Vesa Kuikka, PhLic, Finnish Defence Research Agency, vesa.kuikka@mil.fi
Juha-Pekka Nikkarila, PhD, Finnish Defence Research Agency, juha-pekka.nikkarila@mil.fi
Marko Suojanen, M.Sc.(EE), Finnish Defence Research Agency, marko.suojanen@mil.fi

DEPENDENCY OF MILITARY CAPABILITIES ON TECHNOLOGICAL DEVELOPMENT

Keywords

Modelling military capability, technological forecasting, interdependencies between technologies

Abstract

Our goal is to get better understanding of different kind of dependencies behind the high-level capability areas. The models are suitable for investigating present state capabilities or future developments of capabilities in the context of technology forecasting. Three levels are necessary for a model describing effects of technologies on military capabilities. These levels are capability areas, systems and technologies. The contribution of this paper is to present one possible model for interdependencies between technologies. Modelling interdependencies between technologies is the last building block in constructing a quantitative model for technological forecasting including necessary levels of abstraction. This study supplements our previous research and as a result we present a model for the whole process of capability modelling. As in our earlier studies, capability is defined as the probability of a successful task or operation or proper functioning of a system. In order to obtain numerical data to demonstrate our model, we conducted a questionnaire to a group of defence technology researchers where interdependencies between seven representative technologies were inquired. Because of a small number of participants in questionnaires and general uncertainties concerning subjective evaluations, only rough conclusions can be made from the numerical results.

Introduction

New technologies can provide new and more effective military capabilities. New technologies can present threat or opportunity and their future development is uncertain. The uncertainty that characterises technologies mean that the military cannot know which emerging technologies mature to have profound impacts, how long that maturing will take nor the technological trajectory. Most emerging

DOI 10.1515/jms-2016-0170

technologies represent incremental improvements and enhance the competencies of the military. This kind of technological development presents few challenges to the military, although their adoption into existing platforms can be difficult. In contrast, it is new technologies that are radical, degrade competence and create new sources of military advantage along dimensions not traditionally valued or poorly understood by the military that are the focus of attention and concern. An emerging technology that undermines existing training, equipment and doctrine will have more impact on the military than one that complements or enhances existing military competencies. (James, 2013)

Fundamental concepts of this paper are capabilities, systems and technologies. Each of these has several different descriptions. We provide some of the most common definitions of these three concepts. Capability has been defined as the ability to achieve a specified wartime objective (win a war or battle, destroy a target set). The concept of capability has been used to express the level of will, amount of troops and armament. In many countries capability areas have been standardized as a set of specifications that cover the complete range of military activities. A system is a set of interacting or interdependent component parts forming a complex/intricate whole. Systems share common characteristics including structure, behaviour and interconnectivity. Technology is the collection of techniques, skills, methods and processes used in the production of goods or services. It is the state of knowledge of how to combine resources to produce desired products, to solve problems, fulfil needs, or satisfy wants.

In this paper we examine interdependencies of technologies and impacts of technologies on military capabilities. In our earlier research we have examined impacts of systems on military capabilities (Kuikka & Suojanen, 2014) and impacts of single technologies on military capabilities (Kuikka et al., 2015). In the present work we complement the modelling by taking into account influences of multiple technologies on system capabilities and top-level capability areas. In this respect, our aim is two-fold: to provide the missing piece of the modelling and give the big picture of the modelling results of our earlier research and this paper. To this end, we provide also a literature review of articles that are related to concepts and models of our work. The review is not a comprehensive survey of research in technology forecasting or capability modelling. The review serves as an introduction to the research field and other research projects comparable to our work. The theoretical and methodological literature ground our present work and guide for further investigation.

In this study, a functional dependency of military capabilities on technical development is presented. Questionnaire data is used as an input for modelling relationships between operational tasks, systems, technologies and capability areas. In this context, capability is defined as the probability of successful task or operation, or functioning of a system. The functional form gives an approximation for calculating effects of different technological developments on capabilities.

In literature, describing military capabilities has been examined for a long time. Not many quantitative models have been published. Another problem is the lack of a measure for capabilities. In an earlier study, we have introduced also an alternative measure for strategy (Hämäläinen & Nikkarila, 2015). We propose a model based on a probabilistic measure of capabilities. The same measure is used in all levels of the model: capability areas, systems, tasks and technology areas.

The main idea is to show how to evaluate interdependencies between technology areas. For example, material technology has a significant effect on sensor technology. Progress in the first area implies progress in the latter area. Notice that interdependencies are not necessarily symmetric; for example sensor technology depends significantly on material technology, while the dependency in the opposite direction is weaker. Seven technology areas are considered: sensor, material, communications, stealth, energy source, manufacturing, and autonomous operation technologies. Five different operational tasks are used in the evaluation.

In the literature, different mathematical methods have been used when multiple interdependent variables are affecting the forecast. Examples are principal component analysis (Windrum et al., 2009), simulation methods and time series methods (De Gooijer & Hyndman, 2006). Typically these methods need more data than is available in our study. Some forecasting methods try to identify the underlying factors that might influence the variable that is being forecasted.

Judgmental forecasting methods incorporate intuitive judgments, opinions and subjective probability estimates. This characterization is also valid in our study. In addition, we construct models on the bases of questionnaire results. In this paper, we model interdependency of technology areas and dependency between technology areas and task capabilities. This study is one piece in larger modelling effort trying to increase our understanding of military capabilities. (Kuikka & Suojanen, 2014, Suojanen et al., 2015 and Kuikka et al., 2015 and references therein)

The operational analysis methodologies used in this work include systems modelling, probabilistic mathematical methods, statistical evaluations, information modelling and the use of questionnaires as the input data.

Related Work

In this section, a review of papers related to concepts, methods or application areas used in this paper is presented. First, we review articles on general theory of technological change, which focus on questions like why certain technological developments emerge instead of others, are there regularities in the process of generation of new technologies and in technological progress thereafter, and is there a regularity in the functional relationship between the vast number of economic, social, institutional, scientific factors which are likely to influence the innovation process (Dosi, 1982). After general theory of technological change, we bring up a few articles on technometrics. Technometrics is a discipline that measures and evaluates technological change with important policy implications. The main techniques of technometrics and their potential and methodological difficulties have been presented in (Coccia, 2005). Scenario planning is a method for design and evaluation of capabilities, describing rare events and technology forecasting. Three articles related with scenario planning are referenced. Articles assessing weapon system capabilities, comparison between jet fighter aircraft and decision-analytic approach to reliability-based design optimization are related to methods in this paper. Finally, we give references closely related to our research of interdependency of technologies in the context of technological innovations and capability planning. In the following, we review related research articles and indicate their connections with our research. Similarities as well as different approaches with our method are commented after the references in each section.

The long-run economic innovation has been analysed as the interplay between supply-side and demand-side processes. These are technology-push and demand-pull forces. On the supply-side three different interacting development processes have been identified: growing productive efficiency, the emergence of new sectors and the increasing quality and differentiation of existing products. The time path of economic development cannot be explained by taking into account a supply-side view alone. Without an adequate demand, development processes cannot be generated. The situation can be described as the co-evolution of demand, innovation and supply (Saviotti & Pyka, 2013). Demand influences the selection among competing paradigms and the course of the paradigm after its inception. For example, in the history of computing technology a distinction can be made between periods in which either demand or knowledge development was the dominant enabler of innovation (van den Ende & Dolsma, 2002). Niches in evolutionary theories have been investigated in explaining radical technical change (Schot & & Geels, 2007). Radical change or technological discontinuity is defined as the establishment of a new sociotechnical regime. Sociotechnical regimes carry and store rules for how to produce, use and regulate specific technologies. The difference between niches results from differentiating between whether niches are internal or external to the prevailing sociotechnical regime and whether rules for design are stable or unstable within the niche. Our model describes the course of technological development after its inception with a linear model together with secondary multiplicative linear effects on other technologies. The dependencies between technology areas are linear but the overall effects on capability values are non-linear due to the interdependencies between technology areas.

The model of technological paradigms and trajectories (Dosi, 1982) account for both continuous change and discontinuous change in technological innovations. Continuous changes are related to progress along a technical trajectory defined by a technical paradigm, while discontinuities are associated with the emergence of a new paradigm. Technological paradigm has been defined in accordance with a set of procedures, a definition of relevant problems and the specific knowledge related to their solution. Technology trajectory is defined as the direction of advance within a technology trajectory. A radical innovation is founded on the creation of a new set of technology solutions, and results in a new trajectory that is qualitative different (Dosi, 1982). A model of technological evolution based on replicator dynamics has been presented (Saviotti & Mani, 1995) where the relationship between variety and competition has been studied. Probabilistic entropy statistics and scaling trajectories in 143 civil aircraft designs have been analysed in terms of changes in the product characteristics (Frenken & Leydesdorff, 2000). Distinction has been made between technical and service characteristics. Technical characteristics were defined as variables that can directly be manipulated by producers. Variables that users take into account in their purchasing decisions were considered as service characteristics. In our model, service characteristics can be identified with system services or functionalities and technical characteristics can be identified with technical features or attributes. Our basic model is designed for linear technological changes in technology areas including secondary effects on other technology areas. However, the model can be modified to include jumps triggered at specified levels. This can be easily implemented in a spreadsheet application. The secondary effects follow automatically. Even a more general functional form could be used, for example, exponential development. Our model takes into account the first order secondary effects in other technology areas, but the model does not account for 'economics of scale' which might support an exponential functional form.

The complex relationship between technical and service characteristics has been explored in (Windrum et al., 2009). Principal component analysis (PCA) has been used as a method of the analysis of a dataset of mobile phone handsets. Technological trajectories by means of a detailed case-study of the evolution of tank technology between 1915 and 1945 has been analysed with principal component analysis in (Castaldi et al., 2009). A hierarchic conceptualisation of tank technology with technical and service characteristics has been used in the modelling. Our model of system of systems consists of serial and parallel systems and subsystems. Even a simple system structure may describe high level capabilities and their long term development as well as more detailed hierarchic models or purely statistical methods such as PCA.

The scale of innovative intensity (SIIN) based on the economic impact of the technological innovation on the economic system has been used as a theoretical measure for technological change (Coccia, 2003). The SIIN is similar to the seismic scale of measuring the intensity of earthquakes. Three families of complexity models of technology innovation have been discussed in (Frenken, 2006): fitness landscape models, network models and percolation models. The models are capable of analysing complex interaction structures while avoiding over-parameterisation. Technological developments in the network connecting patents have been analysed in (Schoen et al., 2012). In our model, a probabilistic measure for high level capabilities and system capabilities is proposed. This is a quantitative and intuitive measure suitable for all levels of capability modelling. The probability of success in an operation is considered to be a natural selection in the military context. Especially, when modelling complex interactions and structures, it is important to have an understandable and quantitative method. High uncertainties in long term forecasting support a simple model instead of more sophisticated considerations.

In technology planning, forecasting, strategic analysis, foresight studies, scenarios are used to incorporate and emphasize those aspects of the world that are important to the forecast. A review of scenario planning been presented in (Amur et al., 2013). Scenario-based design and evaluation for military capabilities has been analysed in (Urwinet et al., 2010). Scenarios are helpful in visualizing and understanding the incorporation of new systems within system of systems. The approach is based on the development of measure of effectiveness and performance and the techniques have been illustrated using cases that are relevant to network enabled capability. The measures of performance are independent of an operational scenario and allow the results to be compared with systems that provide the same functionality. In contrast, measures of effectiveness are dependent on an operational scenario. The scenario is composed of vignettes that contextualize the principal phases of systems development to meet a capability need. One or more operational vignettes must be included to test the deployed system (Urwinet et al., 2010). In our approach, three different representative scenarios have been used in the first questionnaire. The functionalities realised by system services and used in the operational tasks are similar in different scenarios. As a result, our second and third questionnaires which are not dealing with capability areas or system capabilities did not use scenarios explicitly. This is in accordance with (Urwinet et. al., 2010).

The practice of scenario planning implicitly accepts that managers are not able to make valid assessments of the likelihood of unique future events and that best guesses of what the future may hold may be wrong (Goodwin & Wright, 2010). Scenarios focus on key uncertainties and certainties about the future and construct vivid descriptions of the world. In their paper Goodwin and Wright review methods that aim to aid the anticipation of rare, high-impact, events. Methods are evaluated according to their ability to yield well-calibrated probabilities or point forecasts for such events. Authors conclude that all the methods are problematic for aiding the anticipation of rare events and provide some remedies. Human judgement is often used to estimate the probabilities of events occurring. Goodwin and Wright point out possible cognitive biases. Events which are vivid, recent, unusual or highlighted by the media are assigned high probabilities. A tendency to ignore base-rate information and frequencies or anchoring on the current value and insufficient adjustment for the effect of future conditions are sources of biases in questionnaires based of human judgment. Our work is also based on questionnaires and human judgment, which should be paid attention when the results are assessed. However, our main objective has been to demonstrate the model building and for this purpose the questionnaire data is sufficient. Rare events occur in very special scenarios which make scenarios an essential tool for investigating rare events. Our method can be used directly for rare events and the results for capability areas and system capabilities can be used in planning and preparing for these rare events. Another way of using scenarios with different probabilities is to calculate an expected value for capability areas or system capabilities. The expected value is obtained with the probabilities of scenarios as weights in the sum of scenario capabilities.

A quantitative comparison between U.S. and U.S.S.R/Russian jet fighters (Bongers & Torres, 2013) estimates the relationship between the first flight date and a set of performance and technical characteristics such as thrust, climb rate, basic avionics, advanced avionics and stealth. Linear regression has been used as a mathematical tool. Another article includes a case study of main battle tank capability (Jiang et al., 2011). Weapon system capability assessment is a multiple criteria decision making problem with both quantitative and qualitative information under uncertain environment. Authors use belief structures model and evidential reasoning approach which were developed to deal with various types of uncertainties such as ignorance and subjectivity. The assessment framework for capabilities is hierarchic. A decision-analytic approach to reliability-based design optimization has been presented in a theoretical article (Bordley & Pollock, 2009). In their work, similar concepts to this paper are used but the approach is more theoretical. Several articles consider uncertain environments and use different methods for this purpose. Using probabilities might be suitable in many of these cases. Linear regression is not a optimal method for forecasting extreme events, such as the first flight day. As we have discussed in (Kuikka et al., 2015), few dedicated methods exist in this area. Because our model deals with interdependencies between technology areas, the method in this paper may be suitable also for these cases. Our method is a candidate for interpreting the first flight days, or comparable events. This can be considered in following studies.

A standardization of terminology of technology by conceptualizing products as complex artefacts that evolve in the form of a nested hierarchy of technology cycles. Such a system perspective provides both unambiguous definitions of dominant designs (stable core components that can be stable interfaces) and inclusion of multiple levels of analysis (system, subsystems, components) (Murmann & Frenken, 2006). A new conceptual model for understanding technological evolution that highlights dynamic and highly interdependent relationships among multiple technologies has been proposed in (Adomavicius et al., 2005). The authors conclude that when technology evolution is discussed, a single technology cannot be considered in isolation. The technology ecosystem consists of a dynamic system that includes the totality of interrelated technologies. The authors identify three roles that technologies play within a technology ecosystem: components, products and applications and infrastructure. Types of interactions between technology roles have been classified as different kind of paths of influence. The use of the model has been demonstrated through the Wi-Fi business case. In this paper, because of the diversity of interdependencies between technologies, a simple matrix formulation is proposed for the modelling of technology areas. Modelling technologies with the principles of system of systems' methods, for example, is challenging because a technology area interacts with all the other technology areas.

A method for hierarchically prioritizing capabilities with an application to military manned and unmanned aerial vehicles provides the linkage between mission requirements to capability delivery options (Bourdon et al., 2014). The method provides a structure for breaking down requirements hierarchically into form against which selected capabilities can be assessed. Planning for military requirements is not bounded by a single threat that was expected to be faced in future conflicts. The planning is based on capabilities needed to win a conflict by defeating a range of threats encountered. The hierarchical prioritization of capabilities provides a broad high-level assessment of potential offered by different unmanned aerial vehicles. The method avoids comparing all the possible pairs of roles and tasks of UAVs as is necessary in the analytical hierarchy process (AHP). Another benefit of the model is that the addition of new missions, tasks, or roles does not invalidate previous assessments. This is not the case with other methods such as AHP in which the relative weights of two alternatives may change based on the introduction of a third alternative. Weapon selection using AHP and TOPSIS (technique for order performance by similarity to idea solution) methods under fuzzy environment has been analysed in (Dagdeviren et al., 2009). The AHP is used to analyse the structure of the weapon system in a fuzzy environment and to determine the wrights of the criteria, and fuzzy TOPSIS method is used to obtain final ranking. Again, the research problems in (Bourdon et al., 2014) and (Dagdeviren et al., 2009) bear resemblance with our research problems. Our method has also a favourable feature that adding a system to a system of systems does not result in recalculating all the pairs of systems.

Interoperability in military systems-of-systems architectures and capability-based quantitative technology evaluation have been addressed in (Wyatt et al., 2012) and (Biltgen & Mavris, 2007). The increasing complexity of net-centric warfare requires systems to be interoperable to achieve mission success. The research surveys existing interoperability measurement methods and assess them from perspective of using interoperability as a metric to evaluate system-of-systems architectures. The purpose of the methodology has been to enable quantitative evaluation of technologies in a systems-of-systems context and enumerate how resources should be allocated to new technology development programs. The methodology provides insight into sensitivities of technologies on top-level capability metrics. In many cases, these sensitivities have been obscured by complexity of the problem. A holistic approach to the modelling and simulation of complex systems facilitates a traceable analysis process. The work demonstrates several ways that surrogate models can leverage to speed up processes, simultaneously examine technologies and tactics, and to enable next-generation visualization capabilities for systems-of-systems. The authors plan to extend their approach to examine multiple capabilities across a range of scenarios and will incorporate variable fidelity models to examine different trends and behaviours at varying levels of detail. Methods used in (Wyatt et al., 2012) and (Biltgen & Mavris, 2007) are different while the research goals and use of the results are similar. Simultaneous examination of technologies and tactics, resource allocation to new technology programs, sensitivity analysis of technology areas on top-level capability areas, system of systems' modelling and variable fidelity of systems and subsystems are common principles with our research methods.

Modelling the Interdependencies between Technology Areas

In this section we go through the steps of our model from technology areas to capability areas. Numerical results will be presented later in this paper, because we need some background from our earlier studies which will be presented in the next section. Our study is based on a questionnaire conducted in Finnish National Defence University in International What If?-data farming workshop. The questionnaire had two parts. In the first part the values for protection, situational awareness and engagement capability areas were asked for two systems and their combined use. The systems used were satellites and UAVs (Unmanned Aerial Vehicles).

In Figure 1 the structure of the overall model is described. In the first part (Q1 in Figure 1) of the questionnaire capability values for three capability areas were asked for satellites, UAVs and combined use of the systems. In the second part (Q2 in Figure 1) the effects of seven technology areas on five operational task capabilities were asked. Relationship "T/C" in Figure 1, is established by identifying three tasks with three capability areas. An additional survey (Q3 in Figure 1) was conducted among five technical persons (5 out of 10) of the same group. The analysis of Q3 results is the subject of this study. In this part, interdependencies between technology areas were asked. The questionnaire structure is summarized in Table 1.

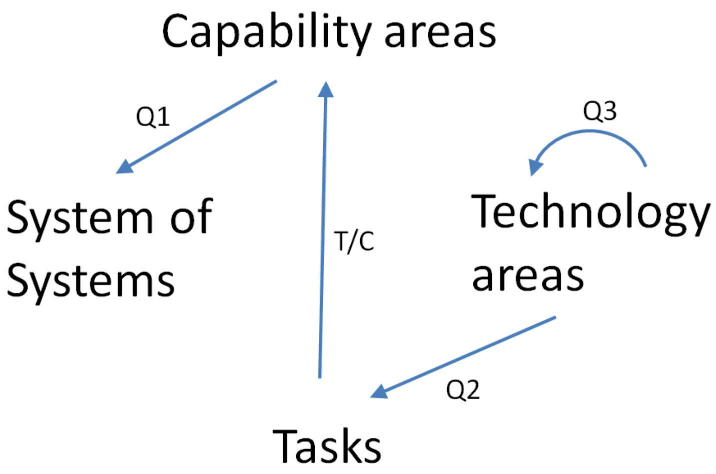

Figure 1. Hierarchic levels of the model. Three parts of the questionnaire are denoted Q1, Q2 and Q3. It is noticeable that there exists a sub model for each Qi (i=1, 2, 3) and the sub-models are modular components in the process flowchart.

In this paper our focus is in technological level. We present the connection between the development of technology areas and task capabilities. Our model consists of three phases corresponding three parts of the questionnaire. In our earlier work, we have presented models corresponding Q1 (Kuikka & Suojanen, 2014) and Q2 (Kuikka et al., 2015). In this paper we examine interdependencies Q3 between different technology areas and present the total process (Fig. 1) as well. With this knowledge, we are able to calculate capability changes caused by different technological changes. Results from part Q2 provide evaluated forecasting for 1 and 10 years. Combined with Q3, forecasting for less or more development of seven technology areas or combinations of different technology area developments can be calculated.

Technology areas used in the questionnaire are: sensor, material, communication, stealth, energy source, manufacturing and autonomous technology areas. We asked the technical persons consisting of five members of the original group of ten respondents, how great are the dependencies between different technology areas. The results are summarized in matrixes D_{UAV} and D_{SAT} in Appendix 1 for UAVs and satellites correspondingly.

Table 1. Three parts of the questionnaire Q1, Q2 and Q3.

	Description	Respondents	Time (T)
Q1	Changes in capability areas when satellites, UAVs or both have been deployed.	5 officers and 5 researchers	1 y, 10 y
Q2	Dependence of task capabilities on development of technology areas for satellites and UAVs.	5 officers and 5 researchers	10 y, 20 y
Q3	Interdependencies between technology areas.	5 researchers (same personnel as in Q1 and Q2)	10 y

In the first part of the questionnaire we have studied the relationship between capability areas and systems. In our previous work we have presented a model giving functional form between system capability values and capability area changes. For a capability area the system capability values can be expressed as functions of changes in capability areas values:

$$X_{SAT} = f_{SAT}(p_1, p_2, p_{12}) \text{ and}$$
$$X_{UAV} = f_{UAV}(p_1, p_2, p_{12}), \qquad (1)$$

where X_{SAT} and X_{UAV} are system capability values with satellites and UAVs in use and p_1, p_2, p_{12} are changes of capability areas values with satellites, UAVs and combined use of satellites and UAVs. Changes are measured between the initial values p_0 (T=0) of capabilities and the final values (T=1, 10).

We present two possible alternatives for the functional forms in Equation (1). Our own model from (Kuikka & Suojanen, 2014) is shortly summarized with the following equations:

$$\mathrm{p}_0 = \mathrm{X}_\mathrm{m}\mathrm{X}_\mathrm{k}$$
$$\mathrm{p}_0 + p_1 = \mathrm{X}_\mathrm{m}(1-(1-\mathrm{X}_\mathrm{SAT})(1-X_k))$$
$$\mathrm{p}_0 + p_2 = \mathrm{X}_\mathrm{m}(1-(1-\mathrm{X}_\mathrm{UAV})(1-X_k))$$
$$\mathrm{p}_0 + p_{12} = \mathrm{X}_\mathrm{m}(1-(1-\mathrm{X}_\mathrm{SAT})(1-X_{UAV})(1-X_k)), \qquad (2)$$

where X_{SAT}, X_{UAV} are the system capability values for satellites and UAVs. And X_m and X_k are the system capability values for serial and parallel systems functioning with the satellite and UAV systems. Equations (2) follow from the probabilistic definition of capabilities. In our basic model the equation are similar for the three capability areas under consideration: protection, situational awareness and engagement.

From Equations (2) we can solve X_{SAT}, X_{UAV}, X_k, and X_m:

$$X_{SAT} = \frac{p_1 + p_2 - p_{12}}{p_2}$$

$$X_{UAV} = \frac{p_1 + p_2 - p_{12}}{p_1}$$

$$X_m = p_0 + \frac{p_1 p_2}{p_1 + p_2 - p_{12}}$$

$$X_k = (1 + \frac{p_1 p_2}{p_0(p_1 + p_2 - p_{12})})^{-1} \qquad (3)$$

Serial and parallel systems need not be specified in more detail, however their capability values X_m and X_k can be used in the analysis if desired. More details of the model (Q1) are presented in (Kuikka & Suojanen, 2014).

Martino (Martino, 1993 and Kim, 2012) introduced a scoring model for rating technology quantitatively:

$$S = \frac{A^a B^b (cC + dD + eE)^z (fF + gG)^y (1 + hH)^x}{(iI + jJ)^w (1 + kK)^v}, \qquad (4)$$

where $c+d+e=1, f+g=1, i+j=1, a+b+z+y+x=1$ and $w+v=1$. In the model A and B are overriding factors and {C, D, E}, {F, G}, and {I, J} are exchangeable factors within brackets. I, J, and K are costs or undesirable factors. The factors $(1 + hH)$ and $(1 + kK)$ represent special cases that must stand alone but cannot be traded off with any other factors. Moreover, they may not always be present. Factor H is not overriding, in the sense that its absence justifies a score of 0. It is an option that increases the score if present but does not affect the score if absent. In the same way, just because undesirable factor K has a value of 0 for some devices does not mean that their score should be infinite. In Equation (4) h and k are constants. The use of this method is an exception to the rule that weights must be normalized to sum to 1.0. Since there is only one factor in each group, however, normalization does not distort the overall score (Martino, 1993). Martino's model can be compared with our model, the serial system X_m can be considered a combination of overriding factors and the parallel systems are exchangeable factors in Martino's formulation. Cost or undesirable factors are not examined explicitly in our model, their effects are included in evaluated capability values. In our method, systems of systems are modelled with serial and parallel systems and no extra factors like $(1+hH)$ exist. Another scoring model with similar ideas has been introduced by Gordon and Munson (Martino, 1993 and Kim, 2012).

From Figure 1, we see that following the chain “Q3-Q2-T/C-Q1” changes in capability areas and systems capabilities can be calculated as a function of technology area developments. The overall model is modular in the sense that in the modelling process sub models Q1, Q2, Q3 or T/C can be changed. For example, in this paper the model for T/C dependency is the simplest choice of just identifying operational tasks with capability areas. A refined model could be a weighted combination or a function of different task capabilities. Another example would be a more detailed system model in Q1 resulting in different functional forms of f_{SAT} and f_{UAV} in Equations (1) and (3). In other words, we have constructed the method in the spirit of system of systems. The idea of the chosen approach is to distinguish the task into two parts: firstly to form an information model for the existence of dependencies; and secondly to construct the detailed models for the dependency structures. The purpose of this paper is to draw together the individual models.

Next we present the relationship between the development of technology areas and task capabilities. In our model, task capabilities are calculated as average values of technological development values:

$$C_j = \frac{1}{7}\sum_{i=1,7} A_{i,j}\,,\ j = 1,\ldots,5\,, \tag{5}$$

where matrix element $A_{i,j}$ describes the development of technology area i on task capability j. Justification for the average value as a measure is that we regard the respondents automatically weighted the importance of each technology area affecting task capabilities. Sum of technology development values is normalized, and as a consequence, we end up with the average value in Equation (5).

We need matrices from second (matrix A) and third part (matrix D) of the questionnaire. Matrix A gives the relationship between technology areas and tasks. Matrix D gives the interdependency between technology areas. In Equation (6) $\Delta_k,\ k = 1,\ldots,7$ describes development in technology area k less or more than forecasted in the questionnaire data. The forecasted values are listed later in Table 5. For example, if $\Delta_1 = 0$ no development in sensor technology occurs, and if $\Delta_2 = 1.5$ material technology develops 50 % better than forecasted. To make this clear, parameter values of Δ_k are listed in Table 8 in Appendix 1.

$$C_j = \frac{1}{7}\sum_{i=1,7} A_{i,j}\left(1 + D_{i,k}\left(\Delta_k - 1\right)\right),\ j = 1,\ldots,5,\ k = 1,\ldots,7\,. \tag{6}$$

In Equation (6) we assumed that only one of the parameter values Δ_k, at a time, is different from one: $\Delta_k \neq 1$. We will relax this assumption later in Equation (8). In Equation (6), if $\Delta_k = 1$, the development of technology area *k* is at the same level as forecasted in Table 5. Matrix element $D_{i,k}$ describes the effect of technology area *k* on technology area *i*. For simplicity, we omit index *k* on the left side of the equation. Next, we calculate a special case of task capabilities where one of the technology areas has no development. In this case $\Delta_k = 1, k = 1,...,k' - 1, k' + 1...,7$ and $\Delta_{k'} = 0$ (for $k = k'$). In Equation (6) the term inside the sum is:

$$1 + D_{i,k}(\Delta_k - 1) = 1 - D_{i,k'} \qquad \text{for } j = 1,...,5 \text{ and } k = k'$$
$$1 + D_{i,k}(\Delta_k - 1) = 1 \qquad \text{for } j = 1,...,5 \text{ and } k \neq k'. \qquad (7)$$

Next, Equation (6) is further generalized in Equation (8). We can calculate iteratively task capabilities when more than one technology area develops less or more than evaluated in Table 5.

$$C_j = \frac{1}{7} \sum_{i=1,7} A_{i,j} \prod_{k=1,7} \left(1 + D_{i,k}(\Delta_k - 1)\right), \; j = 1,...,5, \qquad (8)$$

where the product is taken over all technology areas. In the previous section, we discussed possible extensions of the model in Equation (8). Jumps, triggered at specified levels of capabilities or at some other conditions, can easily be implemented, for example, in a spreadsheet application. Also, we discussed the applications for rare events and expected value evaluations.

In Equations (6) and (8) we assume that technology development is linear having no “quantum leaps” when $\Delta_k \neq 0,1, k = 1,...,7$. These disruptive technological changes may cause dramatic impacts on other technology areas and enable or disable certain capabilities. Also the linear improvement (e.g. capacity of energy storage) does not necessarily correspond linear improvement on the capabilities, but there may be thresholds before any improvements appear. Besides, negative impacts of achievements of the technology areas on the capabilities are possible, for example, improvements in stealth technology or materials may decrease capability to perform surveillance as effectively as today. However, we reported in our first conference article (Suojanen et al., 2014): “Technology development of the RED nation was frozen in the estimation of the capabilities, since the focus was on own assets.” Consequently, no negative impacts caused by the adversary’s technological counter measures exist in the results.

Research Data and Error Analysis

In this section, we present research data from questionnaires Q1 and Q2 in the extent that is needed for analysing the results of questionnaire Q3. Presentation of new results of this paper is postponed to the next section. At the end of this section an error analysis is conducted. The relationship between the score values and the percentage values from questionnaires Q1 and Q2 is assumed to be valid also in questionnaire Q3. This can be justified because five of the experts participated in both questionnaires Q2 and Q3 (see Table 1). Because the data from our earlier work is used, we present the error analysis in this section. The same error levels are assumed to hold in questionnaire Q3.

Two questionnaires (Q1 and Q2 in Figure 1) have been conducted in our earlier research (Kuikka & Suojanen, 2014 and Kuikka et al., 2015). In Table 2 the average capability changes for situational awareness from the questionnaire Q1 are shown. The average value is justified because no scenarios were explicitly used in Questionnaire 2 and at the same time the evaluations were giving on the grounds of three basic scenarios from Questionnaire 1. Another justification is provided in (Urwin et al., 2010) where scenarios are used only in effectiveness measures, not in performance measures. Note that the changes are provided at the level of capability areas, not for satellite or UAV systems. The initial values for the awareness capabilities are 0.8, 0.6 and 0.4 for Scenarios 1, 2 and 3 respectively. For example, in Scenario 1 after ten years development the awareness capability is 0.8 + 0.085 = 0.885 (88.5 %) when UAVs are in use. In Reference (Kuikka & Suojanen, 2014) also results for protection and engagement capability areas are given for 1, 10 and 20 years' time span. In this paper we study situational awareness 10 years development as an example, other cases can be examined similarly. The initial values for protection, awareness and engagement capability areas together with average capability changes for 10 years development are summarized in Table 3.

Table 2. The changes of situational awareness capability produced by satellite and UAV systems for Scenarios 1, 2 and 3 in 10 years. The last column shows the average values of scenarios.

Situational Awareness		10 years			
		Sce1	Sce2	Sce3	average
	SAT	0.063	0.083	0.157	0.101
	UAV	0.085	0.123	0.173	0.127

Table 3. The initial capability values (T=0) for Scenarios 1 – 3 are shown. The average capability value changes with satellites and UAVs are calculated for 10 years development. The average capability changes have been calculated similarly as the average values for situational awareness in Table 2.

Capability area	Scenario 1 T=0	Scenario 2 T=0	Scenario 3 T=0	Average SAT, T=10	Average UAV, T=10
Protection	0.7	0.5	0.5	0.071	0.087
Sit. Awareness	0.8	0.6	0.4	0.101	0.127
Engagement	0.9	0.3	0.4	0.049	0.101

As can be seen from Table 1, both Questionnaire 1 and Questionnaire 2 include evaluations for 10 years technological development. In addition, the evaluated changes have been given in two different formats, in percentages and in score values 0 – 3. The same personnel took part in both questionnaires. These facts give us an opportunity to formulate a functional relationship between scores and percentages. The functional form of the dependence between the score values and the percentage values must be linear, since they describe the same quantity, only the scaling is different. Figure 2 shows the correspondence together with the linear regression fit 7.58*Score-1.39 between the two data sets. In spite of the fact, that Questionnaire 1 and 2 have been conducted one after the other, because of different formats and limited time for answering, the questionnaires can be considered almost independent of each other. As a result, we get a shortcut for estimating error levels of capability changes. The 95 % confidence interval (Levine et al., 2010, Chapter 13, Equation 13.20) for the forecasted mean value 8.9 is (8.9-1.5, 8.9+1.5)=(7.4, 10.4). Another statistic is the coefficient of determination $R^2 = 0.80$ and the corresponding correlation coefficient R = +0.89. These statistics indicate that the linear relationship gives a fairly good description of the data. The matrix element values A_{UAV} and A_{SAT} in Appendix 1 and the corresponding values in Table 5 have been calculated from the linear relationship.

Figure 2 gives us a practical perception about error levels. Because of subjective evaluations and the small number of participants of the questionnaires no detailed analysis, and no detailed error analysis, is meaningful. After all, our main purpose is to demonstrate methods of model building. In Reference (Kuikka et al., 2015) we have presented standard deviation values of the questionnaire data. The results are consistent with the confidence level and the coefficient of determination statistics. The average capability values and the corresponding standard deviations of ten respondents are summarized in Table 4. The standard deviations are considerably higher compared to the previous confidence level estimation. The explanation is that they measure different uncertainties. Standard deviations describe individual points and higher standard deviations are a consequence of different levels of estimation among respondents. In the regression analysis, the confidence level describes the goodness of the regression line to predict the linear relationship between the two data sets. The confidence level approach is more appropriate for the situation at hand.

Table 4. The average Score values from Questionnaire 2 and the corresponding standard deviations (STD) in parenthesis.

	SAT, T=10 Score, (STD)	UAV, T=10 Score, (STD)
Deception (Prot)	1.11 (0.87)	1.53 (0.92)
Surveillance (Awa)	1.27 (0.88)	1.76 (0.74)
Engagement (Eng)	0.91 (0.83)	1.59 (0.86)

Figure 2 shows that the confidence interval close to the mean point (1.5, 10.0 %) is about 2.0 % and 4.0 % for the 90 % and 97.5 % confidence levels respectively. The confidence interval is wider for the values not close to the mean point. The confidence intervals can be used to observe the significant values in Tables 6 and 7. The last two columns in the tables show the 90 % and 97.5 % confidence level values (½*interval) and the significant changes on the confidence level 90 % are bolded in the Tables 6 and 7. The results indicate that the UAV capability changes are statistically significant on the 90 % confidence level except for the engagement capability change. The satellite capability changes are significant for the surveillance and communication capability changes on the 90 % confidence level except for the stealth technology. For the deception capability change the communication and autonomous technologies are statistically significant. These results are intuitively very understandable. (For comparison, the last column in Tables 6 and 7 show the 97.5 % confidence level thresholds. Interestingly, on the 97.5 % confidence level the surveillance capability changes for UAVs are not statistically significant.)

The uncertainties in matrix elements $D_{i,k}$ should be analysed with the help of standard deviations. Because of a small number of respondents (5) the standard deviations are very high. The standard deviations are $2^{1/2}$ times higher compared to the values in parentheses in Table 4. We can only make a rough estimate about the uncertainties: the errors are 30 % on the basis of one unit standard error (error in Tables 6 and 7 values is roughly 0.005).

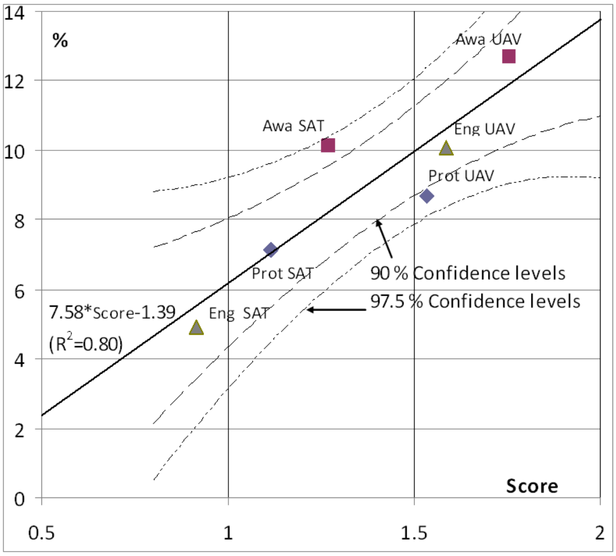

Figure 2. The relationship between Questionaire 1 (%) and Questionaire 2 (Score) data. The regression line and the 90 % and 97.5 % confidence levels are shown. The full set of parameters of the statistical analysis is presented in Appendix 2.

Numerical Results of This Study

The theoretical background has been presented earlier in this paper in section "Modelling the Interdependencies between Technology Areas". In this section the numerical results and some examples of applying the theory for different technology areas are presented. We show also how the results of this study can be combined with the results of our earlier studies.

In Table 5, the capability changes for UAVs and satellites for five operational tasks are calculated from Equation (5). The values correspond to the linear regression fit of Figure 2.

Table 5. The capability changes for UAVs and satellites from Equation (5).

	Surveil-lance	Communi-cations	Engage-ment	Logistics	Deception
UAVs	0.119	0.107	0.106	0.082	0.102
Satellites	0.082	0.094	0.055	0.051	0.071

In Tables 6 and 7, changes downward in percentages are given for UAVs and satellites (Note that because the model for interdependencies is linear, changes upwards are considered similarly). We illustrate the use of the tables by an example. According Table 6, if UAV sensor technology is not developing at all, while other UAV technologies develop as evaluated in Table 5, surveillance task capability of UAV system decreases from 11.9 % (Table 5 UAV Surveillance) to 9.1 % (11.9 % - 2.8 % = 9.1 %). This stands for 23.2 % relative decrease. The situational awareness value is the sum of the initial capability value (Table 3) and the change, for example in Scenario 1 the capability value is 85.2 % (0.8+0.085*(11.9/12.7)-0.028=0.852). Here, we have taken into account the adjusting between the regression line estimate 11.9 % (in Table 5) and the questionnaire result 12.7 % (in Tables 2 and 3), as we have concluded that the regression line approach eliminates some sources of error in the evaluations.

We provide one example how the errors can be evaluated. Based on the estimations in the previous section, the error estimation is roughly 0+0.2*0.085+0.3*0.028=0.025. The initial value has no error because the value 0.8 is defined in the scenario. As a result, the situational capability area value for Scenario 1 UAV systems in use is between 83 % - 85 % (82.7 % - 85.2 %) with no development in sensor technology. Other cases can be evaluated similarly.

Table 6. The decrease of task capabilities when no development occurs on one of the technology areas (UAVs).

Task/Technology	sensor	material	comm	stealth	energy	manuf	autom		$CL_{90\%}$	$CL_{97.5\%}$
Surveillance	**0.028**	**0.029**	**0.026**	**0.025**	**0.027**	**0.027**	**0.025**		0.019	0.032
Comm	**0.024**	**0.026**	**0.027**	**0.020**	**0.025**	**0.024**	**0.022**		0.015	0.024
Engagement	0.023	0.027	0.022	0.025	0.021	0.027	0.022		0.014	0.024
Logistics	**0.015**	**0.022**	**0.018**	**0.013**	**0.020**	**0.023**	**0.018**		0.012	0.020
Deception	**0.023**	**0.028**	**0.020**	**0.023**	**0.017**	**0.025**	**0.026**		0.013	0.022

Table 7. The decrease of task capabilities when no development occurs on one of the technology areas (satellites).

Task/Technology	sensor	material	comm	stealth	energy	manuf	autom		$CL_{90\%}$	$CL_{97.5\%}$
Surveillance	**0.022**	**0.017**	**0.019**	0.007	**0.019**	**0.020**	**0.016**		0.012	0.020
Comm	**0.021**	**0.022**	**0.023**	0.010	**0.022**	**0.021**	**0.017**		0.012	0.019
Engagement	0.014	0.013	0.012	0.006	0.014	0.015	0.012		0.021	0.035
Logistics	0.009	0.015	0.009	0.007	0.011	0.014	0.009		0.023	0.038
Deception	0.014	0.013	**0.019**	0.010	0.013	0.014	**0.018**		0.015	0.025

Analysing the values in Tables 6 and 7 gives an understanding of the level of dependency between technology areas and task capabilities when interdependencies between different technology areas have been taken into account. For example, UAV material and sensor technology has great influence on surveillance. This is an understandable result when we consider how the surveillance task is already enhanced by e.g. SAR (Synthetic Aperture Radar).

For UAV we observe also how the lack of development in material technology has a great effect on all the tasks except logistics. For satellites one observes how the logistics task is not sensitive on the development of sensor technology. It is interesting to see how the lack of development on stealth technology does not affect greatly to any of the UAV tasks and affects weakly to the satellite tasks. In general, the lack of development in any technology area affects more on the development of UAV than satellite capabilities.

If we examine the rows of Tables 6 and 7, we observe two main results. One is that UAV surveillance task is dependent on the development of the majority of the considered technology areas. The other is that the logistics task of UAV is weakly dependent on the majority of the technology areas development and almost independent for satellites.

In the following, we examine surveillance task. Similar results can be obtained for communication, engagement, logistics and deception operational tasks. Figures 3 and 4 show examples of calculations where multiple technology areas have different development behavior than evaluated in Table 5. In Figure 3, less than evaluated technological development, while in Figure 4 more than evaluated technological development, is occurring. Figure 3 is for UAV technologies and Figure 4 shows both UAV and satellite technologies for comparison. Curves are cumulative from left to right: curves at point “energy” have less development in energy technology and evaluated development (Table 5 values) in other technology areas, curves at point “sensor” have less development in “energy” and “sensor” and evaluated development in “comm”, “auto”, “stealth” and so on.

The choices 50 % and 10 % are representative examples for great and small deviations from the evaluated development. Any combinations of $\Delta_k, k = 1,...,7$ and their values can be calculated from Equation (8). The order of cumulative calculation is a choice representing a reliability of a system’s functioning which is another concept than dependency of technological developments. Energy, sensor and communication technologies are the most critical in this respect while material and manufacturing technologies have more profound influence on capabilities because of their enabling role with other technologies. Again, any order, combination or different values can be calculated from Equation (8). In calculating the simultaneous effects of multiple technologies the order of technologies does not change the results in the linear model of Equation (8). Service and technical characteristics is another classification of technologies (Windrum et al., 2009) and from the user point of view services appear more important than purely technical characteristics.

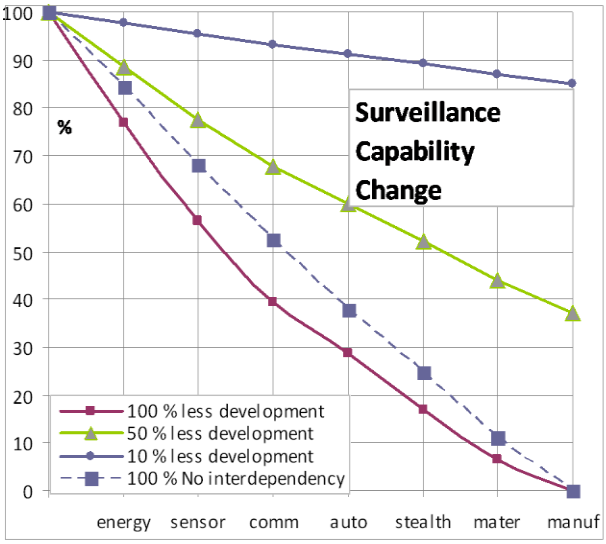

Figure 3. An example showing decreasing surveillance capability when more than one technology area has no development (100 % decrease), 50 % less or 10 % less development than evaluated in the questionnaire. Curves are for UAVs. As a comparison, the dotted curve for 100 % decrease has no interdependency between technology areas.

In Figure 3, the dotted curve shows the case where no interdependencies exist between technology areas. The effect of interdependencies can be more than 10 % when 100 % less (no development) development in more than one technology areas occurs. At point “autonomous technology” none of the technology areas have additional or less development compared to Table 5, so interdependency has no effect. If all technology areas have technology development as evaluated in Table 5, interdependency is already implicitly included in the data.

The application of Equation (8) and Figures 3 and 4 is when unexpected technical inventions and developments change existing information about developments in technology areas. On the other hand Equation (8) can be used as a method for sensitivity analysis of one or several technology areas. The curves 100 % in Figure 4 are only for a sensitivity analysis, because the linear equations are not valid for very large values. From the changed technology developments the effects on capabilities can be calculated as presented in (Kuikka & Suojanen, 2014, Suojanen et al., 2015 and Kuikka et al., 2015).

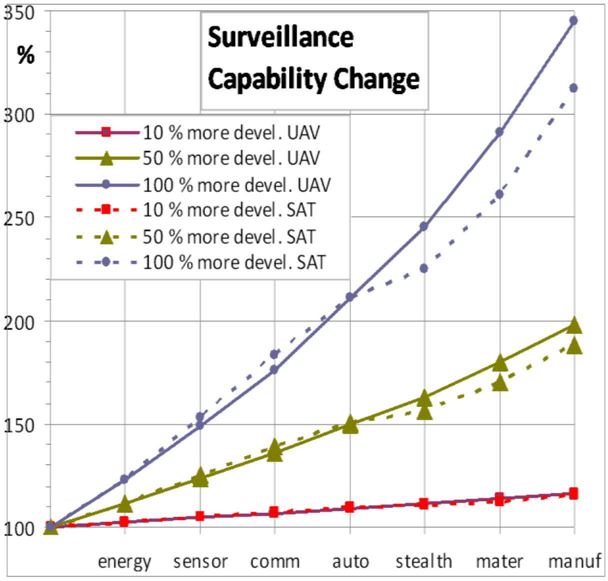

Figure 4. Same as Figure 3 but more development than evaluated in the questionnaire has been assumed. Curves are cumulative as in Figure 3. Solid curves are for UAVs and dotted curve are for satellites.

In Figure 5, we demonstrate the use of Equation (8) in a more complicated situation. In practice, this means we can allow any values for Δ_k we want and brings us closer to determining the total uncertainty (notice analogy to measurement uncertainty analysis). Developments in technology areas deviate from the initial values in Table 5 according $\Delta_k, k = 1,...,7$. For example, the first curve has $\Delta_1 = 0.8, \Delta_2 = 1.5, \Delta_{3,4,5,6,7} = 1.1$. Again, the curve shows cumulative effect of $\Delta_k, k = 1,...,7$ from left to right. Solid curves are for UAVs and dotted curves are for satellites. In Figure 5, significant differences in UAV and satellite surveillance capabilities can be observed. For example, satellites are more sensitive to sensor technologies and UAVs are more sensitive to stealth technologies.

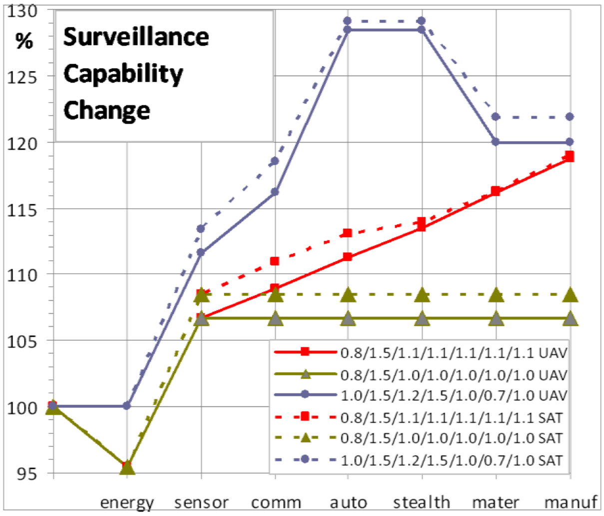

Figure 5. Examples of using the model with different technology area developments. In figure values of $\Delta_j,\ j=1,\ldots,7$ in Equation (8) are shown. Curves are cumulative in Δ_j. Solid curves are for UAVs and dotted curves for satellites. Values of $\Delta_j, j=1,\ldots,7$ are shown for each curve.

Conclusions

In this article, we have presented a process flowchart demonstrating how the developments in technology areas end up to capability area development (and beyond). We formulated mathematical methods in analyzing the intermediate steps of the process. While all the numerical results are computed by the methods in this / these article(s) it is important to notice that one is able to use alternative methods also; one of our main results in this work is to demonstrate the process itself.

On the system level our model makes use of system of systems principles. Satellites and UAVs have been assembled in parallel or in series with other systems. This idea can be compared with the ideas in Martino's more heuristic model. Other models, such as the analytical hierarchy process (AHP), require all the weights to be recalculated after a new system or task is added into the calculation. In our method, if no significant secondary effects exit, a new system can be added in serial or in parallel to an existing set of systems with a limited amount of recalculations (Kuikka & Suojanen, 2014).

We presented also a tool for estimating the interdependencies between technology areas. The numerical results are obtained from a questionnaire asked from 5 researchers. Results of the questionnaire have been presented for the first time in this paper. We show how the proposed method may be applied in conducting sensitivity analysis of the technology development. Our vision is to raise the sensitivity analysis of the technology development to the level that it has e.g. in the measurement technology. In this paper, we provide several examples of the use of the model for technological interdependencies and sensitivity analysis.

One is able to use the proposed method in analyzing the effects of unexpected technical inventions and developments. The analysis can be conducted by knowing the interdependencies of technology areas and to adjust the knowledge with the updated situation (e.g. more effective sensors etc.). Only rough conclusions can be made from results of the three questionnaires because of a small number of participants and uncertainties in human judgment. Nevertheless, the results can be used when the limitations are taken into account. The approach can be used in illustrating general impacts of various technological areas and their interdependencies. This can be used, for example, in balancing resource allocation between technological areas. The results show that material technology has the most widespread influence on other six technology areas examined. UAV material and sensor technology has a great influence on surveillance. This is an understandable result when we consider how the surveillance task is improved by radars and other sensors. Logistics task is not sensitive on the development of sensor technology in satellites. It is interesting to see how the lack of development on stealth technology does not affect greatly to any of the UAV tasks and affects weakly to the satellite tasks. In general, the lack of development in any technology area affects more on the development of UAV than satellite capabilities. As said, questionnaire data has been examined with the model and methods of this paper. More realistic results may be obtained with system modelling or simulation results as input data instead of questionnaires.

We demonstrated how to extrapolate impacts of technology changes on capabilities with a linear model. This does not take into account possible disruptive or threshold effects. If a threshold and its impacts on the technological areas are known a non-linear variant of the model is a straightforward extension of our work. On the other hand, disruptive changes are unpredictable and their timing and effects are difficult or impossible to model.

In our literature review we have made some observations about similarities and differences of methods and models when comparing with our approach. Modelling capabilities is usually based on scoring or other measures with no quantitative interpretation. Our model has an exact interpretation: capability is defined as the probability of success. In the modelling we have concluded that a minimal taxonomy includes capability areas, systems of systems and technology areas. These all have their internal models and interdependencies. Especially, modelling technological interdependencies appears to be a complex task. A basic linear deterministic model has been presented in this paper. The model can be compared with the stochastic correlation matrix of statistics. The correlation matrix is symmetric while the model proposed in this paper allows different values for dependencies depending on the direction of the association.

In our modelling scenarios are used in modelling capability areas while scenarios are not used in modelling technological areas. This simplifies the questionnaires and the modelling efforts. A comparable approach has been presented in (Urwin et al., 2010) where the measures of performance are independent of an operational scenario and allow the results to be compared with systems that provide the same functionality.

References

Gediminas Adomavicius, Jesse C. Bockstedt, Alok Gupta, Robert J. Kauffman (2005). Technology roles and paths of influence in an ecosystem model of technology evolution, *Information Technology and Management*, Vol. 8, Issue 2, 185-202.

Muhammad Amer, Tugrul U. Daim, Antonie Jetter (2013). A review of scenario planning, *Futures* 46, 23-40.

Patrick T. Biltgen, Dimitri N. Mavris (2007). *Capability-based quantitative technology evaluation for systems-of-systems*, IEEE System of Systems Engineering Conference.

Anelí Bongers, José L. Torres (2014). Measuring technological trends: A comparison between U.S. and U.S.S.R./Russian jet fighter aircraft, *Technological Forecasting & Social Change*, Vol. 87, 125-134.

Robert F. Bordley, Stephen M. Pollock (2009). A decision-analytic approach to reliability-based design optimization, *Operations Research* 57, 1262-1270.

Sean Bourdon, Benoit Arbour, Matthew R. MacLeod (2014). A method for hierarchically prioritizing capabilities with an application to military manned and unmanned aerial vehicles, *Journal of Applied Operational Research* 6(1), 39-47.

Carolina Castaldi, Roberto Fontana, Alessandro Nuvolari (2009). The evolution of tank technology, 1915-1945, *Journal of Evolutionary Economics* 19(4), 545-566.

Mario Coccia (2003). *An approach to the measurement of technological chance based on the intensity of innovation*, Ceris working paper.

Mario Coccia (2005). Technometrics: Origins, historical evolution and new directions, *Technological Forecasting & Social Change* 72, 944-979.

Metin Dagdeviren, Serkan Yavuz, Nevzat Kilinc (2009). Weapon selection using the AHP and TOPSIS methods under fuzzy environment, *Expert Systems and Applications* 36, 8143-8151.

Jan van den Ende, Wilfred Dolsma (2002). *Technology push, demand pull and the shaping of technological paradigms – patterns in the development of computing technology*, ERIM report series ERS-2002-93-ORG.

Koen Frenken, Loet Leydesdorff (2000). Scaling trajectories in civil aircraft (1913-1997), *Research Policy* 29(3), 331-348.

Koen Frenken (2006). Technological innovation and complexity theory, *Economics of Innovation and New Technology* 15(2), 137-155.

Paul Goodwin, George Wright (2010). The limits of forecasting methods in anticipating rare events, *Technological Forecasting & Social Change* 77, 355-368.

Jan G. De Gooijer and Rob J. Hyndman (2006). 25 Years of Timer Series Forecasting, *International Journal of Forecasting*, 22 (3), 443–473.

Theodore J. Gordon, Thomas R. Munson (1981). A proposed convention for measuring the state of the art of products or processes, *Technological Forecasting & Social Change* 20, 1-26.

Juhani S. Hämäläinen, Juha-Pekka Nikkarila (2015). *Analyzing Strategy Effectiveness With Resource Profit Ratio Integrals*, ISMS Conference.

Andrew D. James (2013). *Emerging technologies and military capability*, RSIS / Policy Briefs, Retrieved 10.10.2015 from http://www.rsis.edu.sg/search/?q=andrew+james.

Jiang Jiang, Xuan Li, Zhi-jie Zhou, Dong-ling Xu, Ying-wu Chen (2011). Weapon system capability assessment under uncertainty based on the evidential reasoning approach, *Expert Systems with Applications* 38, 13773-13784.

Byoung Soo Kim (2012). Measuring technological change – concepts, methods, and implications in *Technological Change*, Aurora Teixeira (Ed.), Retrieved 10.10.2015 from http://www.intechopen.com/books/howtoreference/technological-change/measuring-technological-change-concept-methods-and-implications.

Vesa Kuikka, Juha-Pekka Nikkarila, Marko Suojanen (2015). *A technology forecasting method for capabilities of a system of systems*, PICMET Conference.

Vesa Kuikka, Marko Suojanen (2014). Modelling the impact of technologies and systems on military capabilities, *Journal of Battlefield Technology*, Vol. 17, No. 2, 9-16.

David M. Levine, Mark L. Berenson, Timothy C. Krehbiel, David F. Stephan (2010). *Statistics for Managers Using MS Excel*, 6th Edition, Pearson, Chapter 13 Retrieved 10.10.2015 from http://www.prenhall.com/behindthebook/0136149901/pdf/Levine_CH13.pdf.

Joseph P. Martino (1993). *Technological Forecasting for Decision Making*, McGraw-Hill, Inc., McGraw-Hill Engineering and Technology Management Series.

Johann Peter Murmann, Koen Frenken (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change, *Research Policy* 35, 925-952.

Pier Paolo Saviotti, Adreas Pyka (2013). The co-evolution of innovation, demand and growth, *Economics of Innovation and New Technology* 22(5), 461-482.

P. P. Saviotti, G. S. Mani (1995). Competition, variety and technological evolution: a replicator dynamics model, *Evolutionary Economics* 5, 369-392.

Antoine Schoen, Lionel Villard, Patricia Laurens, Jean-Philippe Cointet, Gaston Heimeriks, Floortje Alkemade (2012). *The network structure of technological development; technological distance as a walk on the technology map*, Science & Technology Indicators (STI).

Johan Schot, Frank W. Geels (2007). Niches in evolutionary theories of technical change – A critical survey of the literature, *J. Evol Econ*, Vol. 17, 605-622.

Seunghwan Oh, Sungmoon Jung, Jaemin Park, Chang Sun Kim (2013). Measuring technology level on a mixed model: A case of Korean photovoltaic technology, *International Journal of Digital Content Technology and its Applications*, Vol. 7, No. 13.

Jiyeon Ryu, Soon Cheon Byen (2011). Technology level evaluation methology based on the technology growth curve, *Technological Forecasting & Social Change* 78, 1049 – 1059.

Marko Suojanen, Vesa Kuikka, Juha-Pekka Nikkarila, Jari Nurmi (2015). *An example of scenario-based evaluation of military capability areas – an impact assessment of alternative systems on operations*, IEEE International Systems Conference.

Esmond N. Urwin, Colin C. Venters, Duncan J. Russell, Lu Liu, Zongyang Luo, David E. Webster, Michael Henshaw, Jie Xu (2010). *Scenario-based design and evaluation for capability*, 2010 5th International Conference on System of Systems Engineering.

Paul Windrum, Cecilia Diaz, Despoina Filiou (2009). Exploring the relationship between technical and service characteristics, *J Evol Econ* 19 567-588.

Elizabeth Jones Wyatt, Kelly Griendling, Dimitri N. Mavris (2012). *Addressing interoperability in military systems-of-systems architectures*, Systems Conference.

Charles Zaiontz (2015). Real Statistics Using Excel, Retrieved 10.10.2015 from http://www.real-statistics.com.

Appendix 1

We have used the same relationship between scores and probability values (capabilities) as in our previous paper:

Capability = 0.0758**Score*-0.0139. (9)

Scores 0, 1, 2 and 3 have been used in evaluation because probability values are more difficult to estimate. Equation (9) has been derived from the first and second parts of the questionnaire with the help of the fact that the same answers have been given as probabilities and as scores in these two parts of the questionnaire. In Table 1, these are the cases for satellites and UAVs for 10 years development with three capability areas identified with corresponding three tasks: protection with deception task, situational awareness with surveillance and engagement with engagement task. This is justified by the fact that in the second part of the questionnaire general tasks were evaluated with no direct connection with scenarios of the questionnaire. In other words, results concerning task capabilities are averages over three scenarios of the questionnaire.

Matrixes used in calculations for UAVs and satellites. Matrix A gives the relationship between technology areas and tasks. Matrix D gives the interdependency between technology areas. Equation (9) is used in transformation from scores to probabilities (capabilities). Note that the columns and rows are arranged in the same order than in Tables 6 and 7.

$$A_{UAV} = \begin{pmatrix} 0.138 & 0.115 & 0.107 & 0.062 & 0.107 \\ 0.115 & 0.107 & 0.107 & 0.100 & 0.123 \\ 0.130 & 0.145 & 0.107 & 0.085 & 0.087 \\ 0.107 & 0.077 & 0.123 & 0.039 & 0.107 \\ 0.130 & 0.123 & 0.092 & 0.100 & 0.062 \\ 0.092 & 0.077 & 0.100 & 0.100 & 0.092 \\ 0.123 & 0.107 & 0.107 & 0.092 & 0.138 \end{pmatrix}$$

$$A_{SAT}=\begin{pmatrix} 0.123 & 0.107 & 0.069 & 0.039 & 0.069 \\ 0.062 & 0.096 & 0.047 & 0.077 & 0.054 \\ 0.107 & 0.130 & 0.062 & 0.047 & 0.107 \\ 0.032 & 0.047 & 0.024 & 0.032 & 0.054 \\ 0.085 & 0.100 & 0.062 & 0.047 & 0.047 \\ 0.085 & 0.085 & 0.062 & 0.069 & 0.054 \\ 0.085 & 0.092 & 0.062 & 0.047 & 0.107 \end{pmatrix}$$

$$D_{UAV}=\begin{pmatrix} 1.000 & 0.168 & 0.016 & 0.077 & 0.092 & 0.153 & 0.107 \\ 0.047 & 1.000 & 0.107 & 0.123 & 0.062 & 0.123 & 0.016 \\ 0.092 & 0.077 & 1.000 & 0.062 & 0.107 & 0.123 & 0.123 \\ 0.077 & 0.198 & 0.077 & 1.000 & 0.047 & 0.153 & 0.062 \\ 0.032 & 0.123 & 0.047 & 0.092 & 1.000 & 0.123 & 0.047 \\ 0.062 & 0.138 & 0.062 & 0.062 & 0.092 & 1.000 & 0.092 \\ 0.168 & 0.047 & 0.153 & 0.123 & 0.123 & 0.123 & 1.000 \end{pmatrix}$$

$$D_{SAT}=\begin{pmatrix} 1.000 & 0.198 & 0.092 & 0.032 & 0.107 & 0.153 & 0.062 \\ 0.047 & 1.000 & 0.016 & 0.092 & 0.062 & 0.123 & 0.077 \\ 0.092 & 0.062 & 1.000 & 0.062 & 0.107 & 0.092 & 0.016 \\ 0.032 & 0.047 & 0.047 & 1.000 & 0.032 & 0.077 & 0.016 \\ 0.032 & 0.107 & 0.016 & 0.000 & 1.000 & 0.123 & 0.047 \\ 0.077 & 0.123 & 0.062 & 0.032 & 0.123 & 1.000 & 0.092 \\ 0.107 & 0.032 & 0.092 & 0.032 & 0.092 & 0.077 & 1.000 \end{pmatrix}$$

Table 8. Representative values of parameter Δ_k, $k=1,\dots,7$ used in calculations.

$\Delta_k = 0$	No development in technology area *k*.
$\Delta_k = 1$	Same development in technology area *k* than in Table 5.
$\Delta_k = 1.1$	10 % more development in technology area *k* than in Table 5.
$\Delta_k = 1.5$	50 % more development in technology area *k* than Table 5.
$\Delta_k = 2$	100 % more development in technology area *k* than Table 5.
$\Delta_k = 0.9$	10 % less development in technology area *k* than in Table 5.
$\Delta_k = 0.5$	50 % less development in technology area *k* than in Table 5.

Appendix 2

Table 9. Statistical analysis of Figure 2 with full set of parameters is outlined in the table. On the left, the 10 year input data from questionnaires Q1 (%) and Q2 (Score) are shown. The confidence interval (lower, upper) is calculated at point x_0 = 1.5 to show the idea of calculating the 90 % confidence level curves in Figure 2. The Excel worksheet used in the calculations is available from (Zaiontz, 2015).

Confidence Intervals						
Score (x)	% (y)		**Confidence interval for the forecasted value**			
0.91	4.93					
1.11	7.13		n	6		
1.27	10.10		df	4		= n - 2
1.53	8.70		mean(x)	1.36		= AVERAGE(x)
1.59	10.07		x_0	1.5		
1.76	12.70		$\hat{y}_0$	9.979881		= FORECAST(y,x,x_0)
			s_{Res}	1.329159		= STEYX(y,x)
			SS_x	0.505552		= DEVSQ(x)
			se	0.600268		= s_{Res}*SQRT(1/n+(x_0-$\bar{x}$)^2/SS_x)
			t-crit	2.131847		= TINV(0.10,df)
			lower	8.700201		= $\hat{y}_0$ - t-crit * se
			upper	11.25956		= $\hat{y}_0$ + t-crit * se