *of what?*—Of a combat vehicle in an infantry capability system, *for whom?*—For the land component commander in Sweden, and *in what context?*—As described in the annex operational conditions and constraints. Hence, it can be argued that the problem for a decision-maker to solve in this situation can be written: - *What concept has the greatest potential military utility to the land component commander in replacing the combat vehicles of the Swedish army, given the schedule and operational context described?* The next step in a decision process, using the military utility concept for support, should be to operationalize the three dimensions; Military Effectiveness, Military Suitability and Affordability.

In the evaluation model [32,Pt.E] enclosed with the RFQ FMV instead defined six evaluation parameters and a function for how to make a compound measure. The total grading of a tender was obtained as a weighted sum of the identified parameters, see Table 1. Each parameter were to be assessed on a scale from zero to ten corresponding to ‘no commitment’ and ‘very good’. Furthermore they were broken down into sub-parameters, with weights, on one or two more detailed levels. ‘Survivability’ is for example an important sub-parameter in ‘System performance’ having a weight of 0,25. Survivability in turn is the weighted sum of mine protection, ballistic protection, signature management (camouflage, red. remark), etc.

Using the vocabulary proposed for the military utility concept it can be argued that ‘Survivability’ is a measure of compliance to desired outcome on the battlefield and hence one of the indicators needed to assess the Military Effectiveness dimension. In analogy it is easy to see that the sub-parameters of ‘Costs’ are indicators related to the Affordability dimension. The Military Suitability

Table 1
Presents the evaluation parameters, with weights on the top indicator level, in the evaluation model for tenders in the procurement of new armored wheeled vehicles for the Swedish army [32,Pt.E].

Evaluation parameter	W.	Comprises assessments of the following sub-parameters
System performance	0,26	Variant performance, Mobility, Survivability, Command and communication, Availability, Support system performance, Usability, Flexibility and growth
Costs	0,28	Procurement, life operation and life support costs
Through-life responsibilities	0,08	System change, upgrades, governmental work load, disposal solution effectiveness
Contractual conditions	0,23	Title and right of use, fulfillment, liabilities, overall commission, effective cooperation
Implementation	0,09	Schedule, confidence in planning, confidence in system maturity
Program management	0,06	Project-, system engineering-, logistics- configuration-, quality and economic management

dimension is about how well the vehicle fits the users existing capability system. This dimension seems to be addressed in the 'Implementation' parameter, measuring the quality of the plan for obtaining full operation, and in the 'Through-life responsibilities' parameter, measuring benefits for the logistic concept and governance. The remaining sub-parameters, constituting 'Program management', is really about managing the risk of not obtaining the desired outcome objectives in time and within budget and can be regarded indicators of Military Effectiveness and Affordability respectively.

In the end there were two remaining concepts competing for the contract, the Patria and the Nexter concepts. The evaluation ended in favor of the Patria tender, see Table 2 [33].

The example with the new Swedish Armored Wheeled Vehicle (AWV) decision situation thus shows that there is a need for a quantitative concept capturing the phenomena described by the Military Utility concept. It also shows that there are decision-situations were it is both necessary and possible to quantify the assessments. One could say that the evaluation model in the example is one operationalization of the Military Utility concept fitted for administration of an acquisition program. A more straightforward application of the concept would be for Armed Forces to feed such an evaluation model with attributes and weights. That decision-model, for the example above, was however not available for scrutiny.

6. Conclusions

A concept called *Military Utility* is proposed for the study of a central phenomenon in military-technology. This phenomenon, dealing with the technology the military profession chooses, and how it uses that technology, affects the outcome on the battlefield and the sustainment of capabilities over time. The concept is needed to aid effective communication within the defense community and to support decision-making. It was derived through conceptual analysis according to Goertz and is based on related concepts used in social sciences, the military domain and Systems Engineering.

Military Utility is a function of three situational variables: the Element of Interest, the Military Actor and the Context. The concept has three dimensions. The *Military Effectiveness* dimension is a measure of the overall ability to accomplish a mission when the EoI is used by representative personnel in the environment planned or expected for operational employment of the military force. The *Military Suitability* dimension is the degree to which an EoI can be satisfactorily placed in military use in a specified context with consideration to interaction with other elements of the capability system. The *Affordability* dimension is a measure of compliance to the maximum resources a military actor has allocated to the EoI in a time frame defined by the context. In summary, the Military Utility of an EoI, to a military actor, in a specific context, is a compound measure of the military effectiveness, of the EoI's suitability to the military capability system and of the affordability.

Table 2
Presents the resulting evaluation of the two final competing tenders for the new Swedish AWV. The compound figure of merit for the two concepts, calculated using the evaluation model enclosed in the RFQ, is presented on the bottom line [33].

Evaluation parameter	W.	Patria	Nexter
System performance	0,26	5,20	4,43
Costs	0,28	9,18	6,80
Through-life responsibilities	0,08	8,82	4,77
Contractual conditions	0,23	7,14	5,48
Implementation	0,09	8,00	7,50
Program management	0,06	8,00	7,80
Figure of Merit:		7,47	5,84

By using the proposed concept and a system approach it is possible to explain how military capabilities are constituted and affected by: developments in technology; by different use of technology and how military actors and command levels are affected differently. It becomes clear that there are many factors influencing the assessment and apart from providing a common language, which is likely the biggest contribution to theory - Though assessing Military-Technology is still not easy, it becomes evident which primary factors and relationships must be considered in a quality assessment.

The discussion also indicates that the concept has explanatory abilities, i.e. it supports qualitative analysis of technology in military capabilities. This is important to actors in the defense sphere doing technological forecasts, doing defense planning, developing technology or tactics, using it, or analyzing lessons learned. Hence the concept, accompanied by appropriate frameworks and methods, can support military decision-making regarding technology in these areas.

7. Future research

Though examples of Measures of performance are suggested for the indicator level, indicating support for quantitative analysis, the concept in itself does not stipulate specific frameworks or methods. Future research is needed to further validate the concept. This will be done addressing relevant decision situations and fitting frameworks of indicators and methods to specific problems and applications.

Acknowledgments

The authors thank Mr Stephen Henly for language editing the manuscript.

References

[1] B.H. Liddell Hart, Thoughts on War, New edition, Spellmount Publishers Ltd, July 1, 1998, p. 158.

[2] M. Norsell, Foreword, in: Stockholm Contributions in Military-Technology 2010, 2010.
[3] S. Axberg, K. Andersson, M. Bang, N. Bruzelius, P. Bull, P. Eliasson, M. Ericson, M. Hagenbo, G. Hult, E. Jensen, H. Liwång, L. Löfgren, M. Norsell, Å. Sivertun, C.-G. Svantesson, B. Vretblad, Lärobok i Militärteknik, in: Teori Och Metod, vol. 9, Swedish National Defence College, 2013.
[4] Å. Sivertun, Militärgeografi och GIS – delar av militärteknik, K. Krigsvetenskapsakademiens Handl. och Tidskr. (2012) 108–120, 0023–5369, no. 1.
[5] C. Haskins, K. Forsberg, M. Krueger, D. Walden, R.D. Hamelin, INCOSE–SE Handbook, 3.2 ed., INCOSE, 2011 no. January.
[6] J. Anteroinen, Enhancing the Development of Military Capabilities by a Systems Approach, National Defence University, Helsinki, 2013.
[7] C.F. Nachmias, D. Nachmias, Research Methods in the Social Sciences, 1996.
[8] G. Goertz, Social Science Concepts–A User's Guide, Princeton University Press, 2006.
[9] G. Sartori, Concept misformation in comparative politics, Am. Polit. Sci. Rev. 64 (4) (1970) 1033–1053.
[10] B.L. Rodgers, K.A. Knafl, Concept Development in Nursing: Foundations, Techniques, and Applications, Saunders, 2000.
[11] G. Goertz, J. Mahoney, Concepts and measurement: ontology and epistemology, Soc. Sci. Inf. 51 (2) (May 2012) 205–216.
[12] J. Belich, Replenishing the Earth: The Settler Revolution and the Rise of the Angloworld, 2011.
[13] D.P. Rapkin, D. Braaten, Conceptualising hegemonic legitimacy, Rev. Int. Stud. 35 (01) (Jan. 2009) 113.
[14] A. Nuopponen, Methods of concept analysis – a comparative study. Part 1 of 3, LSP J. –Lang. Spec. Purp. Prof. Commun. Knowl. Manag. Cogn. 1 (2010) 4–12.
[15] "Utility," Oxford Dictionaries Online, Oxford University Press, 2014 [Online]. Available:(accessed 19.06.14), http://oxforddictionaries.com/definition/utility?q=utility.
[16] I. McLean, A. McMillan, Utility–Oxford Reference, in: The Concise Oxford Dictionary of Politics, Oxford University Press, 2014.
[17] DoD, Glossary of Defense Acquisition Acronyms and Terms, Defense Acquisition University Press, Fort Belvoir, Virginia, 2012, 22060–5565.
[18] C.S. Wasson, System acceptability, in: System Analysis, Design, and Development–Concepts, Principles, and Practices, John Wiley & Sons, 2006.
[19] M. Kaplan, Value engineering in practice, IRE Trans. Prod. Eng. Prod. 5 (1) (Apr. 1961) 36–38.
[20] C.A. Horner, What We Should Have Learned in Desert Storm, But Didn't, 1994.
[21] U.S. GAO, Operation Desert Storm: Evaluation of the Air Campaign, 1997.
[22] D. Bernoulli, Exposition of a new theory on the measurement of risk, Econometrica 22 (1) (1954) 23–36.
[23] S.S. Stevens, On the theory of scales of measurement, Science 103 (2684) (Jun. 1946) 677–680.
[24] H.H. Gossen, Die Entwicklung der Gesetze des menschlichen Verkehrs und der daraus fließenden Regeln für menschliches Handeln, MIT Press, 1854 (translated 1983).
[25] "Effect," Oxford Dictionaries, Oxford University Press, 2014 [Online]. Available: http://www.oxforddictionaries.com/definition/english/effect?q=effect (Accessed 19.06.14).
[26] Department of Defense Dictionary of Military and Associated Terms, Joint Publication 1-02, vol. 2010, US Department of Defense, 2014 no. February.
[27] A.G. Loerch, L.B. Rainey, Methods for Conducting Military Operational Analysis, 2007.
[28] N.K. Jaiswal, Military Operations Research: Quantitative Decision Making, Springer, US, 2012.
[29] Försvarsmakten, H FM Tek Syst Tekniska System–Definitioner och kostnadsberäkningar, Försvarsmakten, Stockholm, 2013.
[30] A. Lorber, Misguided Weapons (Google eBook), Potomac Books, Inc, 2002.
[31] NATO, Cost Structure and Life Cycle Costs for Military Systems (Structure de coûts et coût global), 2003.
[32] FMV, RFQ AWV 2014, Swedish Defence Materiel Administration, Stockholm, 2009.
[33] A.R.O. Lindström, När AWV Blev AMV, 2008, pp. 4–9.

PAPER III

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Kent E Andersson, Hans Kariis and Gunnar Hult,
A systems approach to stealth on the ground revisited,
Proc. SPIE Vol. 9653, 2015
https://doi.org/10.1117/12.2194844

Invited Paper

A Systems Approach to Stealth on the Ground Revisited

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ABSTRACT

This new security development is expected to increase interest from Northern European states in supporting the development of conceptually new stealthy ground platforms, incorporating a decade of advances in technology and experiences from stealth platforms at sea and in the air. The scope of this case study is to draw experience from where we left off. At the end of the 1990s there was growing interest in stealth for combat vehicles in Sweden. An ambitious technology demonstrator project was launched. One of the outcomes was a proposed Systems Engineering process tailored for signature management presented to SPIE in 2002.(Olsson et.al, A systems approach…, Proc. SPIE 4718) The process was used for the Swedish/BAE Systems Hägglunds AB development of a multirole armored platform (The Swedish acronym is SEP). Before development was completed there was a change of procurement policy in Sweden from domestic development towards Governmental Off-The-Shelf, preceded by a Swedish Armed Forces change of focus from national defense only, towards expeditionary missions. Lessons learned, of value for future development, are presented. They are deduced from interviews of key-personnel, on the procurer and industry sides respectively, and from document reviews.

Keywords: Stealth, Low observable technology**,** Signature Management, Camouflage, Military Utility, Military-Technology, Systems Engineering, Combat vehicle, SEP

1. INTRODUCTION

The worsening security environment in Northern and Eastern Europe increases the need to give priority to national defense tasks. This in turn increases interest in high-end technology. The procurement of new army materiel during the first decade of this century has been characterized by states purchasing off-the-shelf products, and thereby sponsoring only incremental development. The focus of armed forces has been on force protection in asymmetric warfare. Hence, although there has been great development in sensor technology, thereby increasing the potential threat, and in materials science, thereby increasing the possibilities to reduce signatures, the interest in signature management and camouflage for combat vehicles has been modest. However, the emergence of highly capable and possibly adversarial systems in the vicinity of Northern and Eastern Europe highlights the need to look at new concepts for low-signature land platforms, partly by leveraging results from low-signature naval and air systems .

Up until the end of the 'Cold war' Swedish doctrine was tuned to national defense. Significant competence and experience in signature management for combat vehicles was gathered in development projects like the S-tank (Strv 103) and the CV90[†] and also in tests and trials in connection with procuring the Leopard main battle tank (Lindström, 2015). Then in 1996 a joint service program, 'SAT/Mark'[‡] was initiated and was managed within the Swedish Defence Materiel

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[†] Combat Vehicle 90 is a family of Swedish tracked combat vehicles designed by FMV, Hägglunds and Bofors during the mid-1980s and early 1990s (Wikipedia)

[‡] Swedish for Low Observable Technology/Ground

Target and Background Signatures, edited by Karin U. Stein, Ric H. M. A. Schleijpen, Proc. of SPIE Vol. 9653, 965302

Agency's (FMV) R&D organization. It was an integrated effort to consolidate knowledge in low observable technology (LOT) from all services. The initiative was supported by the Swedish Armed Forces (SwAF), the Swedish Defence Research Agency (FOI) and industry representatives. The program included establishing competence networks, enhancing design and system integration skills, developing joint defense standards and coordinating national resources in the signature field. In two technology demonstrator projects the signature management concepts and low observable technologies were tested in practice. The second SAT/Mark demonstrator (See Figure 1) was developed with signature requirements influencing design already from basic construction and was developed by four companies as a joint project. Hägglunds Vehicle AB had responsibility for the chassis, electro-optic sights and environmental situational awareness. Saab Barracuda AB developed the signature reduction coating and an inflatable camouflage system. Bofors Defence AB was responsible for the turret and the weapon system and Saab Tech Systems AB was responsible for the sensor systems. The experiences of both FMV and industry from the development of the SAT/Mark demonstrator also resulted in a proposed ´Systems approach´ to developing stealth on the ground, presented to SPIE in 2002[1].

Figure 1. The second low observable technology demonstrator. On the left the characteristic low radar signature shape of the vehicle is prominent. The picture on the right demonstrates the visual signature at a more tactically relevant distance. Photos courtesy of BAE Hägglunds AB and of Saab Barracuda AB respectively.

For the first time since then, the Systems approach has been implemented in the 'SEP' program. SEP is a Swedish abbreviation for Multirole Armored Platform. The FMV project started in 1994 as a pre-study and was terminated in 2008 without entering series production. The reason for the project was a need identified to replace 7-8000 vehicles in the Swedish Armed Forces (SwAF) during the period 2005 to 2015, ranging from troop transporters to combat vehicles in mechanized units. The SEP concept meant pursuing a solution to replace all these different types of vehicles with a modular concept designed to meet a total of 24 different roles. One of the fundamental design requirements was exchangeable wheeled and tracked chassis. The development originated from an idea that "new technology should bring improvements in cost-effectiveness and performance, initially in the following areas: net load, internal volume, flexibility in conjunction with a high degree of family relationship, signature and survivability, internal environment and system cost."[2] The technologies of special interest to support these development targets were identified at an early stage as: electric transmission, continuous rubber track, decoupled running gear, composite fiber hull , add-on ballistic protection and lastly, multispectral signature adaptation, especially IR and radar. During the study and concept analysis phases there were eight test-rigs built for proof of concepts. The SAT/Mark demonstrators are seen as two of them. In 2006 Hägglunds Vehicles AB (later BAE Systems Hägglunds AB) was awarded a contract for the first phase development of SEP. See Figure 2. In the meantime there was a change of procurement strategy[3] towards off-the-shelf or development only with international partners. In 2008 it became clear that the Swedish government was not going to find a partner and the project was terminated.[4]

Figure 2. This is one of four pre-series SEP vehicles produced by BAE Systems Hägglunds AB in 2009. Photo courtesy of Rickard O. Lindström.

However, SEP is regarded here as a unique combat vehicle development project from a signature management point of view. There were ambitious requirements of the signature from the beginning and an ambition to balance these with requirements for other attributes, drawing on experiences from the technology demonstrator programs. It is some time since the project was terminated in 2008, but since signature management is assessed to be of increasing importance to survivability of ground forces in future conflicts, it is important not to lose sight of the lessons identified. Hence, the scope of this paper is to collect possible new lessons and possibly to complement the systems approach to developing stealth on the ground.

In the second section of the paper the systems approach to development is presented with the aim of capturing key features and earlier lessons. In the subsequent section the interview study method is presented. In the following section results, in the form of statements from the respondents, are presented and discussed. Finally conclusions are drawn and a list of lessons is presented.

2. THE SYSTEMS APPROACH TO STEALTH ON THE GROUND

A literature search on survivability indicates a lot of research into aircraft and ship survivability, but considerably less on ground combat vehicles. This was also one of the main drivers behind the LOT[§] demonstrator program, SAT/Mark, reported on. Therefore, our theoretical basis for using signature management technology to increase survivability is the work presented by Robert E. Ball on *The fundamentals of aircraft combat survivability analysis and design*[5]. Ball states that the interdependence between attributes of a platform due to survivability enhancement features has been the motivation for developing a survivability discipline in systems engineering - thereby advocating a systems approach to development. These points, emphasized as the most important in aircraft combat survivability analysis and design, can easily be transferred to systems engineering in other vehicle domains.

- "The design should be properly, not necessarily evenly, balanced…" between features reducing the probability of being killed given a hit (vulnerability), and features reducing the probability of being hit (susceptibility). "Remember the goals of survivability are to increase the cost effectiveness of the aircraft as a weapon system and to

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[§] Low Observable Technology

increase the likelihood the crew of an aircraft that is terminally damaged will be recovered – not to design the most survivable aircraft possible".[5(pp174–175)]

- "Survivability must be seriously considered by everyone during the early design phases of the aircraft…Retrofitting survivability features into existing aircraft, or adding them in a full-scale development phase, usually creates weight, cost, and other performance penalties that could have been avoided…"[5(p175)]
- "The people who are responsible for the survivability analysis and design of an aircraft weapon system must not work in a vacuum or be ignored. They must have contact with the aircraft designers, the program manager, and the operators on a continuing basis."[5(p175)]

Olsson et al find that what is true for aircraft and ships is also true for ground combat vehicles – a systems approach is necessary. "Signature management involves in principle all the components in a vehicle and it is not always evident how the interactions between sub-systems add up to the total systems signature"[1]. That is to say, an object signature is a system attribute. Their work presented as a systems approach is seen here as a tailoring of the survivability discipline of systems engineering to developing stealthy ground combat vehicles. Their paper presents lessons learned in the process of developing the technology demonstrators, from a signature management perspective, particularly in terms of functional analysis, system requirement analysis and systems modeling. Hence a state of the art generic systems engineering process is a prerequisite. Their lessons have been derived from the text, formulated in bullets and used as background in the study. They are presented, with new lessons, in the conclusion section.

3. METHOD AND LITERATURE

The focus is on the Swedish development of the multipurpose armored vehicle SEP. The SAT/Mark program, including the two signature-management-technology demonstrator projects, is regarded here as an activity within the concept stage of the SEP development process.

Data was collected using semi-structured interviews of key personnel from the stakeholders, the procurer and the suppliers, and from reviews of relevant documents. Note that some of the respondents only took part in the SAT/Mark program. The respondents were chosen in an effort to find people in key roles during the SEP development from initiation to termination (see the list of respondents with roles in the references section).

The basic structure of the interviews was to ask respondents to describe, from their perspective, each step of the development process, and to ask, given their experiences, what could be learned for future projects. For that purpose, this stepped process was assumed to follow the Concept and Development stages in the ISO 15288 life cycle as described by INCOSE in the Systems Engineering Handbook.[6] See Figure 3.

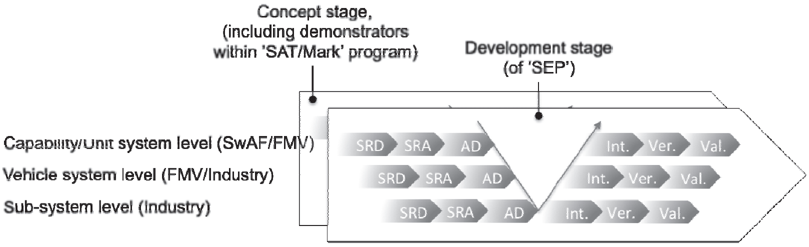

Figure 3 A model of the SEP development process for the Concept and Development consecutive life cycle stages. The technical SE sub processes are seen as steps in the process used recursively at each system level: Stakeholder Requirements Definition (SRD), System Requirements Analysis (SRA), Architectural Design (AD), Integration (Int.), Verification (Ver.) and Validation (Val.). The main actors at each system level are indicated.

Document reviews were used, when such documents were available, to support key statements from the respondents. There are FOI reports (in Swedish) from the early stages of the SAT/Mark program, in 1998, concerning issues in modeling and requirements specification[7,8], and a handbook on signature management for ground vehicles, 2003[9]. Most documentation from the projects is confidential. Two key study documents were, however, made available to the authors: a report on resulting 'FMV guidelines for requirements on signature management'[10] and a 'Preliminary target capability document' specifying SwAF needs[11]. A lessons learned report from the SEP project management to SwAF is partly unclassified and useful for reviewing the schedule and key management events[12].

4. RESULTS AND DISCUSSION – NEW LESSONS?

The semi-structured interviews were transcribed. Only those statements underpinning the discussion are outlined here.

4.1 The stakeholder requirements definition

"*The purpose of the Stakeholder Requirements Definition Process is to define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment.*"[6(p54),13]

In broad terms the SAT/Mark demonstrators were used to show how far it was possible to push signature management requirements, given technologies and production methods available. From measurements obtained and evaluations made in the demonstrator project, the SEP signature requirements were then derived with adjustments for considering: the mission needs, the predicted likelihood of sensor and weapon system occurrence in theaters during the SEP life cycle, and the cost of effective signature reduction in the respective sensor domains.

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. It is described as a result of the so-called 'Swedish development model' and is promoted as a success factor by the respondents, both from the government and industry sides. It is an important factor in explaining how Sweden has been able to produce so many competitive platforms for air, navy and ground forces, one respondent explains. Sweden has become competitive through working collaboratively in integrated project teams of the agencies, SwAF and industry working together. This has allowed industry to benefit from the development and gather expertise. In practice this policy led to a sharing of systems responsibility between FMV and the suppliers. Those were the prerequisites both for the demonstrator projects and for the SEP development project, but changed due to a new strategic procurement policy in 2007[3] before ordering the series vehicles. In the European Union today a similar approach is only possible for procurements of great national security interest – combat vehicles are currently not included.

The end-users were represented during the demonstrator project and hence could convey user needs continuously. Documenting needs in concepts of operations (ConOps) was considered but was decided not to be worth the extra effort, because of strained resources. There is, of course, a risk that traceability to stakeholder needs degenerates with time and that needs are not easily communicated to the whole project. It seems to have worked well here, thanks to the integrated project approach and staff continuity.

Thus, 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 pointed out by one of the respondents.

The participation of the SEP contractor in the requirements specification is especially emphasized. The benefits were highlighted by one respondent describing Hägglunds involvement. Hägglunds participated in the SEP project as early as the SwAF multirole study and in the SAT/Mark program. Therefore, the stakeholder requirements analysis for SEP was considered relatively straightforward from Hägglunds' perspective since, in principle, the requirements from the SAT/Mark project were reused and slightly modified. 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 respondent explains. 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 since a few of the technologies used were assessed as high risk. The system requirements were refined continuously during the process. In total, three demonstrators were built before the SEP development started in 2006, two to demonstrate function and one to de-risk technology. During this process Hägglunds were asked, the respondent explains, not only to design according to system requirements, but also to challenge them. 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 and others were modified, the respondent ends. The description of Hägglunds involvement illustrates how two-way communication is aided. The contractor learns to better understand the needs and the procurer side learns to better understand which requirements are pushing cost and complexity, and hence project risks. An observation is the way of working, promoted by the respondents, is completely in accordance with Ball's third point (see section 2). The net result is likely to be a more balanced requirements specification.

Initially relatively basic high-level requirements were produced by SwAF in a document no longer than one page. The requirements from SwAF were not quantified. Instead they were formulated in relation to what had been accomplished in the CV90 project. This was enough for the early studies. In 2006, in conjunction with an FMV request for a quotation 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 needs to industry. In the preliminary capability target document, SwAF needs were formulated using a configuration of threat sensors with different elevations, very much like the situation depicted in Figure 1 in Olsson et al., 2002[1]. The measures of performance and situational parameters chosen are, however, confidential. Threat scenarios were then derived in integrated working groups putting this threat sensor situation into a relevant context.

There is no clear-cut distinction made by the respondents between stakeholder requirements definition and requirements analysis at different levels in the process described. Nor is this to be expected, since the government and industry participants worked so tightly together. From the description of the system requirements analysis process in the next sub-section, however, it is understood that there is a need for the input of mission scenarios.

4.2 The system requirements analysis

"*The purpose of the Requirements Analysis Process is to transform the stakeholder requirement driven view of desired services into a technical view of a required product that could deliver those services…It results in measurable system requirements that specify, from the supplier's perspective, what characteristics it is to possess and with what magnitude in order to satisfy stakeholder requirements*"[6(p69),13]

The results of the SAT/Mark working group on requirements specification were documented in FMV Guidelines for requirements on signature management[10] (Restricted). One of the respondents, however, highlighted their most important positions on the requirements process.

Firstly, LOT and signature management are needed in order 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 ("not standing still hiding in a forest") since this phase is where the vehicle signature properties are most critical.

Consequently, requirements analysis has to start with analyzing tactically correct movement in typical situations because this dictates the critical signature level. The working group concluded that it is very important to decide upon dimensioning typical situations, where signature management is important to the mission. Discussing signature from a general viewpoint is futile. Hence, what are really needed from the customer when doing requirements analysis are relevant 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.

Another important aspect identified was the probability of the sensor threat occurring in the 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? There might be a new exclusive sensor someone has recently heard of, but should that be allowed to be a factor in the design of the vehicle signature, the respondent asks rhetorically. Instead, 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 see objects. On the other hand, the consequences for the system of interest have to be analyzed. And if a new threat sensor appears somehow, one will have to adapt, the respondent concludes. This was also one of the lessons reported by Olsson et al.[1]

Next the analyst has to consider in what mode the threat sensors are working when detecting the combat vehicle. Some sensors do have an impressive resolution, but perhaps only if working in a very narrow field of view. Maybe the scanning mode instead puts moderate requirements on signature management. If the platform survives the first seconds of the threat sensor scanning its 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 distances. The respondent gave an example when discussing end phase corrected ammunition. Such a weapon is probably not launched unless the target is found using another sensor, and what is the field of view needed for that?

Another important experience of the requirements working group was that signature management requirements are often overstated. It is sufficient to state dimensioning requirements, the respondent states. The working group concluded that solution space should be explored by using simulations in order to find the relevant requirements. However, back then there were less sophisticated simulation tools than there are today, the respondent explains.

Since the signature management requirements for SEP were largely adopted from the demonstrator program (with some exceptions to be noted later), the requirements analysis process, – starting with the identification of dimensioning typical situations, described above and developed during the concept stage – appears to have been validated in the SEP program. It should be noted, however, that the input wanted from the military organization appears to be a rather dense scenario, comprising descriptions of anticipated missions, own tactics and procedures, anticipated physical environments and anticipated adversaries. A comparison with concepts of operations or a further description of the design of such a scenario would be useful.

The dimensioning situation was found to be the advance to contact phase. This of course supports interest in controllable vehicle signatures and emphasizes the need to be able to state relevant and measurable requirements of temporal contrasts in all sensor wavelength bands. Increasing interest in controllability was anticipated by several respondents, especially for exclusive assets, but no suggestions were made regarding metrics or how to handle this category of requirements. Another respondent raised serious doubts about controllability ever becoming a reality. It is technically difficult and its utility on a dirty battlefield would be limited he argues. Controllability results from the demonstrator project were published in 2003[14].

Furthermore, the challenge is not any difficulty in getting the scenario information needed to initiate the process from end-users. However, transforming the mission scenarios or user needs into technical system requirements of the signature does remain a challenge, the respondents admit. In addition, and unfortunately, the Swedish standardization work during the SAT/Mark program did not finish. The respondents' observations in many cases are that this transformation has been avoided by, instead, stating technically oriented requirements, such as what color paint to use or the temperature difference to ambient air instead of background, leading to uncertainty about whether or not the requirements reflect real conditions.

One respondent described an ambition, which arose during the work, to develop a causal chain of measures and methods between what can be measured in the laboratory and what the operator in the field can experience. The approach described aims to derive verifiable signature requirements from contrast measures on pictures of views seen by the threat sensor operators. Promising results are to be published. This has the obvious benefit of making requirements independent of sensor wavelength spectra.

The linking of tactically relevant parameters to verifiable, measurable, technical system requirements is a major issue. The authors' view of the emerging system model for evaluation of signature management in combat vehicles can be seen in Figure 4. The model is transferred from the aircraft combat survivability discipline[5,15] and modified to the land theater to capture issues highlighted by the respondents. The purpose is to illustrate the linkage between the performance of a combat vehicle, threat sensor systems and mission needs. The output measures of performance at one system level are response functions of lower system level inputs and are themselves input to higher system levels. The capability system level has been added because the manner in which a combat vehicle is used in theater greatly affects performance measures, such as 'Time to detection' suggested by respondents.

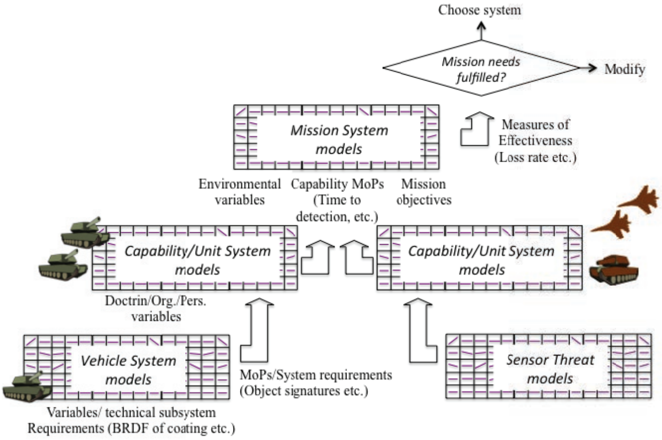

Figure 4. An illustration of the systems model supporting analysis in the development of a combat vehicle with signature requirements. The output measures of performance at one system level are response functions of lower system level inputs and are themselves input to higher system levels. The illustration is inspired by the work of Soban and Mavris (2002)[15].

It goes without saying that, at the vehicle system level, the general measure of performance is object signature. But how should it 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]. A radar cross section is consequently not a signature but a property of the object. One of the respondents exemplifies: For a SAR sensor the signature is the object and its shadow, for an IR sensor hot air from the object affects the background and in the visible spectrum dirt tracks in the background caused by the vehicle should be included. Hence, a requirement at the signature level must be accompanied by a set of situational parameters.

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. However, as recently stated by Åkerlind et al[16], there seems to be no generally accepted set of contrast measures to fill the matrix completely. From the authors' experience there is a lot of research in some of the matrix elements, with several measures to choose between, while in others there is a lack of research. In addition, the work to form a Swedish requirement standard did not finish. However, given the development towards multinational procurement projects, standardization should continue in a multinational context. One of the respondents describes a recent EDA initiative stating generic requirements in an effort to create action preparedness for future joint projects.

An issue touched upon above is the choice of situation parameter sets needed to form signature requirements. The challenge, when compared to other attributes is the statistical nature of signature, i.e. the dependence on physical environment. One of the consequences described by one respondent 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, the respondent states. Another consequence is that it is sufficient to state requirements for dimensioning parameter sets to avoid overstating. Otherwise, this could, of course, lead 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. A reasonable conclusion is that finding arbitrary points in solution space requires sophisticated systems modeling in both cases.

The 'Time to detection' measure of performance was often found to be more important than detection range as the tactical parameter from which to derive vehicle system requirements. In Swedish mission scenarios the range is usually much longer than the line of sight available on the ground, one respondent explains. If the maximum range is 5 km but the target vehicle is standing one km away from the sensor, there is a risk of being detected the whole time. But will the sensor react to the target? That is the important question. Reducing detection range from five to one kilometer using signature management technology is of no use. In this situation it is all about contrasts and the background statistics, the respondent concludes. Another argument put forward was that it is impossible to do a relevant static comparison between the 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. Hence, it is important to formulate requirements for both detection range and time to detection, in scenarios covering the threat sensor suites' different modes of operation, another respondent concludes. A third respondent advocates 'Time to classification' as an important parameter since, in sophisticated sensor threat scenarios, it is difficult to delay detection at short range. The military operator will probably not shoot immediately on detecting a target, unless there is additional information, he argues. That means the vehicle firing will have to get closer to the target, or wait until the target comes closer, in order for the operator to have the required resolution to classify or identify. Detection is about contrast between target and background, but classification is also partly dependent on contrasts within the target, he ends, and implies that this is somewhat easier to control with signature management. In Olsson et al, 2002, it is stated that relevant tactical parameters have to be derived from the context in each case.[1]

Discussing the linking of system requirements to tactically relevant parameters, difficult as it is, does not, however, capture the full complexity of survivability engineering. Returning to the lessons from survivability engineering in the combat aircraft discipline (See Section 2), Ball stresses the need to measure mission outcomes at the next system level (see measures of effectiveness at the top level in Figure 4), or even campaign outcomes, in order to see the real military value of signature reduction features in platforms[5]. Otherwise one might miss penalties in the platforms lethality or availability when doing the evaluation, or one might underestimate the real value of low signature and invest in other attributes instead. The issue is touched upon in Olsson et al, but is limited to comparing different survivability enhancement techniques. The validation results from the SAT/Mark demonstrator are, however, classified; hence it is not clear to the authors what effects signature trade-offs had on the vehicle meeting mission needs.

4.3 The architectural design process and trade offs

"The purpose of the Architectural Design Process is to synthesize a solution that satisfies system requirements…It identifies and explores one or more implementation strategies at a level of detail consistent with the system's technical and commercial requirements and risks. From this, an architectural design solution is defined in terms of the requirements for the set of system elements from which the system is configured…"[6(p94),13]

In their paper Olsson et al describe their system approach to design.[1] Given that signature is an attribute of the whole system of interest and that, at system level, it is difficult to predict the exact effect of signature enhancement measures to subsystems, the design process has to be iterative. The first iteration of allocating system requirements to subsystems is done by breaking them down into subsystem guidelines and subsystem requirements, but within the ambition for the overall design to meet all system level requirements. After evaluation the allocation is adjusted for the second iteration etc. until system requirements are met.

This approach to design seems to have been validated during the SEP development. One of the respondents illustrated the applied approach, and the special implications of signature management design, with an example from the SEP development - how to get rid of excess heat. The system signature requirement originated from a certain acceptable level of heat emission, the respondent explained. Firstly, the system designer distributes permissible heat emission evenly to all surfaces of the vehicle. However, it is then realized that a larger part of the budget has to be allocated to the designer of the exhaust subsystem, who is struggling to conceal the flow of one cubic meter of hot air per second. Now the system designer can no longer formulate requirements from a signature perspective; they would not make sense. The system signature requirements have to be transformed into concrete subsystem design guidelines. In this particular case Hägglunds used counter flows of air, in a design later patented. However, they could not be sure of meeting the system requirement until a prototype of the complete system was integrated and evaluated. In fact the process is recursive and there were several subsystem levels with iterations including tests at every level, the respondent continues. For instance, the exhaust system was first validated in a bench configuration at subsystem level. In contrast to signature requirements, the maximum weight requirement is easy to break down into subsystem requirements. If a vehicle's maximum weight is 25 tons, the transmission can only weigh three, the respondent exemplifies.

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. The priority order is dictated by the consequences of correcting a poor design later on: Radar, TIR and VIS (NIR-VIS-UV). Inappropriately designed inner corners are for example difficult to redesign later. Furthermore, if the infrared signature is considered early, it will be easier to deal with the excess signature using coatings or mobile camouflage systems (MCS) etc. 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 performance attributes of the combat vehicle system. This lesson is also in complete accordance with the first point made by Ball (See section 2).

The purpose of the low observable technology demonstrator was to push stealth performance in a combat vehicle; hence, when stating the signature levels for a supposedly operational vehicle like the SEP, there has to be some trade-offs. For instance, the radar requirements, when compared with the demonstrator, were lowered for two reasons. Firstly, the handles for hatches etc. on the demonstrator were designed with low radar signature in mind – forcing the operator to remove his or her gloves. Secondly, lowering the requirements also made it possible to use traditional components. Hence, for SEP, radar signature was traded for usability and for ease of production. Given the discussion earlier about balancing requirements by taking the probability of different sensor threats into account, the trade-off decision was likely based on systems modeling and an assessment of relatively low probability of radar occurring in theaters at the time, like e.g. Afghanistan. However, slight reductions in both mobility (to benefit from skirts) and situational awareness (fewer electro optical sights to reduce reflections) were accepted, no doubt originating from an assessment that there are many more threat sensors in TIR and VIS.

Another important lesson from the design organization is that a system designer can achieve a lot in signature reduction using standard components - if signature management is allowed to influence design from the beginning. There is a greater effort in the systems engineering involved, but the unit price need not be much higher than it otherwise might, one respondent concludes. This conclusion is from an industry representative. A statement from the government side, however, supports the conclusion, since the respondent cannot remember any trade-offs to cost originating from signature requirements. Validating the statement with a financial analysis is beyond the scope of this study.

4.4 Integration, verification and validation

"The purpose of the Integration Process is to assemble a system that is consistent with the architectural design..." [6(p118),13]

"The purpose of the Verification Process is to confirm that the specified design requirements are fulfilled by the system..." [6(p123),13]

"The purpose of the Validation Process is to provide objective evidence that the services provided by a system when in use comply with stakeholders' requirements, achieving its intended use in its intended operational environment."[6(p133),13]

The respondents state that there was no system level verification and validation campaign for the SEP vehicle because the project was terminated beforehand. There were, however, some technical simulations to validate system performance of the SAT/Mark demonstrator. Although when it comes to validation methods the SAT/Mark project was incomplete, one respondent explains. Validation was based on discussions with the end user. The need to develop methods and tools was identified. There was also some statistical evaluation of how the target fits into backgrounds. Some FOI reports have been published on the subject, but these methods have not been validated and approved to the respondent's knowledge.

For the SAT/Mark demonstrator a new surface with "extraordinary" BRDF (bidirectional reflection distribution function) properties was developed and applied to the vehicle. The surface was about 5mm thick consisting of glossy cones. However, because the cones were directed in so many directions, they mirrored each other resulting in a very deep color, one respondent explains. This coating was to maintain color from all viewing angles. The validation using a new BRDF instrument was reported by Olsson et al.[1] It was, however, difficult to make the surface stick to the demonstrator plates and it has not entered production.

Measuring the BRDF value of a large enough surface sample is one method proposed for linking sub-system requirements to what a threat sensor operator experiences in the field, as touched upon earlier (Olsson et al, 2002). The problem is that requirements are usually stated for the raw material, the flat stock, and not the punched and finished product, a respondent explains. Hence, when verifying these requirements, you are not really evaluating the product seen in the field by a threat sensor and an observer. The problem originates from difficulties in obtaining relevant measurements, the respondent concludes. The authors agree. The dispersive properties of a surface have a huge influence on detectability. Full dispersion for all incident and reflection angles and all wavelengths is described by the BRDF, but, to the authors' knowledge, this can only be measured at a few sites in Europe. FOI (Linköping) and Saab Barracuda (Gamleby), whilst having some limitations, are two of them.

When asked for their view on future challenges, one of the respondents brought up an interesting challenge using modeling and simulation techniques in the verification and validation of signatures. One problem emerging, he said, is that signatures are now becoming very low, which is actually a 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 showing a high signature aspect angle for a brief moment. Is it possible to identify and track that target, the respondent asks rhetorically, and concludes that the system effectiveness measure will have to be more complex, and the simulations will require more detailed data to be relevant.

4.5 The study method

Two facts raise questions about the validity and reliability of the results: Firstly, the SEP has not (yet) been built, verified and validated; so, how can we be certain the requirements specification is well balanced? Secondly, important findings and results, such as signature measurements, are classified. However, this case is unique and scrutiny is well justified. Reliability is helped by having had the opportunity to interview key actors in the case, and by the fact that they are very experienced and still active in the field. Tendencies do not seem to be a severe problem since the respondents are reasonably coherent.

5. CONCLUSIONS– THE SYSTEMS APPROACH REVISITED

The Systems approach to development of stealth on the ground, proposed to SPIE in 2002, was summarized in a shortlist of lessons on modeling and analysis. The shortlist was then brought in as the background to an interview study, from a signature management and systems engineering perspective, on the development of the Swedish Armored Multipurpose Vehicle, SEP. The lessons reported earlier were found to be at least partly validated during the SEP development. No contradictory findings are reported. The complete list of earlier lessons(*), and those identified from the study, are as follows (in logical, not priority, order):

Success factors:

1. *Functional analysis starts with mission needs and weapons/sensor threats as input, to determine the relative importance of stealth compared to other means of survivability. The overall survivability goal is considered under all the different operating modes of the vehicle system. Different sets of system functions form alternative concepts to be evaluated using system modeling or war gaming.[1(pp3–4)]

2. *A model based on weighted probabilities of sensor occurrence is used to derive signature level requirements for corresponding wavelength domains. The boundary condition is set to specify a system with a balance between corresponding signatures in as many backgrounds as possible.[1(pp3, 5)]

3. *The definition of a system model comprises vehicle system models, and sensor threat models for relevant signature areas and environment models, that can deliver a response in the same format as tactically relevant parameters.[1(pp4–5, 7)]

4. *A UV/VIS/NIR sensor model needs at least the following input variables, in addition to background and foreground, to produce a usable response parameter: object size, object shape, object contours, object shadows, atmospheric blurring and noise, atmospheric wavelength dependent attenuation, color (value and gloss) and specular properties.[1(pp7–9)]

5. The signature definition (see section 4.2). It is the basis for defining contrast measures, i.e. the vehicle system measures of performance. There is no international standard.

6. An integrated team approach is an important enabler in the systems engineering of any complex system, but the results indicate that this is especially important in the analysis and design of a stealthy vehicle signature, it being a systems attribute. In an integrated project team, at the concept stage, there should be representatives from the end-users, the procurement agency, scientists and, if any commercial constraints allow, industry experts. Creating an atmosphere of openness and cooperation is essential.

7. *The allocation of system requirements to sub-systems starts from an established conceptual system design, thereby assuming set system signatures, and defining sub-system requirements in the form of design guidelines. Design guidelines typically include requirements for specific functions, material properties, dimensions, shape or surface properties etc. Then the system signature should be evaluated, preferably using system modeling, and the procedure reiterated until system requirements are met. This procedure is necessary because of the systemic nature of the signature attribute, i.e. because signature requirements have no meaning at subsystem level.[1(p6)]

8. When designing a stealthy combat vehicle, (electromagnetic) signature requirements should be considered as early as possible in basic construction to optimize performance and minimize cost. The order of priority should be radar, TIR, VIS (incl. UV and NIR).

9. *Categorization of system requirements should be detection-process-oriented, rather than by sensor type. Methods for analysis and requirements specification tend to be the same, regardless of wavelength. Use of a 3x4 matrix structure with spatial, spectral and temporal contrast on the vertical axis and with unresolved/resolved targets, using either passive or active sensors, on the horizontal axis is suggested.[1(pp5–6)]

Observations:

10. Time to classification is perhaps equally interesting as time to detection as the capability measure of performance conveying military needs to the vehicle system level.

11. There is a need for an agreed standard on preferred contrast measures in all elements of the 3x4 matrix above, see item nine.

12. *In VIS a surface optical response should be modeled, or specified, using its BRDF value. Results show that illumination angle and viewing angle have a greater effect on contrast than choice of color. The BRDF value incorporates this effect.[1(pp9–10)]

13. Stating requirements for dimensioning situation parameters is sufficient. Finding these using systems modeling is a research area.

14. If signature requirements are allowed to influence the procurement process from the beginning, stealth is not expensive.

15. In a well working integrated team there is a risk of being tempted not to produce thorough documentation, thereby impeding the traceability of requirements.

Work needed:

16. The procurer’s stakeholder requirements analysis starts with the analysis of mission scenarios established by the military user organization. The ‘scenario’ concept in this context needs elaboration.

17. The transformation of mission scenarios into measurable, technical systems requirements still needs clarification. An approach establishing linkage between tactically relevant parameters, such as time to detection, through relevant and measurable contrasts in the picture seen by the sensor system operator is suggested.

18. Establishing the linkage from vehicle system measures of performance to tactically relevant parameters is, however, not enough to do trade-offs between signature reduction features and other features linked to lethality or availability. Establishing a mission system model, linking those tactically relevant parameters to mission objective measures of performance is required.

19. The modeling, analysis and formulating of requirements for controllable signatures needs special attention. The dynamic contrast of a vehicle moving against a background should be studied further.

20. There is a need to define measurable contrast measures for those matrix elements lacking candidates, see item nine.

In conclusion the items above are candidate guidelines for a suggested approach to the system engineering of stealthy vehicles. However, the method has not been validated by being applied to a completed procurement case. This should be done as part of a future major procurement project. The ‘Systems approach’ to stealth on the ground, and the projects where it was born, are well worth revisiting!

6. AKNOWLEDGMENTS

This work was financially supported by the Swedish Defence University. The authors would like to thank Mr Stephen Henly for language editing the manuscript, Mr Martin Bang and Mr Anders Grop for valuable inputs and of course the respondents for their generosity with personal time and for sharing their valuable experience.

7. REFERENCES

7.1 Publications

[1] Olsson Ö, Karisson L, Lindwall P, Dickman O, Grop A., "A Systems Approach to Stealth on Ground ; SAT/Mark Technology Demonstrator", Proc. SPIE 4718,1–11 (2002).
[2] Lindström R. O., "SEP: Multirole Armoured Platform", Swedish J Mil. Tech., - (1999).
[3] Försvarsmakten, "Materielförsörjningsstrategin 2007", HKV 23 251:61994, 2007-02-02, 1- (2007)
[4] Lindström R. O., "När AWV blev AMV", Pansar (2), 4–9 (2008).
[5] Ball R. E., [The Fundamentals of Aircraft Combat Survivability Analysis and Design], 2nd ed., Reston, VA: AIAA Education, (2003).
[6] Haskins C, Forsberg K, Krueger M, Walden D, Hamelin D., [INCOSE - SE Handbook], 3.2 ed., INCOSE, (2011).
[7] FOA, "SAT/Mark (MOC) Slutrapport SG modellering", FOA-R--98-00883-615, 1- (1998).
[8] FOA, "SAT/mark (HKC) Slutrapport studiegrupp Krav", FOA-R--98-00874-615, 1- (1998).
[9] Bohman L., [Handbook on signature management technology for ground] (swedish), FOI, (2003).
[10] FMV, "FMV Guidelines for requirements on signature management", FMV 29156/2006 H/R, Issue 13, (2006).
[11] Försvarsmakten, "MS 136 SEP - Reviderad Preliminär Taktisk Teknisk Ekonomisk Målsättning (RPTTEM) för Splitterskyddad EnhetsPlattform (SEP)", HKV H 35 129:80713, 2006-06-12, (2006).
[12] Lindström R. O., Nilsson L, Tapper K, "Slutapport MS 136 SEP", FMV 34719/2009, 2009-11-25, (2009).
[13] ISO/IEC, "ISO/IEC 15288:2008 - Systems and software engineering - System life cycle processes", (2008).
[14] Westin J, Olsson O, Pettersson L, Lindwall P, Grop A., "Active control of infrared signature: system implementation in a ground vehicle", Proc. SPIE. Vol. 5075, 39–48 (2003).
[15] Soban D, Mavris D., "Formulation of a Methodology for the Probabilistic Assessment of System Effectiveness", AIAA Strategic and Tactical Missile System s Conference. Monterey, CA: AIAA, 1–12 (2000).
[16] Åkerlind C, Hallberg T, Kariis H, Fagerström J., "Evaluation criteria for spectral design of camouflage", Proc. SPIE 9653, (2015).

7.2 Interviews

Lars Bohman, MSc, currently head of the department for radar systems at FOI, in a semi-structured interview on the 23rd of April 2015 at FOI in Linköping. Lars Bohman was interviewed in his capacity as senior scientist representing FOI in several working groups during the SAT/Mark program. He was chairman of the sensor threat assessment-working group and of the working group on how to state requirements for signature management.

Ola Dickman, PhD, currently the project manager for FMV signature management R&D, semi-structured interview on the 25th of February 2015 at FMV. Ola Dickman was interviewed in his capacity as the project manager of the SAT/Mark demonstrator project and as project manager of the FMV R&D group on signature management. He was also project manager for the procurement of mobile camouflage systems for some of the combat vehicles during the period of interest and also for R&D projects directed to Barracuda for technological development.

Lars Karlsson, BA, currently consultant involved in evaluation of Saab Barracuda AB products, semi-structured interview on the 8th of April 2015 at Saab Barracuda in Gamleby. Lars Karlsson was interviewed in his capacity as the senior systems engineer representing Saab Barracuda in the SAT/Mark project.

Rickard O. Lindström, MSc, currently strategic specialist for combat vehicles at FMV and POC for international cooperation, semi-structured interview on the 25th of March 2015 at FMV in Stockholm. Rickard O. Lindström was interviewed in his capacity as the FMV project manager of the SEP project from start to finish, 15 years in total. During the SEP development phase he was also program manager at FMV with overall product responsibility.

Örjan Olsson, PhD, currently vice president of BAE Systems Hägglunds, semi-structured interview on the 6th of March 2015 at BAE Systems Stockholm office. Örjan Olsson was interviewed in his capacities as specialist in signature management, during the technology demonstrator project, then specialist and systems engineer during the SEP development project and, finally, project director with overall responsibility for the product.

Kenneth Tapper, LTC (Retd), currently consultant involved in another SwAF development project, semi-structured interview on the 4th of May 2015 at FMV. In 1996 Kenneth Tapper was interviewed in his capacities as system manager in SwAF for mechanized infantry, until 1999, then the SwAF manager of the SEP project, head of the R&D committee for combat vehicles and also the Swedish head representative in a project with the UK on a tentative collaborative procurement of combat vehicles.

PAPER IV

2017 IEEE. Author manuscript in accepted version,
published with permission. If citing, please use:

Kent Andersson,
An exploratory case study on Swedish development of
Low Observable vehicles
International Conference on Military Technologies 2017 (ICMT),
IEEE, 2017. p. 123-129.
https://doi.org/10.1109/MILTECHS.2017.7988743

Author manuscript, accepted version

An exploratory case study on Swedish development of Low Observable vehicles

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***Abstract*—A case study approach, based on interviews and document reviews, was used to analyze the systems engineering processes of the SEP (Armored Multirole Vehicle, in Swedish) and the Visby class corvette cases respectively. The focus was on signature management. The result is a thorough investigation of what worked in the cases studied. The main conclusions can be summarized in three points. 1) A preferred workflow from mission analysis to sub system design has been derived from lessons identified; 2) The three main success factors identified were: building technology demonstrators, having an Integrated Product Team approach, and establishing stealth as a key system design goal; 3) Coherence and traceability between military needs on the battlefield and signature requirements need further research.**

Keywords-component; Low Observable Technology, Stealth, Signature, Survivability, Systems Engineering, SEP, Visby class corvette

I. INTRODUCTION

Until the end of the Cold War, Swedish doctrine was focused on national defense. Significant expertise and experience in signature management for combat vehicles was gathered in development projects like the S-tank and the CV90, and also in tests and trials when procuring the Leopard main battle tank [1]. Here signature is understood to be any characteristic making an object detectable with a sensor. In 1985 an R&D program started with the aim of studying how Low Observable Technology (LOT), i.e. for reducing signature, could be applied to the next generation of surface ships for the Royal Swedish Navy (RSwN). The program resulted in a test vessel called Smyge, which was in operation until 1995. The Smyge test program not only spurred the use of stealth in what became the Visby class corvette, but also inspired a joint service R&D demonstrator program for stealth on land in 1996 called SAT/Mark. In parallel with the launch of the SAT/Mark (LOT/Land, in Swedish) program, a study of replacement combat vehicles for Swedish land forces recommended developing an Multirole Armored Platform concept (SEP, in Swedish). Multispectral signature adaptation, particularly in the infrared (IR) and radar domains, was identified among the technologies of special interest to support the concept [1].

The SAT/Mark project also resulted in the publication of results relating to the development of stealthy land combat vehicles [2,3]. However, in the last decade there have been very few reports of new research into the issue. The survivability focus of the reports found seem to be on vulnerability or active protection (e.g. [4,5,6]), and none of them provide any new guidance on the signature engineering process or on signature requirements management.

Since signature management is of increasing importance in enhancing the survivability of land forces in future conflicts, it is important not to lose sight of lessons identified a decade ago. The question in focus is hence how to achieve favorable conditions for the design of the next Low Observable military vehicle. Therefore, the scope of the first part of the study, reported in this paper, is to collect possible lessons identified from earlier development of balanced stealth designs. The final step will be to analyze these in relation to a presumed European capability development environment of the near future. The focus is on land vehicles, which is why the SEP development process is the primary case studied. The Visby class corvette case is mainly used for comparison in order to support generalization of results.

Next, in the theory section of the paper, the survivability engineering discipline within Systems Engineering (SE), is presented. Thereafter, the research approach, including the case study method and the sources, is described, followed by a short description of the two cases. In the subsequent analysis section, results of the analysis are presented. Finally, the results are discussed and conclusions are presented.

II. SYSTEMS ENGINEERING

This study takes an SE perspective on signature management. SE is recognized among most western states and major defense industries 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 [7]. Best practice SE involves coordinating all specialist engineering activities, including survivability engineering.

Survivability of a platform is enhanced either by reducing its vulnerability or its susceptibility to hostile actions [8]. LOT is used to reduce the passive signature of a platform, thereby also reducing the probability of detection. Thus, it is one way to reduce susceptibility. In this paper survivability engineering activities aimed at meeting signature requirements during development are also referred to as signature engineering.

So far survivability engineering, including signature engineering, has mostly been studied in relation to combat aircraft design. The main challenge originates from the

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[1] Rickard O. Lindström, strategic specialist in combat vehicles at the Swedish Defence Materiel Administration, FMV, interview, 25th of March 2015

interdependence of the attributes of a platform. The combat aircraft community stresses that the goal of survivability engineering is to increase the cost effectiveness of the weapons system, not to design the most survivable platform possible [8]. The shaping necessary to reduce radar signature will for example also reduce maneuverability and payload. It is therefore necessary to find a balance in the corresponding system requirements on the design. According to Ball the most important success factors are [8: p. 44-50, 174]:

- To measure system effectiveness of a combat aircraft in terms of offensive capability, availability and survivability,
- To evaluate the design of a platform as a component in a mission system,
- For the design team to consider survivability at an early stage, because retrofitting survivability features usually adds unnecessary penalties to the design, e.g. weight or cost, and
- For survivability engineers to work continuously in close cooperation with designers, the program manager and operators, and that they should be allowed real influence.

Typically, the main SE effort occurs early in a systems life cycle, i.e. in the concept or development life-cycle stages. The rationale is that already after design some 85% of the total life cycle cost of a complex product is committed [7]. A design is a solution description resulting from the development life-cycle stage. It is based on system requirements derived from the stakeholder needs and the conceptual solution identified in the concept stage, and it is limited by the competence of and the technology available to the development organization [7]. Hence, this study is focused on the search for lessons in the concept and development life-cycle stages and on those SE processes that support the derivation of system requirements and system design.

III. RESEARCH APPROACH

A. Data collection and sources

Data was collected using an exploratory case study method [9]. The two cases studied, development of the SEP combat vehicle and the Visby class corvette respectively, were chosen because of the prominent role signature management played in the systems architecture of each platform. In this respect these projects are currently unique to Sweden, and are two of but a few comparable land or maritime projects worldwide. In addition, because of their uniqueness, these two programs were also the only relevant options where data was available to the author.

The focus of this paper is on land combat vehicles; a comparison between the SEP case and the Visby case is used to support validation of results.

Data in the SEP case was collected using interviews of key personnel from government organizations and contractors, and from a review of relevant documents. The respondents were selected on the basis of having played key roles during development. In the Visby case two respondents were interviewed, who at the time filled roles as signature coordinators in the government project. Table I presents the roles of the respondents in the respective cases.

TABLE I. ROLES OF THE RESPONDENTS

Respondent	***SEP program***	***Visby program***
A	Head of plans and policies in SwAF[a] HQ	
B	SwAF Project Manager (PM) for SEP program	
C	FMV[b] PM for SAT/Mark demonstrator	
D	FMV PM for SEP program	
E	FOI[c] Senior scientist threat assmnt and signature reqs	
F	Contractor PM for SEP, and signature specialist	
G	Contractor signature specialist for SAT/Mark	
H		SwAF product mgr for Smyge demonstrator and FMV Signature coord. for Visby prgm 1995-99
I		FMV Signature coord. for Visby prgm 2000-01

a. SwAF - Swedish Armed Forces,
b. FMV - Swedish Defence Materiel Administration (abbrev. in Swedish),
c. FOI - Swedish Defence Research Agency (abbrev. in Swedish)

The basic structure of the interviews was to ask respondents to describe, from their perspective, each step of the development process, and to ask, given their experiences, what could be learned for future projects. The questions were structured following the technical processes in best practice SE [7].

Document reviews were used, when such documents were available, to support key statements from the respondents. There are reports from the Swedish Defence Research Agency (FOI) from the early stages of the SAT/Mark program, in 1998, concerning modeling issues and requirements specification [10, 11], and a handbook on signature management for ground vehicles [12]. The handbook provides lessons learned in the form of engineering guidelines for the construction and evaluation of low observable vehicles. The experiences of both the Swedish procurement agency (FMV) and industry from the development of the SAT/Mark demonstrator also resulted in conference papers presented to SPIE [2, 3]. A lessons-learned report to the Swedish Armed Forces (SwAF) by the SEP project management is partly unclassified and useful for reviewing the schedule and key management events [13]. Symposium proceedings from presentations given after the launch of the Visby corvette in June 2000 have been used for background information and for general lessons learned in the Visby case [14]. Project documentation concerning numeric measures for system signature requirements and verified results are, however, confidential. Nevertheless, it has been possible to discuss results on a general level with the respondents. This has proven sufficient for drawing conclusions on methods and procedures.

B. Analysis approach

The aim of the analysis was to identify lessons from the development processes of the two cases, using a framework [15] of concepts for best practice systems engineering as a filter. The framework was chosen because it was developed for, and has been used as, the baseline assessment tool in similar evaluations [15, 16, 17]. Because the focus was on the SE technical processes covering requirements analysis, systems architecture and design, the following subset of SE-concepts [15] were used:

1) Requirements management

- "A1. Requirements shall flow down in a coherent and traceable manner from the top level to all lower levels of the system being engineered."
- "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."
- "A3. The government shall integrate the needs of its user organizations with the management activities of its developmental organizations."

2) Systems Architecture

- "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."
- "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."

3) System and Subsystem design

- "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."

4) System and program management

- "I2. The role of systems engineering in program development and management shall be recognized and supported."

IV. CASE DESCRIPTIONS

An overview of the major events and decisions shaping the early stages of the SEP and the Visby lifecycles is presented. Note that the SEP and the Visby development programs were each preceded by R&D Low Observable technology demonstrator projects: the SAT/Mark and Smyge projects respectively. Subsequently, and in this study, these projects can be viewed as knowledge building activities in the respective concept stages, not least in terms of the transfer of knowledge of low observable technology from long-term defense research [2, 18].

A. The SAT/Mark and SEP programs

In 1993 SwAF identified a need to replace about 7000 tracked combat vehicles in the Swedish Army during a period stretching from 2005 to 2015. A SwAF study was initiated in 1995.

There were several demonstrator projects supporting concept development. The SAT/Mark program, for evaluation of low observable technologies and development of standards, was launched in 1996 and was terminated in 2002. There was also a project called High Survivability Testbed evaluating technologies for ballistic protection. In total eight technology demonstrators were built.

The concept idea was to improve cost-effectiveness and performance using new technology. The solution sought was a modular multirole armored platform with: electric transmission, rubber tracks, decoupled running gear, a composite fiber hull, add-on ballistic protection and multispectral signature adaptation.

International cooperation was sought as part of the procurement strategy, e.g. within the West European Armament Group and other Scandinavian countries. There were serious discussions with the UK until 2007.

In 2006 BAE Systems Hägglunds AB was awarded the contract for initial development of SEP. See Fig. 1. The contractor was also to be responsible for the system design and integration. In 2008 FMV decided not to pursue further development because the government failed to find international partners.

Sources: Lindström [1], interview with Lindström[2], and Olsson et al. [2].

B. The Smyge and Visby class corvette programs

In 1988 SwAF initiated the first conceptual study for the next class of surface ships. It resulted in concepts for three types of ships.

Already in 1987 a R&D program for evaluation of low observable technologies, surface-effect-ship technology and integration of weapons in stealth vessels was initiated. The Smyge test vessel was launched in 1991 in order to support sea trials. The program ended in 1994.

The Visby concept idea was to exploit new technology in order to "combine the survivability, flexibility and endurance of a frigate, all in the economy of a corvette sized ship" [18]. The solution sought was a multirole surface vessel with limited crew size, made possible by automated defense systems, and survivability made possible by stealth and countermeasures.

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[2] Rickard O. Lindström, strategic specialist in combat vehicles at FMV, interview, 25th of March 2015

Figure 1. One of four pre-series SEP vehicles produced by BAE Systems Hägglunds AB in 2009. Photo courtesy of Rickard O. Lindström

Figure 2. A Visby class corvette at high speed at sea in 2013. Photo Jimmie Andersson, Swedish Armed Forces

International cooperation was sought and Singapore was involved in the program during the latter part of the concept stage.

In 1995 FMV launched the Visby class development project. Kockums AB was awarded the contract to build the ship but FMV was to be responsible for system design and integration.

In 2009 the first two ships entered service. See Fig. 2.

Sources: Bergman [18] and interview with Mathiasson[3].

V. ANALYSIS

Each subsection presents lessons identified consistent with the corresponding title SE-concept.

A. *Ensure coherent and traceable flow down of requirements (A1)*

In both cases the government established an integrated product team (IPT) approach early on. It enabled representatives of the design organizations to participate in requirements analysis activities at a military mission system level as early as the concept stage, thereby gaining a good understanding of stakeholder needs.

Requirements analysis started with identifying the dimensioning stakeholder requirements from relevant mission scenarios. In both cases it was found necessary to first identify signature critical situations. In the SEP case the advance to contact was found the most important situation and in the Visby case it was the duel with anti-ship missiles.

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 [2]. 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. The probability assessment was found particularly challenging given the multirole concept, because in each mission type scenario there is a new main sensor threat. This places conflicting demands on the design.

Continued analysis then required the identification of the key measures of performance most relevant for desired capabilities. This link assures traceability between the system requirements derived and the stakeholder needs. 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.

The SAT/Mark demonstrator project found that coherence between stated platform requirements and tactical needs on the battlefield requires expressing system requirements as signatures, where signature is defined as “any property, or combination of properties, of an object, that makes it distinguishable from its immediate background by a sensor” [12]. However, 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 derivation of verifiable system requirements was made possible by selecting and specifying configurations with sets of situational parameters, including: sensor threat type, sensor elevations, target vehicle aspects, and typical backgrounds.

There were difficulties reported expressing all system requirements in a system signature format, especially for the radar and infrared sensor domains. In the Visby case the radar signature was for example 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. There are also many different contrast measures 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

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[3] Urban Mathiasson, Cdr and naval engineer SwAF, interview, 12th of January 2016

resulting matrix elements lack relevant candidate measures. In summary, the difficulties identified make coherent flow down from stakeholder requirements, on the military mission level, to system signature requirements a challenge.

At the system level, signature requirements had to be formulated as design instructions when allocating them to design at sub-system level, since signature requirements at the sub-system level was found not to make sense. Instead, the design instructions were iterated and reiterated until the system design fulfilled system requirements. 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.

Furthermore, it is worth noting that 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.

B. Share knowledge between government and contractor (A2)

Until termination of the SEP program in 2008, both development programs, including the demonstrator projects, were implemented in accordance with a national procurement strategy that, at the time, had been in place for decades. It allowed the Swedish defense industry to benefit from development sponsored through government acquisition programs, thereby acquiring the use of expertise in export programs. In return, this expertise could be called upon in the next government acquisition program.

The respondents stated that the national procurement strategy at the time led to close collaboration between the contractors and the government agencies.

The involvement of contractors in the early phases through the integrated product team approach mentioned earlier 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.

In the SEP case risk eliminating studies, of such things as signature requirements, were performed continuously at the contractor. 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.

C. Integrate the needs of the user organization (A3)

The military user organization provided scenarios for the stakeholder requirements analysis in both cases. Ideally these should comprise: descriptions of anticipated missions, own tactics and procedures, anticipated physical environments and anticipated adversaries.

Developing the documentation of input mission scenarios into concepts of operation, as prescribed in best practice 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 IPTs.

D. Establish systems baseline architecture early (B1)

In both cases establishing stealth as a high-level design goal from the inception of the development program was found to be critical. The arguments were that otherwise the end result will not be stealthy, and 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.

E. Employ best judgment in the use of technology (B2)

It seems that innovation in both programs benefitted from the close collaboration between agencies and contractors. The modular principle of the SEP is one example, and the carbon fiber reinforced plastic hull of the Visby class corvette is another.

F. System design shall proceed in a logical and orderly manner (C1)

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” [12]. In the Visby case both the radar and magnetic signatures seem to have had high priority.

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.

G. SE shall be recognized and supported within the program (I2)

Signature management was an influential and integrated element of the systems engineering organization. A system approach was seen as a necessity. 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.

H. Summary

The workflow illustrated in Fig. 3 emerges from the analysis, covering requirements management and design activities.

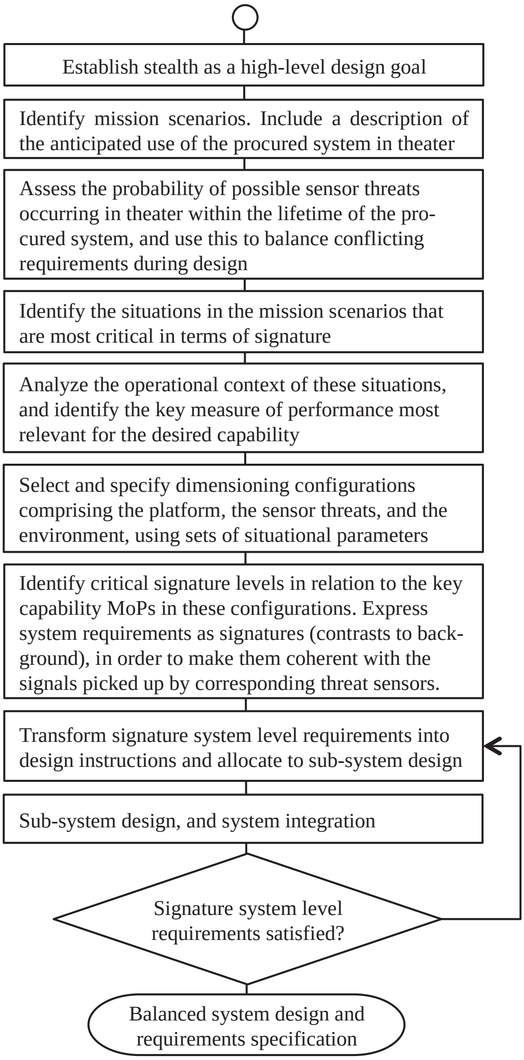

Figure 3. This is the workflow derived from the analysis of the SEP and Visby cases, covering requirements management and design activities.

The final result of the workflow illustrated is presumably a balanced, implementable, Low Observable design, typically documented in system or subsystem specifications.

The following major success factors can be identified:

- Establishing stealth as a high-level design goal at an early stage of system architecture design
- Executing a LOT demonstrator project during the concept life cycle stage reduce technology risks, supports identifying realizable signature levels, supports validating methods for modeling and measurements, and promotes mutual understanding between government agencies and design organizations.
- Establishing a process and organization for continuously monitoring system signatures during the design
- Working in integrated product teams facilitates: sharing of knowledge, sharing of high level measures of effectiveness, as well as a coherent flow down of requirements

In addition, the following major challenges were identified:

- Coherent flow down from military needs to lower levels is a major challenge due to difficulties expressing system requirements as signatures (contrasts to background).
- Stating verifiable signature requirements in the visible and infrared regions is inherently difficult due to the statistical nature of the background.

VI. DISCUSSION

A preferred workflow for requirements management and design have been identified, and overall the results of the analysis is in reasonable agreement with the four success factors pointed out by the combat aircraft survivability community [section II]. (1) Survivability was seen an important part of system effectiveness; (3) survivability was a prioritized design goal established early on, and; (4) there was close cooperation between survivability engineers, designers and program management. Some question marks can, however, be raised regarding to what extent it was possible to analyze requirements on the SEP as a component in a mission system (2). In order to satisfactorily link military needs and system requirements it seems the following research questions need further attention:

- How should capability measures of effectiveness, such as detection range or time to classification, relate to a “cost effective weapon system” [Section II]. Arguably, with a mission system perspective, the design of a stealthy combat vehicle should be evaluated within the framework of a unit, e.g. a battalion conducting operations.

- How should signature measures of performance in the radar and infrared domains be expressed in order to be: coherent with relevant capability measures of performance, verifiable (measurable) and possible to model and simulate? Spatial, spectral and temporal contrasts all need to be included.

- And, how should the statistical variation in background be measured and expressed for the respective sensor domains?

The research approach used relies on both cases having succeeded in delivering properly balanced low observable designs, and there are good reasons to believe that they both did. Analysis of the case study results, using the Friedman-Sage framework, suggests that both development programs adhered closely to good systems engineering practices. This is supported by a consensus among respondents and the end results in both cases seem to be well-balanced designs, which still satisfy signature requirements.

However, there is one major uncertainty in the method. It seems to the author, that the successful end results in the relatively immature domains of radar and infrared signature were not necessarily the result of well-justified, quantified, military needs. The analysis shows that it has been impossible to demonstrate a robust link between the military needs and stated system requirements. Instead, the seemingly successful end results were the result of a disciplined implementation of stealth architectural principles to obtain the best possible result in each domain. In both cases studied the program management strongly supported these principles, and, because there was no serious conflict between optimal stealth solutions and cost or other functional requirements during detailed design, stealth could be implemented with few trade-offs. This raises questions about whether or not the designs really represent the best achievable balance between stealth and other attributes.

Finally, the lessons were identified from studies of development programs governed by a Swedish national procurement strategy that is no longer valid. Hence, in order to generalize and to make recommendations for future development programs it is necessary to analyze the lessons identified in light of the European procurement environment of a near future. This analysis will be part of continued research.

Consequently, the workflow described for requirements analysis and design of Low Observable combat vehicles, with identified success factors, forms a good starting point for continued development and research.

VII. CONCLUSIONS

The work reported is the first part of a research study with the aim to propose guidelines for the procurement of future Low Observable combat vehicles. The engineering processes of two Swedish development programs have been studied using a case study method – the SEP multirole armored vehicle and the Visby class corvette. The result is a thorough investigation of what worked in the cases studied. The following three conclusions are presented:

Firstly, a tentative workflow, tailored for requirements management and design in programs developing Low Observable vehicles, has been derived from lessons identified.

Secondly, apart from the tailored technical processes a shortlist of success factors has been derived. 1) the demonstrator projects (had multiple benefits), 2) the integrated product team approach established already in the study phase of the programs, and 3) establishing stealth as a key system design goal already from inception of the programs.

Thirdly, further research is needed to achieve coherence and traceability from military needs to requirements on lower system levels, including: expanding the system view to a mission system level, and defining measures of performance at all system levels.

ACKNOWLEDGMENT

This work was financially supported by the Swedish Defence University. The author would like to thank Martin Bang and Stephen Henly at the Swedish Defence University, Rickard O. Lindström and Anders Grop at the Swedish Defence Materiel Administration for valuable input, and of course the respondents for sharing their invaluable knowledge.

REFERENCES

[1] R. O. Lindström, “SEP: Multirole Armoured Platform”, Swedish Journal of Military Technology, 1999.

[2] Ö. Olsson, L. Karlsson, P. Lindwall, O. Dickman, and A. Grop, “A Systems Approach to Stealth on Ground ; SAT/Mark Technology Demonstrator”, Proc. SPIE, vol. 4718, 2002, pp. 1–11.

[3] J. Westin, Ö. Olsson, L. Pettersson, P. Lindwall, A. Grop, “Active control of infrared signature: system implementation in a ground vehicle”, Proc. SPIE, vol. 5075, 2003, pp. 39–48.

[4] G. L. Guzie, “Integrated Survivability Assessment”, ARL-TR-3186, US Army Research Laboratory, White Sands, 2004.

[5] W. J. Goh, “Survivability design of ground systems for area defense operation in an urban scenario”, Naval Post graduate School, CA, 2014.

[6] M. Burgess and G. Svetoslav, “Survivability for Deployable Protected Land Vehicles : Concepts, Models and Applications”, J. Battlef. Technol., vol. 18, no. 2, 2015, pp. 7–13.

[7] D. Walden and G. Roedler, Eds., INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4th ed., John Wiley & Sons, Hoboken, NJ, 2015.

[8] R. E. Ball, The Fundamentals of Aircraft Combat Survivability Analysis and Design, 2nd ed., Reston, VA: AIAA Education, 2003.

[9] R. K. Yin, Case Study Research – Design and Methods, 4th ed., Sage Publications Inc., Thousand Oaks, CA, 2009.

[10] Swedish Defence Research Agency, FOI, “SAT/mark (HKC) Slutrapport studiegrupp Krav”, FOA-R--98-00874-615, 1998.

[11] Swedish Defence Research Agency, FOI, “SAT/Mark (MOC) Slutrapport SG modellering”, FOA-R--98-00883-615, 1998.

[12] L. Bohman, Handbook on Low observable technology for ground (swedish), FOI, Linköping, 2003.

[13] R. O. Lindström, L. Nilsson, K. Tapper, ”Slutapport MS 136 SEP”, FMV 34719/2009, 2009.

[14] RSSNS, Navy 2000 Symposium on the Visby class corvette, Royal Swedish Society of Naval Sciences, Stockholm, 2000.

[15] G. Friedman and A. Sage, “Case studies of systems engineering and management in systems acquisition”, Systems Engineering, vol. 7(1), 2004, pp. 84-97.

[16] P. J. O’Brien, J. M. Griffin, “Global Positioning System Systems Engineering Case Study”, US Air Force Center for Systems Engineering, Hobson Way, Ohio, 2007.

[17] B. Kinzig, “Global Hawk Systems Engineering Case Study”, US Air Force Center for Systems Engineering, Hobson Way, Ohio, 2010.

[18] M. Bergman, “The development, in: Navy 2000 Symposium on the Visby class corvette”, Royal Swedish Society of Naval Sciences, Stockholm, 2000.

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Carina Marcus, Kent Andersson and Christina Åkerlind,
Balancing the radar and long wavelength infrared signature properties in concept analysis of combat aircraft – a proof of concept
Aerospace Science and Technology,
Volume 71, December 2017, p 733-741
https://doi.org/10.1016/j.ast.2017.10.022.

Aerospace Science and Technology 71 (2017) 733–741

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Balancing the radar and long wavelength infrared signature properties in concept analysis of combat aircraft – A proof of concept

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 10 August 2017
Accepted 12 October 2017
Available online 16 October 2017

Keywords:
Radar
Infrared
Signatures
Scenario
Evaluation

ABSTRACT

Designing combat aircraft with high military effectiveness, affordability and military suitability requires balancing the efforts of many engineering disciplines during all phases of the development. One particular challenge is aircraft survivability, the aircraft's ability to avoid or withstand hostile actions. Signature management is one way of increasing the survivability by improving the ability to avoid detection. Here, the long-wave infrared and radar signatures are studied simultaneously in a mission context. By establishing a system of systems approach at mission system level, the risk of sub optimization at a technical level is greatly reduced. A relevant scenario is presented where the aim is to incapacitate an air-defense system using three different tactics: A low-altitude cruise missile option, a low and medium altitude combat aircraft option. The technical sub-models, i.e. the properties of the signatures, the weapons and the sensors are modeled to a level suitable for early concept development. The results from the scenario simulations are useful for a relative comparison of properties. Depending on the situation, first detection is made by either radar or infrared sensors. Although the modeling is basic, the complexity of the infrared signature and detection chain is demonstrated and possible pivot points for the balancing of radar and IR signature requirements are identified. The evaluation methodology can be used for qualitative evaluation of aircraft concepts at different design phases, provided that the technical models are adapted to a suitable level of detail.

1. Introduction

When maximizing the military utility of a combat aircraft for the air force operating it, there is a challenge in finding a balance between military effectiveness, affordability and military suitability [1,2]. The technical requirements of the design are often driven by doctrine and derived tactical needs, but the outcome is limited by such things as subsystem performance, properties of materials, cost, weight, volume or power consumption.

Hence, it is an unfortunate fact, well known to aircraft designers, that a combat aircraft is a complex compromise of attributes, and features introduced to enhance one of them risk resulting in sub optimization or even having penalties for the others. Therefore, evaluations to balance key characteristics, such as flight performance, availability, survivability etc., must be performed throughout the design process, as well as evaluations to balance supporting features like sensor placement and signature levels. In doing this it is important to consider both the technical and tactical developments of the concept.

The inherent complexity of this process requires the use of effective tools and methods that simultaneously encompass all relevant engineering perspectives and assess the aircraft in a mission context. A field of research developing frameworks for dealing with this kind of challenge has emerged during the last decade. The field is often labeled Design Space Exploration (DSE) [3,4] and the frequently disparate requirements on characteristics and supporting features can to some extent be accommodated using so called Multidisciplinary Design Optimization, (MDO) [5]. Employing these methods requires compatible quantitative models covering the problem space in order to automate the formulation and evaluation of solutions potentially satisfying the design needs.

A good example of the challenging engineering disciplines in aircraft design is survivability engineering. Its aim is to decrease

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https://doi.org/10.1016/j.ast.2017.10.022
1270-9638/

an aircraft's susceptibility and vulnerability to man-made threats [1], while having minimum impact on other attributes. The intense debate during the last couple of decades, regarding programs such as the B-2, the F-22 and the FA-35, and whether or not the enormous investment in low signature designs to reduce susceptibility pays off, is evidence of this being an important topic – at least to the armed forces in all western countries struggling with shrinking budgets. Here the signature of a combat aircraft is any characteristic that makes it detectable with a sensor. In addition, views on the importance of RF (radio frequency) stealth in the presence of bi-static radar, passive bi-static radar and low-frequency radar systems [6–8] seem to be changing. Low radar (RF) signature, i.e. small radar cross section (RCS), is no longer considered a pivotal feature of future combat aircraft designs, while the infrared (IR) signature is emerging as an increasingly important factor. The cost and size of IR sensors have decreased while their performance has increased, and current developments point towards higher spatial and spectral resolution [9]. Articles about susceptibility seem to address technologies, from the shaping or application of advanced materials (for either RF signature reduction or IR signature suppression) to man portable air defense systems. The latter having sensors sensitive to aircraft exhaust plumes or hot engine parts (3–5 μm).

However, little research addresses the combination of RF and IR, i.e. how low either signature is required to be, given the possibility of detecting the aircraft with the other type of sensor. Long-wave infrared (LWIR) sensors have come to be particularly interesting from an air-defense point of view. Already there seem to be operational surface-to-air units (SAMs) associated with Integrated Air Defense Systems (IADS), that combine LWIR with radar sensors in one control system [10]. This makes sense since it has been shown that, for the front sector of an approaching aircraft, emission from aerodynamic heating and reflected earthshine are the dominant IR sources [11,12], and the intensity peaks for both sources are in the LWIR atmospheric window 8–14 μm.

Hence, the aim of this paper is twofold. Firstly, to establish a quantitative model for studying how the military system effectiveness of flying platforms responds to different signature reduction measures. Secondly, to implement the model for proof of concept and to show how such an approach can be used to support the balancing of RF and LWIR signature properties in a relevant mission context, thereby linking the technical and tactical concept variables to military utility.

The models used are at basic level of detail which has the direct consequence that the results have a limited fidelity. One key point in this paper is to demonstrate the process of the evaluation and how the chain of signatures, propagation and sensors influence the survivability. To obtain results of high fidelity, the models used should be at the appropriately detailed level, which is beyond the scope of this paper.

The paper is organized as follows. The system approach is outlined in Section 2. The mission system level model is described in Section 3. The technical sub-models are defined in Section 4. The results are presented and analyzed in Section 5 and discussed in Section 6. Conclusions are drawn in Section 7 and future development suggested in Section 8.

2. Methodology – balancing signatures

2.1. A system approach

It has been shown that the interdependence of attributes within the survivability discipline, and the context dependence of aircraft signatures, call for a system analysis approach [1,13]. By analyzing an aircraft technical system at the mission system level, the analysis of its military effectiveness becomes a system of systems investigation. Thus, a combat aircraft, and its interdependent attributes, can be optimized to fulfill mission level goals and objectives, instead of risking sub optimization by doing trade-off studies at the technical system level. The analysis in this study was supported by a system model in four levels. See Fig. 1. During the concept analysis phase, the system design activity results in alternative aircraft concepts. These models of potential future aerial platforms are defined using a set of variables representing technical features of its subsystems. This paper focuses on signature reduction features; therefore, the surfaces, size and shape of the airframe are important. These models can in turn be seen as the product of sub system design, as illustrated at the lowest system level in Fig. 1. At the capability system level, several aircraft form a strike package with several tactical air strike options, and at mission system level they engage the corresponding threat system when executing a mission. Furthermore, Fig. 1 indicates how output technical parameters or measures of performance, MoPs, from one system level should be seen as input variables at the next level. Thus, the aim was to construct a mission system model in which the technical variables in the subsystems are linked, through response functions, to the measures of effectiveness, MoEs, at the top. This should allow us to measure the utility of technical developments directly in mission outcomes. In summary, the methodological approach in this study was to develop a meaningful quantitative model of the complete mission system and to use it for the analysis of LWIR and RF signatures.

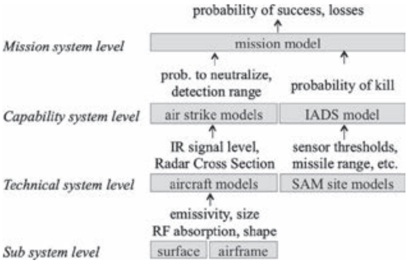

Fig. 1. An illustration of the models necessary at each system level to support conceptual analysis and design.

2.2. The analysis scheme

The analysis scheme used is outlined in four phases similar to an earlier approach [13]. The first three can be seen as part of the modeling activity.

Given the problem, the first phase comprised: establishing reference baseline features and performance for the flying platforms of interest, choosing input and output variables to aircraft, surface-to-air missile (SAM) site and mission models, and defining a suitable scenario with a relevant task and relevant tactical strike options. Input was gathered from interviewing experts.

In the second phase, key decision nodes, and how they were to be modeled, were defined for the strike options studied in the scenario. In our setting we simply used the so-called "kill chain", i.e. the probability of an aircraft being killed is a product of probabilities related to the SAM-units of the air defense system being active, the aircraft being detected, identified and tracked, and then the probability of a missile being launched etc.

In the third phase, a simulation environment was established. This included the identification of response models for the various levels of analysis and their implementation in Matlab. In this paper the focus is on the relation between RF and IR response models at the technical system level. However, in order to acknowledge that the response in military system effectiveness is what matters when

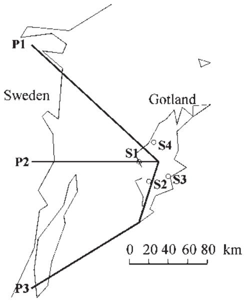

Fig. 2. The scenario, with planned flight paths and SAM sites.

Table 1
The sensor coordinates.

Sensor	Coordinates [x; y; z] [km]
S1	[110; 130; 0.02]
S2	[120; 110; 0.02]
S3	[140; 115; 0.02]
S4	[125; 150; 0.02]

optimizing the balance between signature reduction features, some simple probabilistic response functions were implemented for synthesis at higher levels.

In the fourth and final phase the model was used and the results were analyzed.

3. The mission system model (the scenario)

A systems view of the military utility of signature features was established by relating performance to mission success in a relevant, but notional scenario.

3.1. The mission

The fictive mission was defined as neutralizing a point target defended by short range SAM units in an integrated air defense system in the middle of Gotland (a Swedish island approximately 100 km off the east coast), at the least possible cost, within X hours, using Air-to-Surface Air Operations (air strikes). It is assumed that the air defense is not fully operational in the given time frame. The positions of the SAM units and the flight paths of the planned missions can be seen in Fig. 2 with sensor coordinates given in Table 1.

The three different flight paths were chosen with different tactical ideas in mind and were analyzed as three separate options in order to cover a spectrum of tactical variables. Baselines and key metrics for the depicted strike options are shown in Table 2. All missions were assumed to be conducted in the middle of summer, at midnight and in clear weather conditions.

3.2. The threat

Each SAM unit was presumed to be configured with a short range SAM launcher, a combined reconnaissance and firing radar and a LWIR imaging sensor. Measures of performance data were selected to be realistic, but generic and from open sources. See Table 3. The normal doctrine was presumed to be scan-detect-track using radar, and using the IR-sensor to support identification. However, the IR-sensors could also be used to detect and track, e.g. when facing stealthy aircraft, or using silent procedures. In an integrated air defense system it is possible to get range to target by triangulating signals from two or more sensors. However, this latter feature is not elaborated on in this study.

Table 2
The Cruise missile/aircraft (target) variables. The baseline values are underlined.

Variables	Cruise missile	Attack aircraft
Strike profile/altitude, [m]	P1/50	P2/8000, P3/100
Speed, [m/s]	250	300
Waypoints, [x; y; z] [km]	[0; 250; 0.05] [130; 130; 0.05]	P2/[0; 130; 8] [130; 130; 8] P3/[0; 0; 0.1] [110; 67.5; 0.1] [130; 130; 0.1]
Size, [m^2] (front, side, top)	0.2, 2, 2 or 0.4, 4, 4	6, 25, 50 or 12, 50, 100
Surface coating (emissivity)	0.5, 0.9 29	0.5, 0.9
RCS basic level [m^2]	1, 0.1 0.05 0.01	4, 1, 0.1, 0.01
Load	–	4 × guided bombs

3.3. The cruise missile option

Path one (P1) illustrates the typical flightpath of a cruise missile dropped from high altitude over the mainland descending to and cruising at low altitude, at subsonic speed, straight to target. The main idea of this alternative is to minimize the risk to manned aircraft by using a stand-off weapon. We decided to vary the emissivity of the cruise missile surface in order to study the response in detection range.

3.4. The medium altitude strike option

Path two (P2) illustrates the flight path of an attacking aircraft flying at medium altitude armed with guided bombs. This alternative is typically chosen either if the aircraft is expected to fly above the threat ceiling, or if the probability of the threat radar intercepting the aircraft is presumed to be low.

3.5. The low altitude strike option

Path three (P3) illustrates the navigational polygon of a typical low altitude air strike with aircraft armed with guided bombs. The tactical idea behind this approach is to reduce the probability of detection by staying low, below the horizon seen by the threat sensor, and in the clutter region originating from the terrain below. A drawback with this profile is high fuel consumption and the need to climb before striking the target, i.e. to do a so called "pop-up".

In the two latter options we decided to vary the emissivity of the aircraft surface, the speed of the aircraft, and the size of the aircraft, in order to study the response in detection range.

3.6. Synthesis modeling and measures of effectiveness

In the final step we wanted to relate the detection range obtained, or probability of detection, to measures of effectiveness (MoE) at mission level. Since signature reduction measures aim to increase survivability, we chose loss of aircraft as the principal MoE. By designing aircraft strike packages in the micro-situations above to achieve the mission precisely, we also indirectly included the offensive capability.

Given the mission described above, we chose the following criteria for Mission Accomplished (MA): The objective is to neutralize the point target with 75% certainty within X hours at the least possible cost in lost aircraft and crew. Hence, in probabilistic terms the criteria can be written as follows (see [1] for details)

$$MoE_1 = P_{MA} = (1 - P^{A}_{kill}) P_{N|S} > 0.75\,, \tag{1}$$

Fig. 3. The local coordinate system of the aircraft.

where P_{kill} denotes the probability one aircraft is killed in an engagement with a SAM unit, A denotes the number of aircraft in the strike package, and $P_{N|S}$ denotes the probability one aircraft neutralizes the target, if it survives the engagement. The number of lost aircraft is then given by

$$MoE_2 = Losses = AP_{kill} = AP_D P_{E|D} P_{K|E}, \tag{2}$$

where P_D is the probability of the aircraft being detected, $P_{E|D}$ is the probability of the aircraft being engaged by a SAM unit, if it is detected, and finally, $P_{K|E}$ is the probability of the aircraft being killed if it is engaged. A mission statement usually includes a time requirement, as indicated above, and we could have included a third MoE comprising time to execute. For proof of concept, however, we decided that the MoEs defined above were enough.

4. Technical models

The technical models of the components in the scenario were deliberately kept at a basic level, because the purpose is to demonstrate the methodology and to identify possible pivot points in the design, not to determine absolute levels of performance requirements. It is important to ensure that all models have a compatible level of detail. For example, a detection distance represents a combination of sensor, wave propagation and signature. As long as the combination of these three features yields results that are realistic and where the inherent limitations of use and accuracy are known, the model is useful. The technical systems modeled here consists of an aircraft, a cruise missile, IR and RF signatures and propagation, IR and RF sensors, a surface-to-air missile and attack weapons.

4.1. Aircraft and cruise missile models

The attack aircraft and the cruise missile were rudimentarily modeled as points with a position in space and a velocity. The local coordinate system for the aircraft is shown in Fig. 3 consisting of forward, sideward and upward pointing vectors. It is assumed to move along a straight line aligned with the forward pointing vector at a constant speed. The attitude is such that the side pointing vector is parallel to the ground, assuming a flat earth.

4.2. Signature, wave propagation and sensor models

An RF sensor can provide direction, distance and velocity data, whilst an IR sensor mainly provides highly accurate direction information. With a priori information on the size of the incoming objects, it is possible to determine range and position to some accuracy using an IR sensor, provided that the target spans several pixels in the sensor. In some situations the maximum detection range is limited by the curvature of the earth [14]. In addition, rainy or cloudy weather has a hugely limiting effect on IR, but only a small effect on RF.

The signatures are described as amplitude functions of angles in the local coordinate system. A vector between the aircraft and the sensor is used to determine the signature displayed towards the sensor and the slant range. In the scenario, the four SAM sites are assumed to have one IR and one RF sensor co-located at each position, see Fig. 2.

The sensor models are designed so that if the signal received exceeds a certain value, a detection threshold, detection is assumed to have occurred. The threshold values were derived from open information.

4.2.1. RF models

Radar signature, or Radar Cross Section, σ is a measure of how much RF energy is returned by an object when illuminated by a plane wave. The monostatic (transmitter and receiver co-located) RCS is defined as:

$$\sigma(\theta, \phi, f) = \lim_{r \to \infty} 4\pi r^2 \frac{|E_s|^2}{|E_i|^2}, \tag{3}$$

where θ and ϕ are spherical angles in the local coordinate system of the aircraft, f is the frequency, E_s is the scattered electrical field and E_i is the impinging electrical field. RCS can also be a function of the polarization of the impinging and the scattered field, but this is not considered here. The propagation in the atmosphere is considered to occur without any attenuation, since the frequencies are below 20 GHz and there is no precipitation in the scenario. Although RCS is quantified in terms of an equivalent area, there is normally no correlation between, say, the projected area and RCS for complex shapes. The model of the aircraft and the cruise missile is very basic. They are modeled as angle-independent RCS values representing aircraft ranging from signature-conscious to stealth design levels.

The model of the sensor is based entirely on a basic version of the radar equation:

$$P_{rx} = \frac{P_{tx} \sigma \lambda^2 G^2}{(4\pi)^3 R^4}, \tag{4}$$

where P_{rx} is the power received by the radar, P_{tx} the transmitted power, σ the radar cross section of the aircraft, λ the wavelength, G the gain of the radar antenna and R is the distance between the radar and the aircraft.

The threshold value is obtained by using information about the value of R at which a certain RCS σ is detected. Using this information, which is provided in Table 3 the remaining factors in (4) can be treated as constants. It can be used, as in this paper, to determine whether the signal received by the radar, due to a combination of RCS at a certain distance, is large enough to assume detection. The environment is assumed to be clutter-free and the radar monostatic, see [15].

4.2.2. IR models

The InfraRed Signature contrast Level, $IRSL$, was modeled in the 8–12 µm wavelength band as the apparent contrast irradiance [16] at the sensor,

$$IRSL_{8\text{–}12\,\mu\text{m}}\ [\text{W/m}^2] = \tau_{tgt-de}\left(L_{tgt} - L_{bgnd}\right)\frac{A_{proj}}{R^2}. \tag{5}$$

Here τ_{tgt-de} is the average atmospheric path transmittance between target and detector for the wavelength band of interest, L_{tgt} [W/m^2/sr] denotes the radiance from the target, L_{bgnd} [W/m^2/sr] denotes the absolute radiance from the background at the target, and A_{proj}/R^2 represents the solid angle corresponding to the target seen from the sensor. A_{proj} is the projected area of the target and R is the range between the target and the sensor. See Fig. 4. The model assumes an unresolved target and

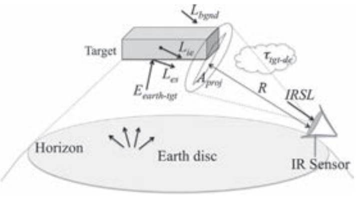

Fig. 4. The IR Signature contrast Level (IRSL) model. It comprises radiation from internal sources in the target, radiation due to reflected earthshine, and radiation from the ambient atmosphere. The target is modeled as a "shoebox".

by treating the background as a source at target range, path radiance can be eliminated. The aerial platform target was modeled as a "shoe box" with varying top, side and front areas.

The transmittance was calculated for points along the scenario flight paths using the Modtran software package and assuming a sub-arctic summer climate. Values for arbitrary target-sensor configurations were obtained from interpolating between data points.

The radiance from the target, L_{tgt}, was modeled comprising two components: the radiance from the target due to internal sources, $L_{ie}(T_s, \varepsilon_s)$, and radiance due to reflections from external sources, L_{re} (ε_s). The former is a function of the aircraft surface temperature T_s [K] and both are functions of the surface emissivity ε_s.

Target radiation from internal sources, L_{ie}, usually comprises radiation from the engine exhaust plumes, the engine hot parts and aerodynamic heating of the airframe. Here, however, the IR model was used to analyze the signature level in the front sector of the aircraft, so the contribution from the engine hot parts could be neglected. Furthermore, the contribution from the aircraft plume is limited to relatively narrow bands in MWIR, outside the sensitivity range of the 8–12 μm detector in the model. Consequently, the dominant component of internal emission was considered to be aerodynamic heating. It was calculated using Planck's law, where T_s is skin temperature, assuming perfectly diffuse grey body appearance with emissivity of ε_s [16]. The skin temperature, was in turn modeled as a function of aircraft velocity,

$$T_s\,[\mathrm{K}] = T_0\left(1 + 0.164M^2\right), \tag{6}$$

where T_0 is the temperature at altitude and M is the target velocity (Mach number) [17].

Target radiation from external sources, L_{re}, generally incorporates reflections from the sun, the sky or the earth [16,12]. In LWIR the contribution from reflected emission is, however, dominated by terrestrial illumination, so called earthshine [12]. And since the missions were assumed to be carried out at night, the sunshine and skyshine contributions were neglected. The earthshine contribution, L_{es}, was in turn calculated using the approach described in detail by Mahulikar et al. [12]. It can be written as

$$L_{re}\,[\mathrm{W/m^2/sr}] \approx L_{es} = (1 - \varepsilon_s)E_{earth-tgt}/\pi\,, \tag{7}$$

where $E_{earth-tgt}$ is the irradiance at the target originating from the earth disc seen by the target, see Fig. 4. Since the front and sides of the airframe only see half of the earth disc, the reflected radiance from these surfaces was calculated to only half of that reflected from the bottom of the aircraft.

The absolute background radiance at the target, L_{bgnd}, in (5) was calculated using the Modtran package.

Finally, solving (5) for the IR detection range yields

$$R_{det} = \sqrt{\tau_p\left((L_{ie}(T_s, \varepsilon_s) + L_{re}) - L_{bgnd}\right)\frac{A_{proj}}{IRSL_{det}}}\,, \tag{8}$$

where R_{det} should be understood as the range from the sensor within which the probability of detection is 1.0. The IRSL threshold for detection, $IRSL_{det}$ (see Table 3), was estimated assuming: an approaching aircraft of F-16 size, in excellent detection conditions, and, in line with tabulated data [10], by solving equation (8) for detection at 30 km.

Table 3
The parameters used for modeling the performance of SAM units.

Parameters	SAM
Radar acquisition threshold [m^2]	1 @ 37 km, ≈18 GHz
IRSL detection threshold, [W/m^2]	$2 \cdot 10^{-7}$
Maximum missile range	20 km
Ceiling	15 km
Mean missile velocity	1000 m/s
σ_{at}	0.25 mrad
σ_{gu}	5 m ($v_{rel} = 2$)
$P_{H\|I}$ (proximity)	1.0 (<6 m)/ 0.65 (<9 m)
$P_{K\|H}$	0.8
Doctrine	detect, track 20 s, one shot

4.3. Weapon models

Susceptibility studies do not focus on models of weapons; hence, they are kept at a basic level here. However, since the ambition is to support evaluation of the military utility of signature reduction features at mission system level, we do need to include possible responses from variables in the signature models. From Table 2 we find that these are the size, speed and altitude of the aircraft. Emissivity is presumed not to influence the effectiveness of the weapons; it only reduces the IR signature of the aircraft.

4.3.1. Surface to air missile

The SAM model is based on the lead angle trajectory principle, i.e. the missile has a direct path on a constant bearing to the target trajectory from launch to intercept. Both the missile and the target are assumed to have constant velocities. The miss distance is the shortest distance between the missile and the aircraft. It can be expressed as the total miss distance standard deviation, σ_{miss}, and is a function of the SAM system tracking error, and of the missile control and guidance error [1]. If circular symmetric errors are assumed, and the range tracking error is neglected, the expression can be written as

$$\sigma_{miss} = \sqrt{(R^2\sigma_{at}^2) + \sigma_{gu}^2}\,, \tag{9}$$

where R is the slant range to the target, σ_{at} is the circular standard deviation of the angular tracking error in radians (see Table 3), and σ_{gu} is the circular standard deviation of the missile control & guidance error in meters [1]. Because the velocity of the missile relative to the target is of importance for the end game, and because we need to consider the target velocity in our model, as stated earlier, we have chosen to approximate σ_{gu} using:

$$\sigma_{gu} = 2\sigma_{gu(v_{rel}=2)}/v_{rel}\,. \tag{10}$$

Here, the ratio of the missile velocity to the target velocity is denoted by v_{rel}. Using this crude first order approximation, the tracking errors and the control & guidance errors are comparable at maximum range and $v_{rel} = 2$. Furthermore, σ_{gu} and σ_{miss} decrease as the missile to target velocity ratio increases, as would be expected. Using a cookie cutter approximation [18] the probability of intercept on engagement, $P_{I|E}$, is equal to the probability of the miss distance being less than a radius of intercept, R_{icpt}. This can then be expressed as:

$$P_{I|E} = 1 - \exp(-R_{icpt}^2/2\sigma_{miss}^2)\,. \tag{11}$$

The radius of intercept, R_{icpt}, is in turn modeled as the sum of the target radius, approximated to a sphere, and the maximum

Table 4
The parameters used for modeling the performance of attack weapons.

Parameters	Cruise missile	Guided bombs
σ_{be} (CEP)	8.5 (10) m	11.0 (13) m
R_{kill}	20 m	15 m
Maximum drop range (Ceiling)	60+ (−)	27.8 (13.7) km
Minimum drop range	–	9.3 km

proximity fuse (see Table 3). Consequently, the size of the target has influence, as mentioned earlier. Finally, the probability of the aircraft being killed by the SAM, if engaged, is obtained from our version of the kill chain:

$$P_{K|E} = P_{I|E} P_{H|I} P_{K|H}\,, \tag{12}$$

where the probability of the target being hit, if intercepted, $P_{H|I}$, and the probability of the target being killed, if hit, $P_{K|H}$, are estimated using values from Table 3. If the maximum range or ceiling is exceeded $P_{K|E}$ is zero.

4.3.2. *Cruise missiles and guided bombs*

The target is assumed to be a point target. In addition, the attack weapons are assumed to have circular normally distributed ballistic errors with a mean point of impact at the center of the target. Using a cookie cutter approximation, the probability of a kill with a single shot, P_{ss}, can be expressed as:

$$P_{ss} = 1 - \exp(-R_{kill}^2/(2\sigma_{be}^2))\,. \tag{13}$$

The assumed kill radius, R_{kill} and the standard deviation in miss distance due to ballistic error, σ_{be}, are given in meters. The ballistic error for a weapon is often tabulated as the Circular Error Probable (CEP) and σ_{be} is then obtained through the relation $\sigma_{be} = 1.1774/CEP$. The parameters used in the given scenario are listed in Table 4.

The model is straightforward and Jaiswal's textbook on military operational research can be consulted for details [18].

5. Results and analysis

The data obtained from the simulations using the models and the scenario is presented as graphs, showing detection curves and weapons effectiveness. Condensed results for the mission system level are presented in tabular form. The RCS, the size and the emissivity of the aircraft and the cruise missile are varied according to the values given in Table 2. The SAM site and the weapon variables can be found in Tables 3 and 4 respectively.

These two forms of presentation offer different viewpoints and ways of understanding the results. In the graphs, the detection curves represent signature, wave propagation and sensors as one entity. The curves allow instant comparison of several different signature reduction technologies and their impact on detection ranges, given different sensor functions and performance, for one aircraft in a specific strike option. The table offers a synopsis of what this performance of a single aircraft means, if putting several aircraft together in a sufficiently large strike package for a successful mission. The results indicate whether the task can be accomplished by technical improvements, or if the tactics need to be adapted.

5.1. *Analyzing strike options*

The distance indicated on the x-axis in the graphs is the shortest distance between the ground track of the aircraft and the point target, which is at zero. The SAM units are not at the same location as the point target, which explains why the lethality curve ($P_{K|E}$) of the SAM forms an arc, where the peak roughly coincides with the position of the SAM site. For each strike option, the SAM site closest to the aircraft is assumed to engage. Where applicable the bomb drop, either single or multiple, is marked with diamonds.

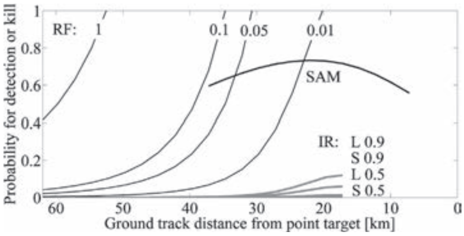

Fig. 5. Detection curves and weapons threat for P1, cruise missile option.

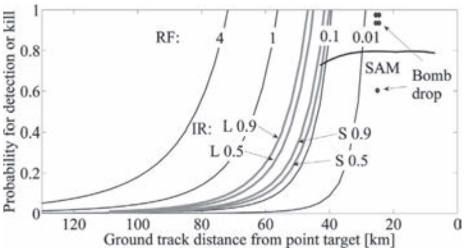

Fig. 6. Detection curves, weapons threat and bomb drop for P2, medium altitude option.

The detection curves are obtained by normalizing the received signal level to the presumed detection threshold of the sensor, hence, below 1.0 the aircraft is not yet detected, see section 4 for details. The variables used are indicated near each curve, where black lines are associated with RF and the numbers represent RCS levels in equivalent square meters. Similarly, IR curves are grey and "S 0.5" means the small aircraft with a surface emissivity of 0.5.

5.1.1. *Balancing signatures for the cruise missile option*

Fig. 5 shows that the LWIR sensor is unable to detect the cruise missile, regardless of size or emissivity, because none of the detection curves reach the threshold. In contrast, the radar detects all missiles, regardless of RCS, but at different distances. If the target is detected and tracked for more than twenty seconds (in accordance with the shooting doctrine), and it is within SAM range, $P_{E|D}$ is considered to be one and hence P_{kill} is equal to $P_{K|E}$, see (2) and (12). Consequently, it can be seen from the graph that, in our setting, the probability of a missile being killed is at least 0.6.

Our calculations show that one cruise missile is enough to accomplish the mission, $P_{N|S} > 0.9$, because it is not detected. However, meeting the mission objectives with the desired certainty, using the best missile modeled here, requires six missiles – solution for A in equation (1). Hence, there is clear potential in adapting the RF signature to increase the military utility of the cruise missile option. Fig. 5 indicates that a radar signature of 0.01 m^2 is sufficient.

5.1.2. *Balancing signatures for the medium altitude strike option*

Fig. 6 shows the results for an aircraft in a medium altitude strike option.

The diagram indicates that the baseline aircraft is detected by the LWIR sensor at about the same time as it comes within SAM range, about 15 km before the planned drop point. Given the aircraft speed of 300 m/s, there would then be a 50 second window of opportunity for the SAM unit to engage. The large aircraft seems

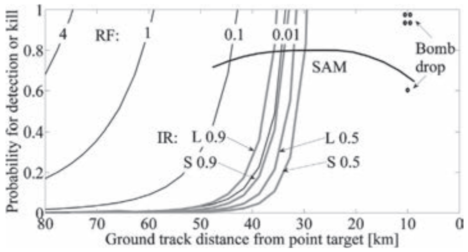

Fig. 7. Detection curves, weapons threat and bomb drop for P3, low altitude option.

to be detected already about 25 km before drop point. The emissivity has negligible impact. Thus, P_{kill} is about 0.8 for all sets of IR variables investigated. However, if the SAM unit relies only on radar detection, an RCS in the 0.01 m^2 range seems to deny engagement opportunities prior to bomb drop.

Thus, the results seem to suggest that if operations usually occur in clear weather conditions, i.e. when LWIR sensors are effective, there is little to gain from designing an RCS lower than 0.1 m^2. In addition, some other technical or tactical means would probably have to be adopted for this option to reach acceptable risk levels. If, on the other hand, the climate frequently offers weather with low visibility, e.g. due to rain or cloud cover, an RCS in the 0.01 m^2 range seem to be well justified.

5.1.3. Balancing signatures for the low altitude strike option

Fig. 7 shows the results for an aircraft in a low altitude strike option.

It can be seen that the aircraft are detected by the LWIR sensor as far as 20 to 30 km from the planned point of drop, which is comparable to a relatively low RCS, i.e. in the 0.01 m^2 range. If an aircraft is traveling at 300 m/s, this gives a 70 to 100 second window of opportunity for the closest SAM to engage. Furthermore, a comparison of the low and medium altitude options illustrates that the IR signature is significantly dependent on the angle of elevation in relation to the sensor.

For example, at medium altitude, the LWIR sensor detects all aircraft before the radar detects the one with 0.1 m^2 RCS. In the low altitude strike mission, on the other hand, the IR signatures are comparable to an RCS of 0.01 m^2. It can also be seen that reducing the size of the aircraft by half, i.e. corresponding to exchanging a large attack aircraft for the baseline aircraft, results in only about 10 s less time for the SAM site to enhance tracking quality and for decision-making. Reducing emissivity, though, has a significant impact. In this setting the time for SAM engagement is reduced by about 30 s.

Still, the window of opportunity seems to be large enough from an air defence point of view. However, it should be noted that SAM site 2 is directly under the flight path and that our models show that the probability of detection by sensors further away is much lower.

For the low altitude strike option in the scenario depicted the results thus indicate that great efforts are needed if stealth design is to be the primary survivability measure. Some tactical modifications, as in the former option should be considered. A toss bomb maneuver at the anticipated time of detection may be feasible to increase the drop range; although this would increase the risk of collateral damage and decrease the probability of neutralizing the target. The results also seem to encourage careful reconnaissance and navigational planning to avoid flying in close vicinity of SAMs. However, the latter suggestion is increasingly difficult because modern SAM units are highly mobile.

Table 5
The results at mission system level if expressed in the chosen measures of effectiveness.

Option	SAM	P_{kill}	$P_{N\|S}$	A	P_{MA}	Losses
1	4	0.74	0.94	6	0.78	4.4
2	1	0.79	0.97	7	0.79	5.5
3	2	0.80	0.97	7	0.77	5.6

5.2. Synthesis at mission level

The synthesized results for a version of each strike option are presented in Table 5. The options and measures presented were described in Section 3 and the missile and aircraft modeled were assigned baseline values. For simplicity we chose to use tracking information from the closest SAM site in each case, i.e. from the same SAM site that engages the aircraft/missiles. From an aircraft design perspective it would be advisable instead to use the least favorable result when determining the need for signature adaptation.

As shown in Table 5 the cruise missile strike option (row one) needs to be composed of at least six missiles (column A) in order to meet the mission criteria of neutralizing the target with the required certainty of at least 75% certainty (column P_{MA}). In the scenario modeled 4.4 missiles (column Losses) are expected to be shot down before reaching their targets. Note that no aircraft or crew is in danger using this option because the missiles are launched well out of SAM range. In the two remaining options the strike packages are instead composed of seven aircraft with guided bombs in order to meet the criteria for mission accomplished. As can be seen, in these cases the losses are expected to be high. Unless the mission is of key importance to an operation of national security, one would expect that these losses are in fact unacceptable. However, since the aim in this paper is to study the impact of signatures on the mission level MoEs, the focus is not on the absolute values. One could, for instance, complement the models with electronic warfare or suppression of enemy air defense, thereby influencing the probability of the SAM sites being active in the first place; alternatively, one could equip the aircraft with countermeasures reducing the probability of the aircraft being hit etc. However, unless modeling to choose between these features, they would only make interpretation of the results more difficult.

6. Discussion

Survivability engineering deals with the issue of balancing features introduced to enhance survivability, while possibly penalizing other design goals. The aim of this paper is to establish a quantitative mission system model to support the evaluation of different signature reduction features on flying platforms, and to implement this model to show how it can be used to support the balancing of RF and LWIR signature properties. The overall results suggest that the proposed system model is feasible for combat aircraft analysis at the concept phase, i.e. to support requirements analysis, concept validation or design space exploration. They show how technical variables, such as RCS or surface emissivity, or tactical parameters, such as speed, altitude or SAM positions, affect measures of effectiveness, such as probability of success and losses.

However, there are a few notes to be made on the limitations of the implementation of the model in the setting reported here. Firstly, the technical and tactical input parameters are discrete and the data set is very limited. One example is that either the aircraft, or missile, pass directly above a SAM site or right in between two sites. This has great impact on estimated losses. For the purpose of this paper, doing a comparative analysis, this implementation is sufficient. Arguably, a real decision situation would instead require a systematic study of input variations. When using the model we suggest exchanging the discrete input variables used in our demonstration with stochastic variables and then to execute a Monte Carlo simulation.

Secondly, the models used here are kept at a basic level. The intention in this paper is, after all, not to produce accurate numerical results, but to be able to identify possible pivot points in the balancing of RF and IR signature levels. The reader is encouraged to replace the models with those more suitable for their particular task.

Nevertheless, the applied proof of concept does indicate that, for a combat aircraft dueling with integrated ground-based air defense systems, it is important to balance the requirements of LWIR and radar signatures. The results show that there are situations in which expensive efforts to reduce the radar signature, below the corresponding LWIR signature level, could very well be in vain, because the aircraft might be detected and tracked by co-located LWIR sensors.

We also found that the earthshine component seems to have a significant influence on the LWIR signature in the strike options studied. This has been suggested in earlier research (e.g. [12]), but, as far as we know, has not been clarified in a mission context until now. This is of interest because the IR signature is then composed of two important components; One component with behavior proportional to emissivity (the radiation from internal sources), and one component with behavior proportional to one minus the emissivity (the earthshine). Consequently, there is also a balancing issue at a lower level, and this will be investigated in a second study.

In this setting the basic modeling of the IR signature, as a function of the projected area of a shoebox, and the RF signature, as fixed values, are deemed sufficient. For potential future studies of the side or aft aspects of the aircraft, where hot engine parts may become the dominant IR source, the model needs further work and possibly the inclusion of a medium wavelength infrared sensor model.

It is also important to point out that, when discussing multispectral signature adaptation, it is important to consider how measures intended for one part of the spectrum may affect the signature for other wavelengths. In the technical models used for this study, no explicit links between RF or IR signatures were implemented. Hence, implicitly we made the assumption that the problem of producing non electrically conducting low emissivity coatings [19], thus radar transmitting, has been solved.

It is also worth taking particular note of the importance of evaluating technical signature reduction efforts at a mission system level. It has been shown how changes in technical or tactical variables might very well decrease the detection range; however, if the reduction is not large enough, there is little or no change in the outcome measures of effectiveness at mission level. The military end result is thus unchanged, except perhaps when measured in development costs.

Therefore, by using the model at a suitable level of detail, it should be possible to find pivotal performance requirements of signatures, i.e. precisely those efforts sufficient for a significant increase in military utility.

7. Conclusion

In this work we have presented a quantitative model for use in the evaluation of signature reduction measures aimed at increasing the military utility of a combat aircraft. In addition, it has been shown how the model can be applied, during concept definition, to the problem of balancing radar and long wavelength infrared signature properties, within a relevant mission context. The results suggest that the methodology supports quantitative evaluation of aircraft concepts and, consequently, that it is, in all likelihood, a contribution to the area of DSE.

8. Future work

The methodology presented in this paper is focused on the balancing of signature properties in an aircraft concept development phase and the implementation is therefore somewhat limited seen in an MDO context. It remains to be shown how the proposed model can be integrated in a system simulation environment in order to include effects of signature reduction efforts on features like shape, mass and volume, in turn affecting important aircraft characteristics like flight performance, fuel consumption or endurance.

Radar signature, and the reflected part of the IR and optical signatures, depend on the illumination and observation angles of the object and the scattering properties as a function of frequency or wavelength. It would be interesting to improve the models used in this paper to support signature analysis with higher angular and spectral resolution as well as bandwidth. The signature models need to match the sensor models in order to achieve results with satisfactory fidelity, but be simple enough not to cause prohibitively long simulation times.

Conflict of interest statement

No conflict of interest.

Acknowledgements

The authors deeply appreciate the efforts of LtCol M. Bengtsson, LtCol A. Nygren, LtCol L-J Nordlund and LtCol M. Reberg at the Swedish Defence University when sharing their valuable experience in the definition of a relevant mission scenario. We are also grateful to Prof. S. Mahulikar and Dr. T. Hallberg for their valuable input and to S. Henly for proofreading the manuscript. This research was financially supported by Saab Aeronautics, the Swedish Defence University and by the Swedish Armed Forces.

After submission the proposed model and methodology have been used in a more detailed study of the earthshine influence on the LWIR-signature of an aircraft. These results have been published elsewhere [20].

References

[1] R.E. Ball, The Fundamentals of Aircraft Combat Survivability Analysis and Design, 2nd edition, AIAA, 2003.

[2] K. Andersson, M. Bang, C. Marcus, B. Persson, P. Sturesson, E. Jensen, G. Hult, Military utility: a proposed concept to support decision-making, Technol. Soc. 43 (2015) 23–32, http://dx.doi.org/10.1016/j.techsoc.2015.07.001.

[3] C.I. Grant, M.R. Braun, Rapid design space exploration for conceptual design of hypersonic missions, in: AIAA Atmospheric Flight Mechanics Conference and Exhibit, C3S2E '12, AIAA, 2011.

[4] T. Saxena, G. Karsai, Towards a generic design space exploration framework, in: 2010 IEEE 10th International Conference on Computer and Information Technology (CIT), 2010, pp. 1940–1947.

[5] J.R.R.A. Martins, A.B. Lambe, Multidisciplinary design optimization: a survey of architectures, AIAA J. 51 (9) (2013) 2049–2075, cited by :222, www.scopus.com.

[6] M.I. Skolnik, An analysis of bistatic radar, IRE Trans. Aerosp. Navig. Electron. ANE-8 (1) (1961) 19–27, http://dx.doi.org/10.1109/TANE3.1961.4201772.

[7] H. Griffiths, Developments in bistatic and networked radar, in: 2011 IEEE CIE International Conference on Radar (Radar), vol 1, 2011, pp. 10–13.

[8] S. Choi, D. Crouse, P. Willett, S. Zhou, Multistatic target tracking for passive radar in a dab/dvb network: initiation, IEEE Trans. Aerosp. Electron. Syst. 51 (3) (2015) 2460–2469, http://dx.doi.org/10.1109/TAES.2015.130270.

[9] E.K.-w. Huang, A. Haddadi, G. Chen, A.-M. Hoang, M. Razeghi, Active and passive infrared imager based on short-wave and mid-wave type-ii superlattice dual-band detectors, Opt. Lett. 38 (1) (2013) 22–24, http://dx.doi.org/10.1364/OL.38.000022, http://ol.osa.org/abstract.cfm?URI=ol-38-1-22.

[10] C. Kopp, KBP 2K22/2K22M/M1 Tunguska SA-19 Grison/96K6 Pantsir S1/SA-22 Greyhound SPAAGM, Tech. rep. Air Power Australia, 2009, http://www.ausairpower.net/APA-96K6-Pantsir-2K22-Tunguska.html.

[11] L. Jianwei, W. Qiang, Aircraft-skin infrared radiation characteristics modeling and analysis, Chin. J. Aeronaut. 22 (5) (2009) 493–497, http://dx.doi.org/10.1016/S1000-9361(08)60131-4.

[12] S.P. Mahulikar, S.K. Potnuru, G. Arvind Rao, Study of sunshine, skyshine, and earthshine for aircraft infrared detection, J. Opt. A, Pure Appl. Opt. 11 (4) (2009) 045703, http://dx.doi.org/10.1088/1464-4258/11/4/045703, http://stacks.iop.org/1464-4258/11/i=4/a=045703?key=crossref.2fd77bd37121f8a3560b2f927c99c45f.

[13] D. Soban, D. Mavris, Formulation of a methodology for the probabilistic assessment of system effectiveness, in: AIAA Strategic and Tactical Missile Systems Conference, AIAA, Monterey, CA, 2000, pp. 1–12.

[14] P. Gerdle, Lärobok i telekrigföring för luftvärnet – Radar och radartaktik, Försvarsmakten (2004).

[15] M. Knott, E.F. Tuley, J. Shaeffer, Radar Cross Section, SciTech Publishing, 2004.

[16] J.R. White, Aircraft Infrared Principles, Signatures, Threats, and Countermeasures (September), NAWCWD TP 8773, September 2012, Naval Air Warfare Center Weapons Division, Point Mugu, CA 93042, url: http://www.dtic.mil/get-tr-doc/pdf?AD=ADA566304.

[17] J.D. Mcglynn, S.P. Auerbach, IR signature prediction errors for skin-heated aerial targets, in: SPIE, vol. 3062, 1997, pp. 22–30.

[18] N.K. Jaiswal, Military Operations Research: Quantitative Decision Making, Kluwer Academic Publishers, 1997.

[19] K.E. Andersson, C. Åkerlind, A review of materials for spectral design coatings in signature management applications, in: D. Burgess, G. Owen, H. Rana, R. Zamboni, F. Kajzar, A.A. Szep (Eds.), SPIE Security + Defence, International Society for Optics and Photonics, 2014, p. 92530Y, http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1922108.

[20] K. Andersson, Modeling the impact of surface emissivity on the military utility of attack aircraft, Aerosp. Sci. Technol. 65 (2017) 133–140, http://dx.doi.org/10.1016/j.ast.2017.02.017, http://www.sciencedirect.com/science/article/pii/S1270963817303206.

PAPER VI

Kent Andersson,
Modeling the impact of surface emissivity on the military utility of
attack aircraft, Aerospace Science and Technology,
Volume 65, June 2017, p 133–140
https://doi.org/10.1016/j.ast.2017.02.017

Aerospace Science and Technology 65 (2017) 133–140

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Modeling the impact of surface emissivity on the military utility of attack aircraft

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 2 February 2017
Accepted 20 February 2017
Available online 28 February 2017

Keywords:
Military utility
Spectral design
Emissivity
Earthshine
Combat aircraft

ABSTRACT

An analysis scheme and a mission system model were applied to the evaluation of the military utility of efforts to reduce infrared signature in the conceptual design of survivable aircraft. The purpose is twofold: Firstly, to contribute to the development of a methodological framework for assessing the military utility of spectral design, and secondly to assess the threat from advances in LWIR sensors and their use in surface-to-air-missile systems. The modeling was specifically applied to the problem of linking the emissivity of aircraft coatings to mission accomplishment. The overall results indicate that the analysis scheme and mission system model applied are feasible for assessing the military utility of spectral design and for supporting decision-making in the concept phase. The analysis of different strike options suggests that LWIR sensors will enhance the military utility of low emissive paint, at least for missions executed in clear weather conditions. Furthermore, results corroborate and further clarify the importance of including earthshine when modeling.

1. Introduction

It is well known that any combat aircraft is a complex compromise of attributes, and that features introduced to enhance one of them risk having penalties for others. Design is always a trade-off between offensive capability, survivability and availability [1]. Recently it was suggested [2] that effective solutions to these kinds of problems, while acknowledging that a technical system is but one of the components of a capability (e.g. [3,4]), benefit from formulating the problem to maximize the military utility of the technical system in focus. The military utility [2] of a technical system is a compound measure of: the military effectiveness in a specified context, the assessed technical systems' suitability to the military capability system, and affordability to the military actor operating it. It is anticipated that the concept will support holistic decision-making, but is in need of a framework for performing assessments.

In this study survivability engineering is of particular interest. Its aim is to decrease an aircraft's susceptibility and vulnerability to man-made threats, while having minimum impact on other attributes [1]. Considerable sums of money are spent on low observability technology in contemporary combat aircraft development programs, like the F/A 35, in order to reduce signature and hence susceptibility. Here the signature of a combat aircraft is any characteristic that makes it detectable with a sensor. A reduced signature leads to shorter detection range from an adversary's weapon systems, and consequently shorter response times, giving increased survivability and freedom of action. Due to developments in bi-static and passive radar, and the fact that low-frequency radar systems are becoming operational [5–7], investments in stealth radar are being questioned. In addition, the cost and size of infrared (IR) sensors have decreased, while their performance has increased, and current developments point towards higher spatial and spectral resolution [8].

Research has shown that, for the front sector of an approaching aircraft, emission from aerodynamic heating and reflected earthshine are the dominant IR sources [9,10]. Since the intensity peaks of both sources are in the long wavelength IR (LWIR) atmospheric transmission window (8–14 μm), LWIR imaging sensors are of particular interest. Early versions of LWIR sensors are already operational [11]. This calls for further analysis of the implications for the duel between attacking aircraft and defending surface-to-air missile systems (SAMs); what can be done to increase aircraft survivability? Since emissivity is the most important surface property affecting the magnitude of IR radiation [12], it is important, from a signature adaption perspective, to study whether an optimum can be found.

In a first paper from this study [13] a model and method for quantitatively assessing signature reduction efforts on aerial plat-

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http://dx.doi.org/10.1016/j.ast.2017.02.017
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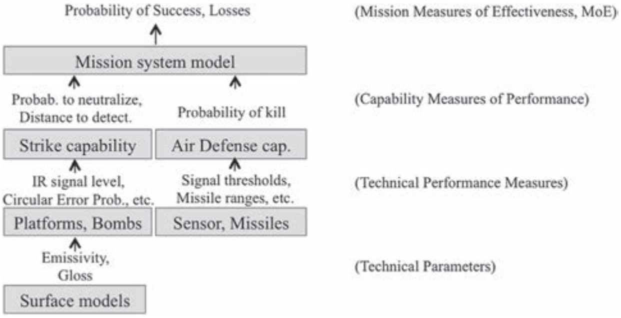

Fig. 1. An illustration of the models necessary at each system level to support analysis, and the variables of interest needed to link them.

forms were developed. It was shown that the LWIR sensors integrated with SAMs are indeed an increasing threat to aircraft and that efforts to reduce signature in radar and LWIR need to be balanced. The aim of this paper is to use a tailored version of the same model for assessing the military utility of features to reduce LWIR signature in more detail. The focus is on efforts to adapt surface emissivity. The purpose is twofold: Firstly, to continue contributing to the establishment of a methodological framework for assessing military utility, and secondly, to contribute to the survivability of combat aircraft.

In the first section the methodological approach using modeling is outlined. The starting point is survivability and the concept of military utility. Then the mission system level model and its technical sub-models are described, followed by analysis and discussion of the results. Finally, conclusions are drawn and presented.

2. The methodological approach

2.1. The military utility concept

The interdependent nature of the attributes of combat aircraft calls for a system approach to design. Researchers in the field of combat aircraft survivability have shown that trade-off studies on the effectiveness of aircraft design should be at the mission system level or higher, to avoid the risk of sub-optimization [1,14]. This approach is compatible with the concept of Military Utility mentioned previously. It is defined [2] as having three dimensions:

- The Military Effectiveness dimension is a measure of the overall ability to accomplish a mission when the Element of Interest (EoI) is used by representative personnel in the environment planned or expected for operational employment of the military force.
- The Military Suitability dimension is the degree to which an EoI can be satisfactorily taken into military use in a specified context, taking into consideration interaction with other elements of the capability system.
- The Affordability dimension is a measure of compliance with the maximum resources a military actor has allocated to the EoI in a timeframe defined by the context.

A military capability is hence viewed as a system composed of various interacting elements, such as doctrine, organization, training, personnel, materiel, facilities, leadership and interoperability, as in NATO publications. In this paper a combat aircraft is the element of interest in a potential military capability for air to surface operations. The bottom line is that a component, in this case a combat aircraft, only has military utility if it is seen as a contributory element in a capability system [4,2].

In the first paper from this study [13] an analysis scheme and a model, adopting the view on capabilities described, were developed for assessing the military utility of a low observable aircraft in attack missions. The model allows for low observable properties to be obtained through varying different parameters, tactical or technical, and observing responses in mission outcomes. The first phase of the study concerned the balancing of efforts to reduce radar and LWIR signature. In this paper the spectral design activity deciding the LWIR signature is of particular interest. Spectral design is here understood as the engineering activity to vary surface structure and materials to obtain the desired spectral properties [15]. Hence, the methodological approach is to analyze a tailored version of the mission system model developed earlier, but to focus on responses from varying the surface emissivity.

2.2. Modeling the military effectiveness dimension, including a surface

There are rapid developments in materials for spectral design coatings and it seems safe to assume that there will be suitable paints available for surface coatings once the preferred IR emissive properties are known [16,15]. This simplifies the exploratory part of the study since it will not be necessary to model the military suitability or the affordability dimensions of the military utility concept in detail. It can be assumed that exchanging the quality of paint will not require changes in maintenance concepts, maintenance facilities, training facilities etc., which is why the military suitability dimension will not be directly affected. Furthermore, for our purposes, the increased life cycle cost for more advanced paint is presumably negligible and will not affect affordability for the aircraft operator. Consequently, any differences between different aircraft concepts in terms of their military suitability or affordability will only be identified as a direct result of potential differences in their military effectiveness. Thus, the problem is reduced to modeling the military effectiveness dimension in sufficient detail; i.e. a more survivable aircraft will, for example, allow doctrinal development, or reductions in the life cycle cost for the aircraft system as a whole.

In order to be able to analyze the military effectiveness of spectral design at mission level, a functional system model has to link surface models to mission measures of effectiveness, MoEs. See Fig. 1.

In the system model developed, see [13] for details, it is sufficient to gauge military effectiveness through probability of success and own losses at the mission system level. At the capability system level the model requires assembly of strike packages and selection of a mission profile. Correspondingly, on the defending side, SAM systems, surveillance and firing doctrines have to be chosen in order to define the air defense capability. The capability measures of performance defined link the capability models to the

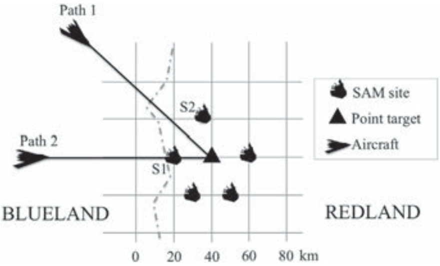

Fig. 2. The scenario, with planned flight paths and SAM sites.

MoEs. At the technical system level the aircraft, weapons and sensors are modeled with response functions based on their respective technical performance. At the lowest system level the aircraft surface is modeled. In this paper the surface performance is linked to the aircraft signature via its emissivity.

3. The mission system model – framing the problem

3.1. The mission

The fictitious BLUELAND mission was defined as the neutralization of a point target defended by short range SAM units in an integrated air defense system, at lowest possible cost, within *X* hours, using air strikes. The positions of the REDLAND SAM units and the two alternative flight paths of the planned mission can be seen in Fig. 2.

For the analysis it is sufficient to include only one of the SAM sites, S1, positioned 20 km west of the defended point target. The flight paths are chosen so that the attacking aircraft passes between two SAM sites, S1 and S2 (Path 1), or directly above S1 (Path 2).

Since the LWIR signature is dependent not only on target properties, but also on the physical environment, some assumptions had to be made. All missions were presumed to be conducted in the Baltic Sea region, at midsummer, at midnight and in clear weather conditions.

3.2. The air defense model – the threat

Each SAM unit on the REDLAND side was presumed to be configured with a short range SAM launcher, a combined reconnaissance and firing radar and a LWIR imaging sensor. The normal doctrine is arguably scan–detect–track using radar, with the IR sensor to support identification. However, since the focus is on IR sensing, the IR sensors in this scenario were used to detect and track while the radar was only used during engagement. Given current developments in IR sensors, this is not an unlikely scenario in the near future, especially in the event of air defense facing stealth aircraft and radar homing missiles. Single SAMs give the bearing to the target. Two or more SAMs in an integrated air defense system (IADS) also produce range by triangulating bearings. Furthermore, a firing doctrine of detect, track for twenty seconds, then fire one missile, was presumed. The delay is chosen to summarize all delays in the command and control system of the SAM system, including classification, identification and the decision to engage. Several targets could be engaged simultaneously.

3.3. The air strike capability model

BLUELAND air strikes were executed using a strike package of a number of aircraft armed with guided bombs (GBU) attacking the point target via Path 1 or 2 in Fig. 2. A medium to high altitude option is typically chosen if either the aircraft is anticipated to fly above the threat ceiling, or if the probability of the threat sensor intercepting the aircraft is presumed to be low, e.g. if the strike package consists of stealth aircraft. Otherwise a low altitude strike option is chosen. The tactical idea behind the latter approach is to reduce the probability of detection by staying low, below the horizon seen by the threat sensor and in the clutter region originating from the terrain below. The low altitude option requires a bomb drop closer to the point target.

Both the speed of the aircraft and the altitude influence the IR signature and the probability of the aircraft being killed by a SAM. For this study, a speed of 300 m/s and altitudes of either 8000 m or 100 m were chosen as tactical input parameters to the technical modeling.

3.4. Synthesis and measures of effectiveness

A probabilistic approach makes it possible to design strike packages for the capability modeled above to precisely accomplish the mission, i.e. to achieve a desired probability of mission success. This makes it possible to evaluate the military effectiveness of different alternatives simply using own losses as the principal MoE.

Given the mission stated above, the following success criterion was chosen for the study: The objective is to neutralize the point target with 75% certainty within *X* hours at the lowest possible cost in terms of lost aircraft and crew.

This success criterion relates well to measures of military effectiveness in the military utility concept described [2]; the desired outcome translates to the point target being neutralized, the cost in losses being minimized, the task being completed within a schedule of *X* hours, and, finally, the force being designed so that the risk of failure is less than 25%.

In probabilistic terms the criteria can be written as follows (see [1] for details)

$$MoE_1 = P_{Success} = (1 - P_{kill}^{A}) P_{N|S} > 0.75, \tag{1}$$

where P_{kill} denotes the probability of one aircraft being killed in an engagement with a SAM unit, A denotes the number of aircraft in the strike package, and $P_{N|S}$ denotes the probability that one aircraft neutralizes the target, given that it survives the engagement. The number of lost aircraft is then given by

$$MoE_2 = Losses = A P_{kill} = A P_D P_{E|D} P_{K|E}, \tag{2}$$

where P_D is the probability of the aircraft being detected, $P_{E|D}$ is the probability of the aircraft being engaged by a SAM unit, given that it is detected, and finally $P_{K|E}$ is the probability of the aircraft being killed, given that it is engaged.

4. Technical models – producing input to the mission level

Technical models were developed for the aircraft, the bombs, the radar, the IR sensor and the surface-to-air missile. However, since this paper focuses on the impact of emissivity on measures of military effectiveness, only the IR modeling is reproduced in detail. For detailed information on previous models see Marcus et al. [13].

4.1. The aircraft and weapon models – in brief

The attack aircraft is modeled as a large “shoe box” moving in level flight along a straight line at constant speed. The size corresponds to a small attack aircraft with a front/side/top area of 6/25/50 m^2. The surface of the platform is approximated by having a perfectly diffuse gray body appearance (no gloss). The emissivity,

Table 1
The parameter set.

Air strike parameters		Air defense parameters	
Altitude	8000/100 m	Missile range	20 km
Speed	300 m/s	Ceiling	15 km
Size	$6 \times 25 \times 50$ m^2	Missile vel.	1000 m/s
Emissivity	0.1–0.9	Ang. track. err.	0.25 mrad (bas.)
Load	4× GBU	Guidance. err.	5 m (baseline)
Drop range	25/10 km	$P_{H\|I}$ (proximity)	1.0(<6 m)/0.6(<9 m)
CEP	13 m	$P_{K\|H}$	0.8
Doctrine	Maneuver After drop	Doctrine	Detect, track 20 s, One shot

ε_s, the independent variable in this study, is varied in the range 0.1–0.9. The higher value is considered the baseline. Note that this approximation of aircraft geometry and surface is assumed sufficient only for evaluation in the development concept phase.

One aircraft is presumed to carry four GBUs with a 13 m circular error probable (CEP), if dropped at a range of 25 km to target, for medium to high altitude strike options, or if dropped at 10 km for low altitude options. With these input parameters the probability of the point target being neutralized, if the aircraft survives to bomb drop, $P_{N|S}$, is estimated to be 0.97.

The surface-to-air-missile model is based on the lead angle trajectory principle, which is why the missile has a direct path with a constant bearing to the target trajectory, from launch to intercept. Both the missile and the target are assumed to have constant velocities during the engagement phase. The probability that the aircraft is killed by the SAM, given engagement, is obtained from our version of the kill chain:

$$P_{K|E} = P_{I|E} P_{H|I} P_{K|H}, \tag{3}$$

where the probability the target is hit, given intercept, $P_{H|I}$, and the probability the target is killed, given a hit, $P_{K|H}$, are estimated from tabulated values. The probability of intercept, given engagement, $P_{I|E}$, is modeled as a function of the SAM system tracking error and the missile control & guidance error [1]. Thus, the altitude, the velocity and the size of the aircraft have an impact on the probability of the aircraft being killed – as one would expect. In this setting the resulting $P_{K|E}$ is in the 0.6–0.8 range, if the aircraft is within range. If the maximum range or the ceiling of the missile is exceeded, $P_{K|E}$ is zero.

A summary of the tactical and technical parameters influencing the modeling results are presented in Table 1. The weapon parameters are based on tabulated data [11,17].

4.2. The sensor model – including atmosphere and IR signature

In this scenario the imaging LWIR sensor is used for detection and tracking, not identification, which is why only the unresolved case, i.e. signal level of one pixel, is developed. The detection range in the model is limited by the curvature of the Earth [18]. Furthermore, attenuation of the IR signal in the atmosphere is significant. Rainy or cloudy weather has a huge limiting effect. IR transmittance to the sensor for points along the scenario flight paths, τ, was calculated using the Modtran® software package, assuming a sub-arctic summer climate. Values for arbitrary target–sensor configurations were obtained from interpolating between data points.

4.2.1. IR signature

The contrast signature level was modeled (see Fig. 3) in the 8–12 μm wavelength band as the apparent effective difference between the irradiance at the sensor from the target aerial platform, E_{tgt}, and that from the sky background, E_{bgnd}. If the sky background is treated as a source at target range, the path radiance can be eliminated [12]. The contrast signature level is then given by:

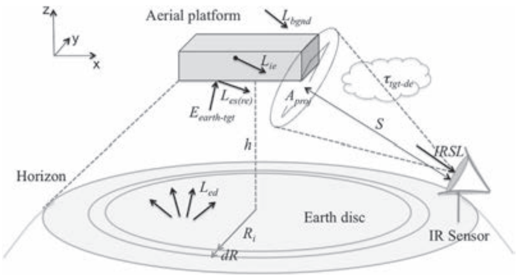

Fig. 3. The IR signature level model (adopted from [13]). It comprises radiance from internal sources in the target, reflected earthshine, and from the ambient atmosphere. The target aerial platform is modeled as a large “shoe box”.

$$IRSL_{8\text{–}12\,\mu\mathrm{m}}[\mathrm{W/m^2}] = E_{tgt} - E_{bgnd} = \tag{4}$$

$$\tau_{tgt\text{-}de}\left(\left(L_{ie}(T_s, \varepsilon_s) + L_{re}(\varepsilon_s)\right) - L_{bgnd}\right)\frac{A_{proj}}{S^2} \tag{5}$$

where $\tau_{tgt\text{-}de}$ is the average atmospheric path transmittance between the target and the detector for the wavelength band of interest; L_{ie} denotes the radiance from the target due to internal sources and L_{re} denotes the radiance due to reflections from external sources. The former is a function of the aircraft surface temperature T_s and both are functions of the surface emissivity ε_s. L_{bgnd} is the absolute radiance from the sky background and finally, A_{proj}/S^2 is the solid angle corresponding to the target seen from the sensor. Here A_{proj} is the projected area of the target and S is the slant range between the target and the sensor. In this study the IR sensor model was used to analyze the IRSL in the front sector of the aircraft; therefore, contributions to L_{ie} from the rear fuselage of the aircraft, heated by the engine, could be neglected. Furthermore, the contribution from the aircraft plume is limited to relatively narrow bands in the 4 μm range and, therefore, outside the sensitivity range of the 8–12 μm detector modeled. The contribution from aerodynamic heating was calculated using Planck's law with skin temperature T_s and with emissivity ε_s [12]. The skin temperature was, in turn, modeled as a function of aircraft velocity,

$$T_s[K] = T_0\left(1 + 0.164M^2\right), \tag{6}$$

where T_0 is the temperature at the aircraft's altitude and M is the target velocity in Mach numbers [19]. In LWIR the contribution from reflected emission, L_{re}, is dominated by earthshine [10], and since the missions were assumed to be executed at night, the contributions of sunshine and skyshine were neglected. The earthshine contribution, L_{es}, was in turn calculated using the approach described in detail by Mahulikar et al. [10]. It can be written

$$L_{es}[\mathrm{W/m^2/sr}] = \frac{(1-\varepsilon_s)}{\pi}E_{earth\text{-}tgt} = (1-\varepsilon_s)\sum_{i=1}^{N}\frac{\tau_i L_{ed} h^2 2R_i dR}{(R_i^2 + h^2)^2} \tag{7}$$

where $E_{earth\text{-}tgt}$ is the irradiance originating from the earth disc at the aircraft at altitude h, see Fig. 3. The irradiance can be written as the sum of the radiation reaching the aircraft from N circular strip increments of the earth disc. In Fig. 3 it is shown how an increment's area is defined by the width of the strip dR and the radius R_i. The earth disc radiance L_{ed} from each increment is attenuated with its corresponding mean transmittance to the aircraft τ_i. In this scenario L_{ed} is approximated to the radiance from a gray body with emissivity of 0.98 (water). L_{bgnd} in (5) was calculated assuming gray body behavior at the temperature of the

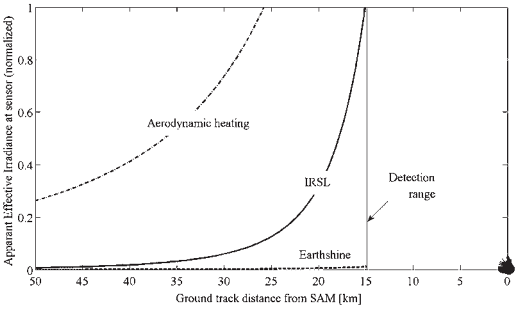

Fig. 4. The composition of the LWIR signal, from an aircraft on Path 2, with surface emissivity 0.9, at an altitude of 100 m, detected by a sensor at SAM Site 1.

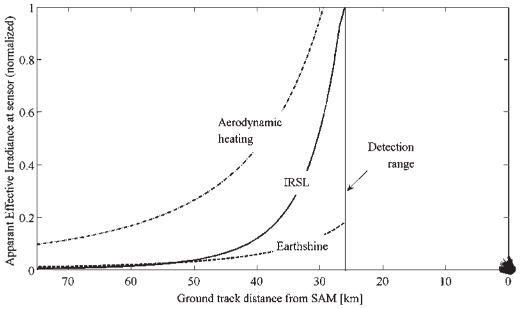

Fig. 5. The composition of the LWIR signal, from an aircraft on Path 2, with surface emissivity 0.9, at an altitude of 8000 m, detected by a sensor at SAM Site 1.

target's ambient air and with emissivity of 0.8 [20]. Finally, solving (5) for the IR detection range yields

$$R_{det} = \sqrt{\tau_p \left((L_{ie}(T_s, \varepsilon_s) + L_{re}) - L_{bgnd} \right) \frac{A_{proj}}{IRSL_{det}}}. \tag{8}$$

The sensor threshold contrast, $IRSL_{det}$ was estimated as $4.5 \cdot 10^{-7}$ W/m^2, assuming an approaching aircraft in excellent detection conditions and by calibrating against tabulated data [11]. Using this model, the probability of detection, P_D, is presumed to be unity, if the range to the engaging SAM is less than R_{det}; otherwise it is presumed to be zero.

5. Analysis

The mission model was implemented and simulated using parameter values from Table 1. Firstly, the IR signature response to changes in surface coating emissivity was analyzed in some detail. Then the resulting impact of the IRSL on the mission measures of effectiveness was investigated.

5.1. The signature response to varying altitude and emissivity

In our model the contrast signature level from an aircraft detected by a LWIR sensor comprises three components: the irradiance from the airframe due to aerodynamic heating, the reflected earthshine, and lastly the contrasting apparent irradiance from the sky background at the target position. When the baseline aircraft, with a normal high emitting surface coating of 0.9 [16], is first detected in the low altitude strike option, at a range of 15 km, the irradiance from aerodynamic heating is the dominant component, while earthshine is negligible, as shown in Fig. 4. Note that the IRSL has been normalized with the estimated detection threshold value.

However, at higher altitudes, e.g. 8000 m, the earthshine can no longer be neglected, as can be seen in Fig. 5. Furthermore, if the emissivity is reduced, to 0.3, for example, as seen in Fig. 6, the reflected earthshine then becomes the larger component. The range to detection increases with altitude to about 26 km, but does not seem to change with emissivity.

This impact of altitude on the relative importance of the components of the IRSL can partly be understood by examining equation (6). At low altitude the skin temperature is relatively higher than at high altitude because of the different temperatures of the ambient air. Consequently, thermal radiance from the airframe is relatively high at low altitudes. For the baseline aircraft, with emissivity of 0.9, the modeled radiance from aerodynamic heating is estimated to be in the 50 W/m^2/sr range for the low altitude strike paths, and around 23 W/m^2/sr for the high altitude strike paths. Instead, emissivity dependence is determined by the gray body appearance of the components, and the radiance from aerodynamic heating is simply proportional to the surface emissivity. In Fig. 7 the component is plotted as a function of emissivity for both a low and high altitude strike option. The corresponding radiance from the modeled background at target altitude is also indicated.

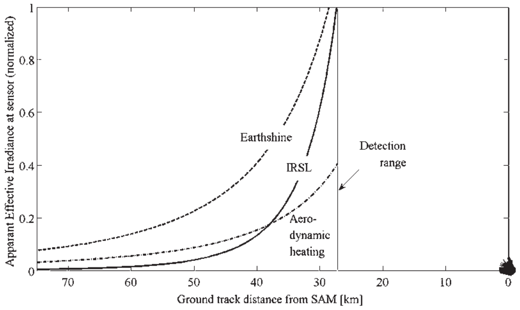

Fig. 6. The composition of the LWIR signal, from an aircraft on Path 2, with surface emissivity 0.3, at an altitude of 8000 m, detected by a sensor at SAM Site 1.

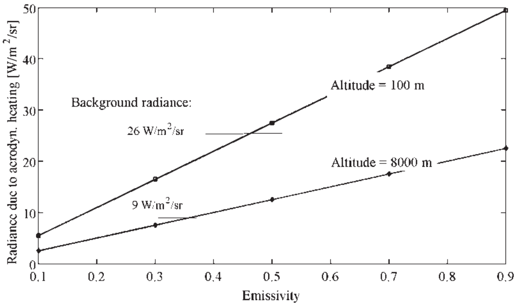

Fig. 7. The radiance from the airframe due to aerodynamic heating as a function of emissivity and altitude.

By looking only at these graphs, thereby omitting earthshine, it is deceptively easy to draw the conclusion that the aircraft should always be coated with a low emitting coating in the range 0.4 to 0.5, in order to minimize contrast with the background. Instead, however, the earthshine component is proportional to $(1 - \varepsilon_s)$, as given by equation (7), and the altitude behavior of the reflected

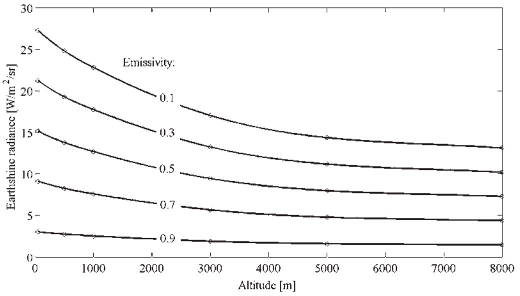

Fig. 8. The reflected earthshine radiance from the underside of an aerial platform as a function of emissivity and altitude.

earthshine component is not as intuitive. The size of the illuminating earth disc increases with altitude and, at the same time, attenuation due to the atmosphere between the earth and the aircraft also increases. In Fig. 8 the apparent earthshine radiance reflected from a surface parallel to and facing the earth disc is plotted as a function of altitude and emissivity. These results are consistent with earlier research [10].

The bottom graph in Fig. 8 can be seen as representing reflected earthshine radiance from the underside of the baseline aircraft. In general the reflected earthshine component increases with reduced altitude and emissivity. By comparing Fig. 7 and Fig. 8 it can be seen that for high altitude flight paths, and emissivity around 0.4, the two IRSL components are of comparable strength and, if emissivity is reduced further, earthshine becomes dominant.

However, since the sensor is situated close to the horizon, there is also the shape of the aircraft to consider. The irradiance at the sensor due to aerodynamic heating originates from the entire projected area of the aircraft, while the earthshine component originates from terrestrial reflections. It seems reasonable to assume that the front and side of the platform emit proportionally less than the underside of the aircraft. This contribution has been included in the model using a geometrical factor. For a shoe box shaped aircraft, as in this case, the geometrical factor should be 0.5, since the side or front of an aircraft in level flight only sees half of the earth disc. This affects the impact of altitude on the relative importance of the earthshine component in the IRSL. At low altitude the area projected towards the ground sensor is mainly the front or sides, while at higher altitude, and closer to the sensor, the underside becomes the more prominent reflecting surface. Arguably, the geometrical factor for a real aircraft should be somewhat lower, assuming that part of the surfaces seen by the sensor will be in shadow from earthshine.

5.1.1. The response in capability measures of performance

In order to synthesize results at the capability system level, detection range was calculated and plotted as a function of emissivity, altitude and flight path, see Fig. 9.

It can be seen that, irrespective of emissivity, as long as the aircraft is above the horizon, the detection range is greater for the Path 1 option. This should be expected, since the aircraft projects more of its area towards the sensor on Path 1 than it does on Path 2. Furthermore, while it seems possible to minimize the detection range to aircraft at low altitude, by reducing surface emissivity below 0.4, the detection range to corresponding aircraft at medium altitude seems to increase slightly. These results are consistent with the analysis of the IRSL above. At low altitude aerodynamic heating dominates the IRSL; consequently, detection range is reduced with decreasing emissivity. At higher altitude, however, reflected earthshine compensates for reduced aerodynamic heating.

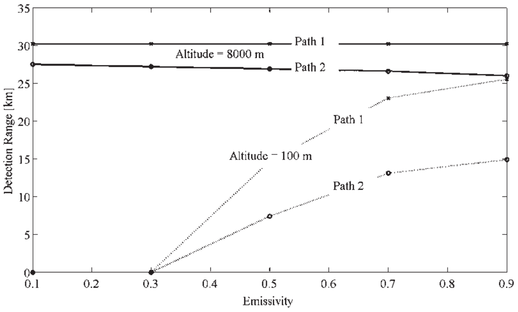

Fig. 9. The detection range, from a LWIR sensor at SAM Site 1 to an aircraft on flight Paths 1 and 2, as a function of the aircraft surface emissivity.

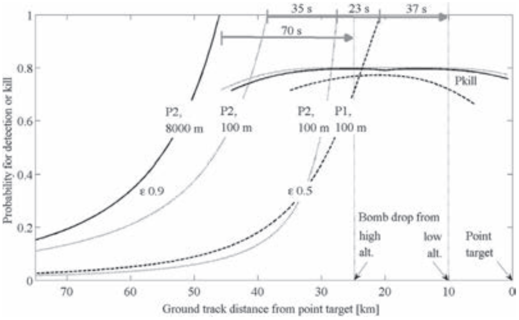

Fig. 10. The detection range, from a LWIR sensor at SAM Site 1 to an aircraft on flight Paths 1 and 2, as a function of the aircraft surface emissivity.

5.1.2. The response in mission measures of effectiveness

The analysis of the response at the mission system level is based on the diagram in Fig. 10. It shows the modeled normalized IRSL of different attacking aircraft, and the probability of the aircraft being killed, integrated into one diagram. The probability of the aircraft being detected is presumed to be zero, if the normalized IRSL is below unity, and one if it is above. The probabilities are given as a function of the aircraft ground track distance to the point target. The planned bomb drop points are indicated with their associated air defense windows of opportunity, which are illustrated with arrows. After bomb drop the aircraft are free to maneuver and P_{kill} is assumed to decrease considerably.

The two left-hand IRSL curves in Fig. 10 originate from an aircraft with a surface emissivity of 0.9 at different altitudes in strike Path 2. They are detected 70 s and 95 s, respectively, before their planned bomb drop points. Reducing this window of opportunity by a 20 s delay in the SAM command and control system still gives considerable time to engage. Hence P_{kill} is assumed to be 0.79 for both scenarios. The third IRSL curve from the left shows that detection can be significantly delayed, if the aircraft is coated with a low emissive paint. Nevertheless, the effort is not good enough to improve the mission measures of effectiveness. The air defense window of opportunity is still too wide. However, the fourth curve from the left shows that by combining a reduction in emissivity with tactical selection of a flight path between SAM sites (Path 1), a tipping point is identified. The window of opportunity is now only 37 s wide. This equals the sum of the delay in the command

Table 2
The results at mission system level expressed in the chosen measures of effectiveness.

Scenario	P_{kill}	$P_{N\|S}$	A	P_{Succ} (MoE_1)	Losses (MoE_2)
1–3	0.79	0.97	7	0.77	5.6
4	<0.74	0.97	5	>0.75	<3.7

and control system and the missile fly-out time. Consequently, any further efforts to enhance survivability from this point can be expected to have significant effects on mission measures of effectiveness. Hence, the P_{kill} value, 0.74, read from the diagram 20 s after detection can be considered a conservative estimate.

Table 2 shows the synthesized results for the scenarios analyzed. The MoEs were obtained by inserting the results into equations (1) and (2).

The preferred strike option has significantly lower expected losses. Because the aim of this paper is to study the impact of efforts to reduce IR signature at the mission level, this difference in MoEs is satisfactory. If the goal had been to find a strike option that minimizes losses, the models would have to be complemented with other means to increase survivability, such as suppression of enemy air defense capability or active counter measures etc. Note however, that when analyzing results at mission level it is important to remember that the model is only valid for the front sector of the attacking aircraft. As the aircraft approaches the SAM site, at some point, hot parts of the rear airframe, due to heat from the engine bay, will become visible and thus enhance the IRSL, even in LWIR.

6. Discussion

The results show that use of the proposed mission system model, with its current level of technical detail, is feasible for quantitative assessment of the military effectiveness of spectrally designing aircraft coatings. If the results reported previously by Marcus et al. [13] are included, the overall results from the study suggest that the model and analysis scheme support the conceptual analysis of aircraft survivability. Such assessments are usually important elements of, for instance, trade-off analysis in studies of various military capabilities or in technology forecasts.

The importance of evaluating technical signature reduction efforts at a mission system level has been demonstrated because it has been shown how changes in technical variables, such as surface emissivity, might very well decrease detection range, without significantly changing the military outcome. If the reduction is not large enough, there is no change in the outcome measures of military effectiveness at mission level. It was also shown that by using the procedure demonstrated, it is possible to find tipping points in military effectiveness, i.e. those efforts that really make a difference to mission outcome.

We have reason to believe that the impact of the emissivity of paint on military suitability or affordability is negligible. Therefore, assessment of its military utility only involves military effectiveness. However, when modifying the IR signature of an aircraft by tuning other technical variables, such as size or shape, it is likely that changes will also have unwanted effects on affordability or military suitability. Hence, when comparing concepts, any analysis of alternatives would generally be more fruitful if overall military utility is compared.

The more detailed analysis of the impact of emissivity on IR signature corroborates earlier results regarding the importance of earthshine as a phenomenon to consider. Its influence on LWIR signature, and thereby on detection range, is further clarified in this study. The results indicate that earthshine cannot be ignored for aircraft at medium or high altitudes. At these altitudes earthshine seems to nullify the use of low emissive paint to reduce LWIR signature in the front sector of an aircraft. However, the results do show that low emissive paint has the intended effect at low altitude, where earthshine has little influence in relation to aerodynamic heating.

The limitations of the model raise some uncertainties, in particular in the analysis of the low altitude options. For aircraft flying extremely low, or far away, the results indicate that the earthshine contribution is dependent on the geometry of the aerial platform. Nevertheless, in our investigation, even if the earthshine contribution in the IRSL from the low flying aircraft were doubled, it would make no significant difference. In this setting, perhaps, the assumption of a perfect scattering surface is more important. Real surfaces usually emit less at high angles to the surface normal, which implies that the model used overestimates radiance picked up from aerodynamic heating. On the other hand, in a more realistic background model these phenomena might drown in clutter originating from the terrain. In conclusion, background and geometry are important; therefore, more detailed background, shape and surface models are needed for effective assessment of the military utility of specific aircraft designs.

The results are also only valid for sub-arctic conditions in clear weather at mid-summer. To get a more generally accepted value of measures of effectiveness, one might have to take results from different conditions into consideration. However, this should be straightforward, assuming availability of weather statistics for the operational area of interest. On the other hand one might also consider optimizing the system for specific weather conditions, incorporating tactical considerations into the capability design.

Finally, the requirements for the level of detail in the technical models used seem to be modest for our purposes. They do, however, need to incorporate possible responses from important signature variables such as speed or size. Otherwise it will be impossible to identify potential penalties to other attributes of the aircraft, and the purpose of the system approach will fail.

7. Conclusions

An analysis scheme and model proposed in earlier research was used to evaluate the military utility of efforts to reduce LWIR signature in the conceptual design of survivable aircraft for strike missions. The model was specifically applied to the problem of linking aircraft coating emissivity to mission accomplishment. The overall results, taking uncertainties into consideration, support the use of the proposed system model and analysis scheme for assessing the military utility of spectral design, in the development concept phase. In some situations, such as assessing the military utility of paint with tailored emissivity for aircraft surface coatings, the results suggest that it is sufficient to assess its military effectiveness. The results indicate that low emissive paint on the front sector of an attack aircraft has significant military utility in low altitude missions, but its utility is uncertain in high altitude missions. Furthermore, in some situations earthshine constitutes a significant part of the LWIR signature and should not be ignored in the analysis.

Conflict of interest statement

There is no conflict of interests.

Acknowledgements

The model used was initially developed in cooperation with Carina Marcus, Saab Aeronautics AB, and Christina Åkerlind, Swedish Defence Research Agency. The author would like to thank Johan Eriksson and the Signature project group at the Swedish Defence

Research Agency, and Michael Reberg, Lars-Johan Nordlund, Magnus Bengtsson, Anders Nygren and Stephen Henly, Swedish Defence University, for their valuable input.

References

[1] R.E. Ball, The Fundamentals of Aircraft Combat Survivability Analysis and Design, 2nd edition, AIAA Education, Reston, VA, 2003.

[2] K. Andersson, M. Bang, C. Marcus, B. Persson, P. Sturesson, E. Jensen, G. Hult, Military utility: a proposed concept to support decision-making, Technol. Soc. 43 (2015) 23–32, http://dx.doi.org/10.1016/j.techsoc.2015.07.001.

[3] H. Lawson, A Journey Through the Systems Landscape, College Publications, 2010.

[4] J. Anteroinen, Enhancing the Development of Military Capabilities by a Systems Approach, Ph.D. thesis, National Defence University, Helsinki, 2013, http://www.doria.fi.

[5] M.I. Skolnik, An analysis of bistatic radar, IEEE Trans. Aerosp. Electron. Syst. ANE-8 (1) (1961) 19–27, http://dx.doi.org/10.1109/TANE3.1961.4201772.

[6] H. Griffiths, Developments in bistatic and networked radar, in: 2011 IEEE CIE International Conference on Radar (RADAR), vol. 1, 2011, pp. 10–13.

[7] S. Choi, D. Crouse, P. Willett, S. Zhou, Multistatic target tracking for passive radar in a DAB/DVB network: initiation, IEEE Trans. Aerosp. Electron. Syst. 51 (3) (2015) 2460–2469, http://dx.doi.org/10.1109/TAES.2015.130270.

[8] A. Rogalski, Recent progress in infrared detector technologies, Infrared Phys. Technol. 54 (3) (2011) 136–154, http://dx.doi.org/10.1016/j.infrared.2010.12.003.

[9] L. Jianwei, W. Qiang, Aircraft-skin infrared radiation characteristics modeling and analysis, Chin. J. Aeronaut. 22 (5) (2009) 493–497, http://dx.doi.org/10.1016/S1000-9361(08)60131-4.

[10] S.P. Mahulikar, S.K. Potnuru, G. Arvind Rao, Study of sunshine, skyshine, and earthshine for aircraft infrared detection, J. Opt. A, Pure Appl. Opt. 11 (4) (2009) 045703, http://dx.doi.org/10.1088/1464-4258/11/4/045703, http://stacks.iop.org/1464-4258/11/i=4/a=045703?key=crossref.2fd77bd37121f8a3560b2f927c99c45f.

[11] C. Kopp, KBP 2K22/2K22M/M1 Tunguska SA-19 Grison/96K6 Pantsir S1/SA-22 Greyhound SPAAGM, Tech. rep., Air Power Australia, 2009, http://www.ausairpower.net/APA-96K6-Pantsir-2K22-Tunguska.html.

[12] J.R. White, Aircraft Infrared Principles, Signatures, Threats, and Countermeasures, TP 8773, NAWC, US, 2012.

[13] C. Marcus, K. Andersson, C. Åkerlind, Balancing the radar and long wavelength infrared signature properties in concept analysis of combat aircraft – a proof of concept, Aerosp. Sci. Technol. (2017), unpublished results, submitted for publication, http://dx.doi.org/10.1016/j.ast.

[14] D. Soban, D. Mavris, Formulation of a methodology for the probabilistic assessment of system effectiveness, in: AIAA Strategic and Tactical Missile Systems Conference, AIAA, Monterey, CA, 2000, pp. 1–12.

[15] K.E. Andersson, C. Åkerlind, A review of materials for spectral design coatings in signature management applications, in: D. Burgess, G. Owen, H. Rana, R. Zamboni, F. Kajzar, A.A. Szep (Eds.), SPIE Security + Defence, International Society for Optics and Photonics, 2014, p. 92530Y, http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1922108.

[16] B.P. Sandford, D.C. Robertson, Infrared reflectance properties of aircraft paints, ESC-94-1004, in: IRIS Targets, Backgrounds and Discrimination, 1994.

[17] MilitaryPeriscope.com/Joint Direct Attack Munition (JDAM), 18 Mar. 2016, 2010.

[18] A. Sandqvist, P. Gerdle, On electronic warfare for the ground based air defense – radar and tactics (Lärobok i telekrigföring för luftvärnet – Radar och radartaktik), Swedish Armed Forces, 2004.

[19] J.D. Mcglynn, S.P. Auerbach, IR signature prediction errors for skin-heated aerial targets, Proc. SPIE 3062 (1997) 22–30.

[20] P.A. Jacobs, Thermal Infrared Characterization of Ground Targets and Backgrounds, 2nd edition, SPIE, 2006.

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ISBN 978-951-25-2998-8 (pbk.)
ISBN 978-951-25-2999-5 (PDF)
ISSN 2342-9992 (print)
ISSN 2343-0001 (web)

Puolustusvoimat
The Finnish Defence Forces