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Modelling & Data Fusion to support Acquisition in Defence

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Abstract

The Ministries of Defence (MoDs) are used to deal with the obsolescence of their legacy systems and assets while replacement are delayed usually due to financial reasons. On the other hand, they must also face evolving high-intensity threats and challenges. Innovative technologies and systems shall then be integrated with legacy assets, to upgrade military capabilities.
In order to support the decision-makers in the aforementioned process, there is the need to create tools capable of providing the required support. These tools shall be able of handling a large number of different types of data, coming from various sources. This work provides an extensive review of the state-of-the-art methodologies in the domain of cost, performance and risk analysis, and information and data fusion. Finally, the ones potentially capable of providing the best decision-support to MoDs are proposed.

Keywords: Cost Performance-Risk Assessment, Data Fusion, Procurement Process, Defence, Homeland Security

1. Introduction

The importance of innovation in the defence and security field is greatly expressed by US retired general Martin Dempsey who stated: "My greatest concern is that we will not innovate quickly or deeply enough to be prepared for the future, for the world we will face 2 decades from now. ... the true risk is that we will fail to achieve the far-reaching changes to our force, our plans, our posture, our objectives, and our concepts of warfare." [1]

The defence and security sectors have always been considered among the most significant aspects both from a socioeconomic as well as from a geostrategic perspective for any nation, political union, international alliance, or military organization.

Nowadays, the framework used to conduct the procurement process in these domains is becoming more and more ineffective due to the emerging threats and new technologies. So, there is the need to create a tool capable of supporting decision makers during all the phases of the process.

Defence and security aim to reduce the possible risks related to new and emerging crises. To achieve this, it is needed to address not only the security and defence environment, but also the economic and social spheres need to be considered. The technological development is happening at an ever-increasing speed allowing state and non-state actors to get more powerful and disruptive weapons. Hence, nations need to improve their research speed and innovate the current defence sector. One of the effects of this technological advancement is the occurrence of new types of conflicts like the ones in the cyber domain, that are becoming more and more effective especially in Western countries. [1] However, governments all around the world nowadays tend to spend less money in defence, due to the limited resources available, so there is the

need to better invest in order to increase security and be ready to deal with emerging threats. Therefore, there is the need for tools able to provide the required support, to choose, under constraints of limited resources and time, between many alternatives that are often undetermined over a number of dimensions. Such tools shall be capable of handling a large number of different types of data coming from diverse sources.

MoD Acquisitions are strongly relying on the use of innovative methodologies including modelling and AI, in facts US DoD promoted the development of innovative approaches leading to the development of System of Systems Engineering, while within Europe UK was among the first ones to follow, by adopting concepts such as SBA (Simulation based Acquisition) for supporting new programs.[3], [4], [5], [6], [7], [8]

The main goal of this work has been to review and identify the most suitable methodologies and approaches for performing Cost Performance and Risk (CPR) Assessment, and Information and Data Fusion, as key tools to support decision-makers involved in the procurement process for security and defence.

2. State of the Art Review

The objective of a Cost-Performance-Risk (CPR) analysis is to have a complete picture of cost, performance and risk of a project or a technology. This analysis is really useful in the decision-making process. In particular, the cost analysis provides information about the cost of a project, from the very beginning to final phases, including a complete study of all parameters that could affect the overall cost of the project. Hence, the cost analysis refers also to the life cycle cost of a particular system. Cost analysis is a technique that weights and compares costs and benefits of a Course of Action (CoA). Performance analysis provides parameters about the overall execution of the program. It involves systematic observations to enhance performance and improve decision-making. It is based on identifying Key Performance Indicators (KPIs) which provide an objective measurement parameter and an indication of how certain systems or elements of system work. Risk analysis allows for better understanding of all possible parameters for which a project might fail or might get delayed and is probably the most important assessment because of the uncertainty factor that a system must deal with. This analysis can compare different alternatives and solutions, identifying factors, conditions and system components that are critical with respect to the risks. It also provides a demonstration of the effect of various mitigation policies, with respect to each risk, that must be performed to satisfy regulatory requirements and to enable risk-based decision-making support. CPR analysis enables Decision Makers (DMs) to identify the parameters of each problem, in order to analyse them and obtain outcomes that can facilitate the decision-making process. [9], [10], [11]

In many and diverse fields there is the need to estimate parameters based upon different elements that could come from different sources. In order to facilitate the process of acquisition and merging of different data, the Data Fusion methodology is introduced. [12], [13] Data fusion has been defined as a challenging task for many reasons. Firstly, some data is generated from sources that create values based upon many processes and variables which we do not have access to. Secondly, the scope of the research question can be very large. Then, it can be incredibly difficult to find a way for exploiting the advantages of each of the dataset used and, at the same time, suppress the respective drawbacks. [14]

The goal of the following literature review is to analyse in detail the most commonly used methodologies concerning cost, performance, and risk assessment, and information fusion.

2.1. CPR Assessment Methodologies

Real Option Valuation: in order to evaluate the possible costs, performances, and risks of a technology, NASA classified the maturity of a technology through their Technology Readiness Level (TRL). Real Options Valuation is a methodology based on models which are used to value financial instruments and projects. The "real option" concept is basically conceptualized as the value of alternatives from active management and strategic interactions. The options are created to evaluate the chance of abandoning a project and not making a follow-on investment after the initial one. [15] Real options valuation approach is based on the following equation:

$$v(t,T) = e^{(-r(T-t))}E\left[\max\left(0, W(T)\right)\right] \qquad (1)$$

The value v of a real option that pays off $W(T)$ at time T is calculated. E denotes the expected value in a risk-neutral world, r is the riskless discount rate, and t the current time. [16]

Cost-Benefit (CBA) & Cost-Effectiveness (CEA) Analysis: CBA is an approach to measure the benefits and costs of a project. It is a supporting tool used to seek questions about the direct and indirect economic effects of project proposals. To deal with this method there is the need to transform all attributes in monetary values for performing the expected Net Present Value. If there is the need to deal with qualitative data, it will be necessary to perform CEA. This approach refers to the evaluation of alternatives according to both their costs and their effectiveness in producing certain outcomes. A modified version of the Cost-effectiveness approach is widely used in the NATO environment. The value of effectiveness is obtained by determining the principal attributes of Measure of Performance and Measure of Effectiveness, converting them to a single Figure of Merit. Graphically, performances are compared to costs. This is done by taking into account the uncertainty related to weights, scoring, and cost. [16]

Failure Modes and Effect Analysis (FMEA): it is an inductive method which, for each component of the system, investigates what happens if a component fails. It examines the components one by one, assuming the perfect functioning of the others. The analysis gives a complete representation of all possible failure modes and how they can affect the system's performance. [9]

Fault Tree Analysis (FTA): It is a logical diagram that shows the relationship between system failures. The 'top event' is the undesirable event and the different component failures are the 'basic events', which are not just mere technical failures, but can refer also to human errors or external conditions. [9]

M5 Model Tree: This approach is analogous to a piecewise linear function. M5 model trees have an advantage over regression trees with respect to compactness and prediction accuracy, due to the ability of model trees to exploit local linearity in the data. M5 model tree algorithm is optimized to both learn known cases and predict unknown cases. It is also smaller, easier to understand, and its average error value on the training data is lower than other methods. It can determine the right set of independent variables by construction. This approach is useful even when little data is available and provides great results from large data sets dealing with both quantitative and qualitative variables. [17]

Development Of a Risk Assessment methodology to Enhance security Awareness in Air Traffic Management (ATM) (DORATHEA): it is composed of three top-down iterative processes which perform the hazard assessment, the preliminary security assessment, and the overall security assessment. The top-down approach is used to perform the classification of the risk according to the likelihood of occurrence and the impact level. The estimation of the Security Risk is given by the combination of the likelihood of a given security hazard (L_{sh}) and the impact of its consequence on the system (I_c):

$$Security\ Risk = L_{sh} * I_c \qquad (2)$$

The risk is then classified through a scheme which combines the likelihood of occurrence with the class of the impact. [18]

2.2. Data Fusion Methodologies

Particle Filter: it is a recursive implementation of the sequential Monte Carlo method. This method is used to analyse complex systems and it provides better result for non-linear systems with a non-Gaussian noise. This technique creates the posterior density function using a large number of random particles that are propagated over time with a combination of sampling and resampling. At each iteration, the sampling step is used so that some particles are discarded to increase the relevance of regions with higher posterior probability. The estimation is the result of weighted sum of all the particles; the weights associated to the particles represent the quality of the particles. [12], [19]

Bayesian theory: it is a probability theory, and it defines the probability of an event that might happen under the condition of another event. In information fusion it provides a method for combining evidence according to the probability theory rules. In this method, uncertainty is represented by the conditional probability term that stands for the beliefs and can assume values between zero and one. Zero means that there is completely lack of belief, while one means that the event will happen. [12], [19]

Aggregation Operators: these operators refer to mathematical functions that are used for information fusion; they combine values and return a single value in the same domain. These types of operators are parametric, meaning that additional knowledge on the sources, like background knowledge, can be considered in the fusion process. Mathematical functions that are part of this category are, for example, the Arithmetic Mean, the Weighted Mean, Bajraktarević's Means, but there are many others. [20]

Clusters ensembles: it is a method that has been widely used in cases in which overlap regions are allowed among clusters. The aim of cluster ensemble is to combine different classifiers or clusters to improve the performance of measure metric. So, it applies ensemble learning theory that generate the final result by fusing multiple different clustering results either from the same cluster with different initial values or from different clustering algorithms. [21]

Probabilistic Linguistic Preference Relation (PLPR): this methodology is applied in the case of Group Decision Making and can deal with ignorance information. It provides a normalization method consisting of optimistic, pessimistic, and neutral mechanisms. Moreover, it is implemented as a consensus-driven model so that the maximum group consensus is achieved and simultaneously the consistency level is maintained. [22]

Neural Networks (NNs): The 'Network' refers to the inter-connections between 'neurons' distributed across different layers of each system. The system needs to be trained, like other machine learning systems, to be able to give a correct estimation of the outputs. During training, weights are used to manipulate the data in the calculation. Yet, it is fundamental to establish the correct activation function that converts a weighted input into its output. The training focuses on examples, that the system has to learn from, to be able to manage inputs, classify them, and finally process them for the final result. In the risk assessment field, NN are used to generalize and associate data to find acceptable outcomes against uncertainty in the input data. [23] NNs are a quite effective method for data fusion because of their fast calculation speed, fault tolerant ability, and good performance of classification. [24]

3. Analysis of the methodologies

The methodologies are analysed taking into account the type of data on which they would have to work in the defence and security acquisition.

Given that there is the need to assess together cost, performance and risk, the methodologies that should be considered are the ones which can combine all the parameters. For this reason, Real Option Valuation, CEA, M5 Model Tree seem to be the most complete methodologies. In particular, since the capability of Real Option Valuation to completely analyse all the different options and their relative outcomes, it could be combined with CEA to analyse in detail the costs of an option in relation with its effectiveness and the risk associated. The arbitrary internal representation of M5 Model Trees means that there can be variations between networks trained on the same data. In comparison with NNs, the M5 system is transparent, and the model tree construction is repeatable. In addition, DORATHEA is really useful when dealing with risk assessment. It appears as a complete tool, which aims to take into account all possible risks related also with human error. On the other hand, FTA and FMEA can be useful only when dealing with failures, so they need to be integrated with other methodologies in order to perform a CPR assessment.

Regarding Data Fusion, some of the methodologies analysed have to be discarded. Particle Filter, despite being able to deal with nonlinear dependencies and non-Gaussian densities in the dynamic model and in the noise error, has significant drawbacks. For instance, it requires a large number of particles to obtain a small variance in the estimator, and that affects the computational cost significantly. Moreover, this methodology is typically used to deal with filtering problems, which is not the type of issues present in the procurement process. Clusters Ensembles could be taken into consideration, but Ministries of Defence may not have the full set of information available about the procured equipment, which is needed to compare and classify information. On the other hand, the Bayesian theory could be used to compute probabilities regarding the CPR assessment. Aggregation Operators could be very useful to simplify the procurement process, given their simplicity and ease of development. They could be used in many scenarios. As an example, the Weighted Means could be used in the CPR process to fuse together the values of cost, performance, and risk, by taking into account the preference of the user through weights. Moreover, if experts are involved in the acquisition, PLPR could be considered to take into account their opinions.

NNs are probably the most complete methodology because with them it is possible to create ad hoc solution depending on which type of data they are expected to work on, or which type of task they are expected to accomplish. They can be used to create solutions for both the CPR Assessment and Data Fusion.

4. Conclusions

The proposed approaches consider how to use Strategic Engineering in this field and get benefits of previous research in this area and existing models. This work highlights potential methodologies devoted to support the whole procurement process as well as the model structure to be used to deal with it.

As mentioned, through a combination of approaches it could be possible to have a more complete picture of the CPR Assessment. Concerning Data Fusion, the methodologies analysed could be suitable to fuse a huge amount of various types of data, providing support for a more advanced procurement process in the defence and security fields. Moreover, data fusion techniques could also be used to aggregate data generated by cost, performance, and risk analyses methodologies.

Future research work will explore combinations of approaches to provide a unique methodology capable of performing a whole CPR Assessment. Also, the most suitable and powerful data fusion methodologies will be explored in detail to demonstrate their potential benefits to the procurement process.

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