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Prediction of requirements engineering using a multi scale probabilistic approach: case study FFG(X) combat ship

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By

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Prediction of requirements engineering using a multi scale probabilistic approach: case study FFG(X) combat ship

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Requirements engineering in a system-engineering project is a key factor in the success of a project. In the current state, stand-alone research has been conducted tackling this area, however, few studies addressed the requirements based on a probabilistic approach. In this thesis, a multi-scale probabilistic approach has been developed, named Bayesian Network, to evaluate the requirements engineering of a complex systems In order to pursue the aim of this paper, the FFG(X) navy ship is chosen to serve as a case study and to validate the proposed model. Results indicate the sub-requirements that highly affect the FFG capability/performance. These sub-requirements are: 1) guns, 2) ballistic missiles, 3) anti-submarine, and 4) radar.

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"To believe in an ideal is to live it till the end."

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CHAPTER 1

INTRODUCTION

In 1980, different organizations all over the world faced several challenges related to product quality and performance. Then in the 1990s the pressure on costs, the capacity for innovation and deadlines were added to these challenges. The need to speed up the design process between the client and its supplies progressively necessitates the adoption of collaborative platforms. These platforms essentially allow the sharing of structural and physical data of the system as well as the project data, but not the requirements. Nowadays, these environments are no longer needed thanks to the provision of digital communication between entities. Innovation provided a significant management system dedicated to changes. Another issue detected was the waste of time in identifying and predicting requirements. To solve this issue, requirements engineering is an approach which implement all the components necessary for the prediction and management of the effects associated with the control or non-control of the requirements. Therefore, it relates the object, the manner of producing it, and the benefits obtained for it. Requirements engineering consists of two concepts: 1) requirements and 2) engineering. Engineering refers to the branch of science that focuses on solving daily life problems using technology (Sheppard et al. 2007). While requirements are the formalization of needs taking into account internal and external sources in their contexts. However, requirements and needs are two different things. According to the International Institute of Business Analysis, the requirement is capability required by stakeholders to resolve the undesired condition or achieve a goal. On the other hand, a need is simply a purpose. By definition, one needs consists of one or more requirements, while those requirements do not depend solely on the customer voice. Requirements might be generated from the service function as well as from specific standards that must be respected originated from major risks and business rules. Therefore, requirements engineering is the process during which these requirements will be clarified and transformed throughout the design of a project. The scientific literature refers to this concept of requirements engineering and defines it as the purpose of determining and defining the requirements. Another concept involved in complex systems is capabilities-based project. The intent of these type of projects is to meet the capabilities needed to achieve certain goals. The issue consists of predicting those capabilities and matching them with the appropriate requirements. Based on IBM, there is a significant relationship between requirements and capabilities; every requirement is matched with a specific capability. According to the literature, there is a significant lack on the prediction of capabilities in complex systems.

1.1 Problem statement

The observation reported in 2005 by the Standish Group in its famous reports "Chaos" is without appeal: one of the main causes of these difficulties results directly or indirectly from poor consideration of requirements. A hypothesis then becomes generalized: the more the problems are identified and dealt with upstream, the less costly it is to solve them (Jorgensen, 2006; Glass, 2006). Within the practice of complex systems engineering, there is a lack of comprehensive models to predict, evaluate, and select requirements. For instance, the Body of Knowledge (BoK) is prevalent with models to measure system-level requirements, but there is scant evidence that demonstrates successful creation and implementation of models to address this problem within a complex system level. This gap in the BoK is echoed in practice, particularly within the Defense and Aerospace sector. Addressing this problem at this level cannot be a mere extension of the system level solution, because the number of requirements and degree of complexity is increased significantly. This research aims to develop a unique capability requirement model that can be continuously applied across the life cycle of a complex system.

1.2 Literature survey

In this section, two folds are presented. First, we outline the existing literature about requirements engineering and capability requirements. Second, this section presents the Bayesian network as a decision-making tool

1.2.1 Systems Engineering

Today, systems engineering is experiencing a new crisis like that experienced by computers in the 1990s (Suh, 2016; Jackson, 2010). Companies can no longer keep up with cost constraints and delays, and early versions of the system suffer from a considerable lack of maturity. This is why Weck et al. (2011) identified the need for a new systems engineering that we call: Systems engineering of complex socio-technical systems. The current systems resulted from the integration of complex technical systems. For instance, the integration of the complex transportation system and the complex communication system has given rise to the complex GPS system. The integration of the complex transportation system and the complex electrical system has given rise to the complex system of electric vehicle systems. Furthermore, these systems are no longer purely technical. This new engineering field must allow engineers to design solutions that take into account long-term social effects. For example, the System of Systems (SoS) corresponding to the electric vehicle network addresses the problem of sustainable development. System engineering, which includes requirements engineering, is a collaborative and interdisciplinary scientific method dedicated for industry. Requirements Engineering (RE) is anchored in this challenge: reducing the frequency and amplitude of system development problems by applying upstream technical methods and tools which guarantee - by their systematic dimension - better consideration of requirements in the systems development. The proper management of system requirements is a key factor in the success of an industrial project. A normative or even legislative framework, constraining the system in its design and its exploitation during its life, often carries these requirements. Compliance with standards, certification, regulatory bodies, economic, political, historical, environmental contexts are all factors impacting a system as a whole, and for what interests us, the requirements that define it.

1.2.2 Requirements Engineering

1.2.2.1 Definition

Requirement, known also as “system requirement”, is defined as “a statement which prescribes a function, an aptitude or a characteristic which it must satisfy a product or a system in a given context" (Scukanec et.al, 2007). The requirements, therefore, translate the needs and the expected properties of the system, which will thus constrain the design of the solution. The first reference to the need for requirements engineering actions was made in the mid-1970s. According to Bell et al. (1976) "the requirements for a system do not arise naturally; instead, they need to be engineered and have continuing review and revision." RE was then recognized as a discipline in the mid-1980s, since then, a large number of methods and languages have been proposed (Lamsweerde, 2000). Requirements engineering is an engineering process that can be described in several tasks. The breakdown proposed by Cheng et al. (2008) results in stages of elicitation, modeling, analysis, validation and verification and finally management. An overview of the field shows that it is a particularly complex subject: It is a multidisciplinary subject, with an important human factor. Moreover, it is considered as an unstable space, subjected to high variability during the development and operation. Finally, there is no comprehensive approach towards the subject.

1.2.2.2 Capabilities Engineering

Capability can be defined as the ability of a training, system or process to generate a given performance to produce a desired effect. It is necessary to be taken into account for an efficient use of the available resources. A holistic analysis of capability requirements assesses the ability to produce results that meet customer requirements. To adequately estimate the capability of the current process and obtain a reliable forecast of the capability of the process in the future, the data must come from a stable process (Bothe, 1991; Kotz, 2002). In general, complex systems result from the collaborative operation of constituent systems which can work autonomously to fulfill their own operational mission. Its aim is to obtain additional operational capabilities by assembling constituent systems, while benefiting from the emergences due to their synergy. According to Lane (2012), capability engineering beginning with comprehending the wanted capability and determining ways to reach the specified capability. Capabilities have paramount importance in the military domain especially in the defense area (Henshaw et al. 2011). Capability engineering belongs to the defense industry. This notion is nowadays employed in other different industries that deal with complex systems such as communication, automotive, etc. By reviewing the literature, it has been noticed that the capability engineering discipline did not get much attention.

1.2.2.3 Requirements Management Process

The requirement management process is useful not only for tracing requirements but also for managing the changes applied to the requirements repository. A requirements management execution plan, in which the requirements are organized in a tree structure, is initially created. Each of the requirements is then traced to a requirement belonging to the higher system level. During the requirements management process, it is important to ensure that each of the requirements is validated. This means that it results directly or indirectly from an expectation of a stakeholder. In addition, each of the requirements must be verifiable. A verification method such as simulation, inspection, etc., is needed to verify if the design meets the requirements. Finally, when the requirements are at an acceptable level of maturity, they must be frozen in a reference configuration, which serves as a benchmark for evaluating and executing change requests. Maintaining consistency between operational scenarios, requirements and architectures guarantee the smooth running of the process. The requirements management consists of three processes: (1) the process of defining stakeholder expectations; (2) the technical requirements definition process; and (3) the requirements management process (NASA, 2007). The process of defining stakeholder needs begins with the identification of stakeholders. These are then concerted in order to define the mission, objectives and, criteria for verifying the system. This process should lead to an operational definition of the system answering the question: What should users be able to do with the system? The process of defining technical requirements transforms stakeholder expectations into a set of requirements that the system must meet. These requirements are then derived from the subsystems, recursively, down to the elementary constituents. Unlike stakeholder needs, the requirements meet various quality criteria which means that they must be complete, unambiguous, achievable, unique, etc. For each building block, the technical requirements must specify inputs, outputs, and input-output relationships.

1.2.2.4 Requirement Engineering from a DoD perspective

American defense institutions including National Aeronautics and Space Administration (NASA) and United States Air Force (USAF) were the first to take an interest in systems engineering (Krob, D. 2017). In the 1960s, they attempted to organize the development of military and space programs, named the Apollo program, from more rational industrial approaches. The reports of technical or economic failures such as the ineffectiveness of command systems during wars, the loss of satellites and the explosion of the space shuttle, etc., highlight the faults of systemic origin due to little expressed requirements, imprecise specifications, solutions not justified or not validated and confusion of responsibilities between customer (Krob, D. 2017). In 1991, the International Systems Engineering Council (INCOSE) was created. This organization capitalizes on and disseminates intellectual activities and the exchange of good practices for the development of complex systems requiring the interaction of several disciplines. Today, INCOSE is continuing its actions and is trying to answer many problems around systems engineering. They notably published the document SE Handbook. INCOSE also is in charge of updating the System Engineering Body of Knowledge (SEBoK) (INCOSE. 2015). According to the International Council on Systems Engineering (INCOSE), the System of Systems SoS is "is a collection of independent systems, integrated into a larger system that delivers unique capabilities (INCOSE. 2015). The independent constituent systems collaborate to produce global behavior that they cannot produce alone." A comprehensive literature review conducted by Klein and Vliet (2013) illustrated the importance of complex systems in the defense and national security domain. GAO (2011) emphasized this fact by providing three examples of complex systems from air missile defense capabilities to demonstrate the systems engineering processes. Their research outcome highlighted the importance of identifying the overall system requirements to cope with the complexity efficiently. In Lewis et.al (2009), the authors described the challenges of RE in complex systems as a multi-domain, decentralized control, and rapidly changing environment. To cope with this type of system, they suggested a combination of bottom-up and top-down approaches. In the same context, Ncube et.al, (2018) pointed on the challenge of RE discipline in dealing with the complexity. In another study, Katina et al. (2014) proposed a requirement elicitation process based on a holistic approach, which takes into consideration the high levels of ambiguity, uncertainty, and emergence. Dahmann, (2008) presented the different features of a system of systems as well as the experiences of multiple practitioners and identified principles required to achieve a successful system of engineering. In Nuseibeh, et al. (2000), the core requirements engineering activities and their integration into a single process were introduced. Moreover, Nuseibeh et al. (2000) argued the different techniques used for the integrated RE process and provided some suggestions for future studies. The outcome of the Government Accountability Office (GAO) report showed that inadequate requirements management mainly causes projects failure (GAO, 2011; GAO, 2015).

1.3 Thesis organization

This thesis is organized as follows. A general introduction, addressing the requirement engineering concept, is presented in CHAPTER 1. In CHAPTER 2, the methodology used in this study is highlighted. Following this chapter, a case study that has been chosen to validate the developed model is introduced. Finally, results from different analysis are demonstrated and interpreted in CHAPTER 4.

CHAPTER 2

METHODOLOGY

This chapter includes four parts. The first part represents an explanation of the fundamentals of the Bayesian Network. In the following part, the proposed framework is described. The third part refers to the identification of the factors composing the framework. In the last part, the developed Bayesian Network model is depicted.

2.1 Current methods and tools

The essential decision-making activity in requirements engineering is prioritization. Prioritizing means ordering a set of objects by priority. In requirements engineering, requirements are prioritized. When the requirements of a customer are too numerous, the supplier must select a subset whose implementation maximizes customer satisfaction according to the budgets and deadlines. The recent research conducted by Achimugu et al. (2014) lists no less than 49 requirements prioritization techniques, each with more or less established popularity. Figure 2.1 summarizes the 15 most popular methods by the number of citations. All these prioritization techniques can be arranged within three main approaches: (1) multi-criteria decision analysis, (2) optimization techniques, and (3) Data mining. Most decision analyses have been used to prioritize a set of requirements. The most basic method, in or out, is used by agents who review each of the requirements and decide which ones should be developed for the next version of the product (Wiegers et al. 2013). If the list is limited to 10 requirements per stakeholder, then we are talking about: Top-Ten Requirements (Berander et al. 2005). Another solution, the one that is implemented in all the requirements management tools, consists of assigning an ordinal qualitative priority (low, medium, high) to each of the requirements. For objective estimation, the three-level scale refines the definition of priority in combining two criteria: the importance - the client needs or does not need this requirement -, and the urgency - the client may or may not wait for the next version of the product (Wiegers et.al, 2013). For instance, if a requirement is important and urgent, then it has a very high priority. These techniques can be used to order requirements, but their subjectivity does not facilitate taking strategic decisions. When it is too difficult to select or order the requirements directly, pairwise comparison can be used. If an order of preference is established for each of the $n(n-1)/2$ pairs of requirements, then the requirements are ordered in order of priority. Techniques based on pairwise comparisons are appreciated because they give robust results (Karlsson, 1996) and are easy to apply. Bubblesorting also requires n (n-1)/ 2 comparisons (Karlsson et al., 1998), while a Binary Search Tree is a little slower to execute; prioritizing a set of 1000 requirements requires approximately 10,000 comparisons (Laurent et al., 2007). One of the most popular methods, Analytic Hierarchy Process (AHP) uses pairwise comparison in a rigorous analytical framework that minimizes subjectivity (Saaty, 1987). Its particularity of being built on mathematical fundamentals ensures a minimum of and establishes trust with its user robustness (Karlsson et al., 1998). The AHP multi-criteria analysis method has been used in many fields, including Product Lifecycle

Management (PLM), in particular, to prioritize requirements (Zhang et al., 2013; Perini et al., 2009; Karlsson et al., 2004). The AHP method remains non-extensible, difficult and slow to implement (Ahl, 2005; Karlsson et al., 2007). Despite these shortcomings, the pairwise comparison remains a fundamental element for many methods, which are applicable to a few dozen requirements (Achimugu et al., 2014). In addition to multi-criteria decision analysis, there are negotiation techniques. For example, the $100 method also called cumulative voting, each stakeholder has a fictitious sum of $100 of which they allocate a part to each of the requirements. It is one of the easiest and quickest methods to implement on a very limited number of requirements (Ahl, 2005). Chatzipetrou et al. (2010) go a little further by offering a Multivariate Compositional Data Analysis (CoDA) platform to explore the data of a cumulative vote. Finally, the WinWin negotiation process makes it possible to prioritize requirements by taking into account not only conditions that make a stakeholder win but also conflicts and alternatives solution (Ruhe et al., 2002; Ruhe et al., 2003; Boehm et.al, 2006). These single or multi-criteria decision-making analysis techniques have various advantages and disadvantages. Since they are generally unsophisticated, they are relatively simple to use or automate. However, these techniques have more disadvantages than advantages, we can site: - Not extensible: These methods do not allow prioritizing several hundred or thousands of requirements (Perini et al., 2007; Tonella et al., 2013; McZara et al., 2014). They are therefore not directly usable in our context. - Not demonstrated: We also see that there is a plethora of methods for prioritizing requirements, but very few are equipped and validated on a volume that corresponds to industrial practices (Achimugu et al., 2014). - No universal criteria: Criteria Decision analysis require defining one or more criteria for qualitatively or quantitatively estimating the priority of the requirements. There are no universal criteria. Although cost, value, risk and time are almost omnipresent, most of them are defined by context. For example, Azar et al. (2007) use criteria derived from the business world such as sales, marketing, competition, strategy, etc. The criteria, therefore, differ according to the company, the project, the product, etc. In their state of the art, Riegel et al. (2015) identified no less than 280 criteria used to prioritize requirements. Very few companies will accept a rigid solution whose criteria are pre-defined by the tool supplier. - Subjective: These decision support techniques also face difficulties linked to uncertainty, to bad human intuition. This is even more true for methods that do not use pairwise comparisons. Estimates, often qualitative, of requirements, are difficult achievable (Lehtola et al., 2004, Svensson et al., 2011). Therefore, they are more of an intuition/opinion. In addition, when the method becomes too complicated, the decision-makers lose confidence vis-a-vis the results (Lehtola et al. 2004). - Combinatorial explosion: To overcome this subjectivity, various methods of decision support require pairwise comparisons. However, these techniques face a combinatorial explosion. - Not usable: To conclude on these decision support methods, we can wonder about the ability of an expert to objectively estimate a requirement without having a contextual view related requirements such as the requirements prescribed by the applicable external documents referenced, requirements belonging to the same theme, etc. For example, all solutions based on comparisons are sometimes unusable because the user may be unable to give an order of preference between two statements isolated from their context.

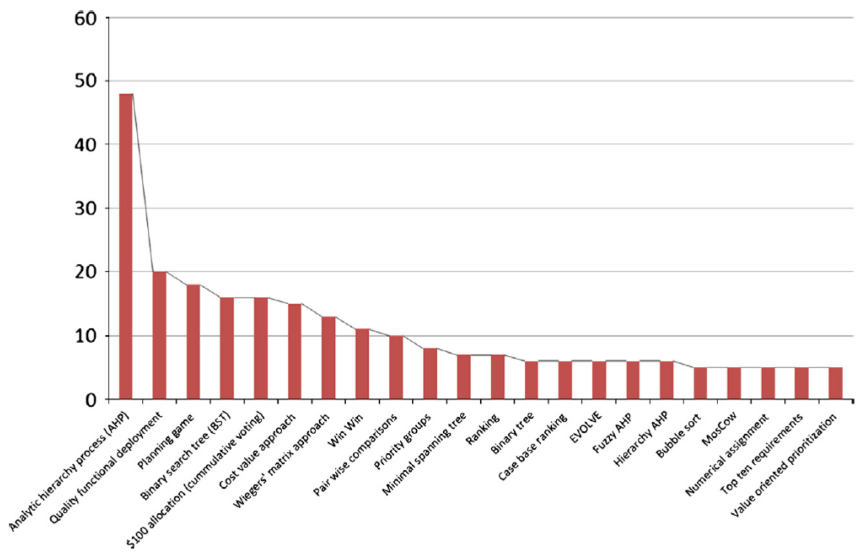

Figure 2.1: The most popular requirements prioritization techniques in terms of citations (Achaimugu et al., 2014)

It is evident from the above discussion that research was conducted tackling the requirements engineering and complex systems problems, however, there is no research has been conducted to evaluate the requirements engineering of complex systems based on the Bayesian network. The purpose of this research is to address the current gap in the literature. Change it to current methods, change sos to coplex systems, put 2 phrases to have prediction instead of prioritization. Add paragraph for capabilities.

2.2 Fundamentals of Bayesian Network

Bayesian networks are part of the family of probabilistic graphical models in the same way that the Markov fields (Besag, 1974). These networks allow a concise representation of the joint probability distribution on a set of random variables. It is possible to find in the literature different names for these networks, such as probabilistic networks or belief networks. Bayesian Network (BN) is an innovative probabilistic model for the representation of knowledge, based on a graphic description of the random variables. It represents large multidimensional distributions while avoiding combinatorial explosion (temporal and spatial complexity). Bayesian networks make it possible to represent the functioning of real systems and in particular, the causal links between the variables of the graph. Conversely, interpreting the arcs learned from data in terms of causality is not immediate. A similar technique is the case of Markov equivalent networks of which some arcs do not have a strong orientation; these can then be reversed without changing the set of induced independence. In this case, only the noninvertible arcs of the graph have a real causal direction. It is also known as a Directed Acyclic Graph (DAG). In BN, the joint distributions of random variables are depicted and encoded. BN is composed of nodes, which refer to random variables and arcs indicating the causal relationships between these variables (Nielsen & Jensen 2009, Cockburn et.al, 2012, Hager et.al, 2010). This network takes into account the conditional independence between the variables to simplify the joint law given by the generalized Bayes theorem:

$$P(A|B) = \frac{P(\frac{B}{A})P(A)}{P(B)} \tag{2.1}$$

In the above equation, P(A|B) refers to the conditional probability of A for given B describes the posterior probability that examines the uncertainty about A based on B. The likelihood of evidence is $P(B|A)$ (Nielsen & Jensen 2009). A Bayesian Network $G = (K, L)$ is defined as:

$K = \{X, E\}$, directed graph without circuit whose vertices are associated with a set of random variables $X = \{X_1, X_2, ..., X_n\}$, $L = \{P(X_i|pa(X_i))\}$ set of probabilities for each node X_i conditionally to the state of his parents $pa(X_i)$ in K. Pearl (2000) showed that Bayesian networks make it possible to compactly represent the joint probability distribution over all variables:

$$P(X_1, X_2, ..., X_n) = \prod_{i=1}^{n} P(X_i|pa(X_i)) \tag{2.2}$$

The above equation represents the fundamental of Bayesian networks. It is the basis of the first works on the development of inference algorithms, which calculate the probability of any variable in the model from even partial observation of the other variables. By reviewing the literature, it has been noticed that there is a scarcity in the use of Bayesian Networks (BNs) to improve the requirement engineering process. Aguila et al. (2016) supported this finding. The authors conducted a thorough literature review regarding the use of BNs in the area of requirements engineering. They found that only 20 studies have tackled the subject, however, several other studies supported the employment of BNs in the field of requirements engineering. For instance, Russell (2004) emphasized that Bayesian Network is useful tool in making decisions during the requirements volatility phase of developing a system. In another study, Donohue et al. (2003) developed a model of decision making, named “good enough to release” based on validation and verification techniques as well as Bayesian belief networks for assessment. Later on, Donohue et al. (2005) conduct a study in which they demonstrate the basics of a probabilistic methodology to evaluate the overall quality of a developing software. Aguila and Sagrado (2012) proposed a meta model based on Bayesian network that aims at supporting decisions during the development of a system. The authors also conducted a study in 2010, in which they evaluated the usefulness of using a Bayesian network for the purpose of prediction of the quality of a requirement.

2.3 The proposed framework

In this research, we illustrate the adaptability of the Bayesian Network (BN) in the requirements engineering discipline from a complex systems' perspective. BN is an efficient decision-making tool since it depicts the effect of the different conditional variables on the output variables. In BN, each variable has its Conditional Probability Table (CPT) that illustrates the probability of the resulting observations/evidence (Constantinou and Fenton, 2018). Furthermore, the BN provides both the diagnostic and predictive inference, minimize the burden of parameter acquisition, cope with subjective and objective data and update probabilities. Bayesian networks have been used in different studies and disciplines, e.g., to assess risk and reliability; evaluate resilience; predict uncertainty in manufacturing; categorize and manage projects. Various studies were conducted using Bayesian Network such as the works of Perez-Minana (2012) (natural resource management); Zhou et al., (2018) (safety risk analysis), Kabir et al. (2012) (water system), Ghosh et al., (2017) (project management), Goyal and Chanda (2017) (financial institution) and many more. In this study, the proposed framework was developed based on the existing relevant literature of the requirement-engineering context. To acquire a relevant framework, an extensive literature has been proceeded, reviewed, and selected using Scopus through keywords such as requirement engineering. Based on the existing literature and expert opinion, the different factors and sub-factors pertaining to requirement engineering were identified and quantified. To validate the proposed framework, we have conducted a belief propagation analysis. The purpose of this study is to address the existing gap in the literature: lack of studies in modeling and assessing the requirement engineering software using the Bayesian Network approach. The proposed framework consists of five phases:

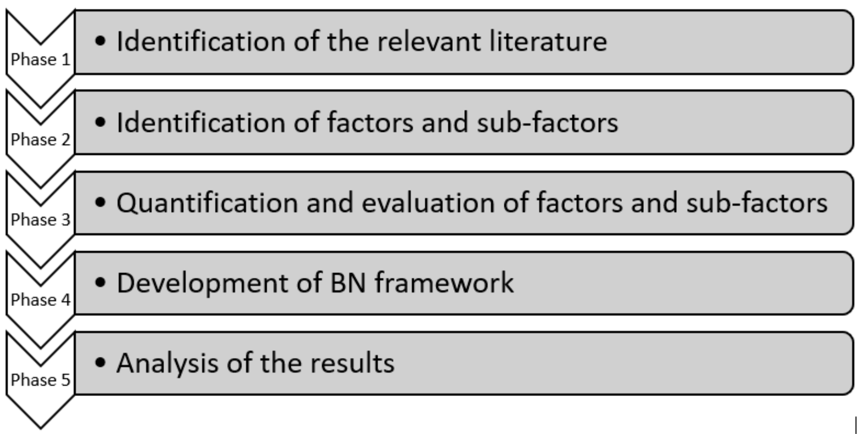

Figure 2.2: Proposed 5-phases requirements engineering prediction process

1. Identification of the relevant literature: In this phase, the literature associated with the requirements engineering has been reviewed.

2. Identification of factors and sub-factors: the second phase refers to the labeling of factors and sub-factors consisting in the requirements engineering.

3. Quantification and evaluation of factors and sub-factors: the following phase is to quantify the determining factors and sub-factors, and evaluate the probability of each variable using the node probability table (NPT) based on the expert opinion.

4. Development of BN framework: the fourth phase is to develop the framework to examine the requirements engineering probability.

5. Analysis of the results: In the end, the results obtained from the model are analyzed using advanced techniques such as belief propagation analysis and sensitivity analysis.

2.4 Identification of factors

To conduct its security and defense policy, the U.S Navy has implemented a global strategy, which brings together the different strategies corresponding to the military, civil, economic, social and cultural fields of defense. The forces participate in the overall strategy through the general military strategy. This has but supported the defense of the fundamental interests of the Nation, to contribute to security through the prevention and resolution of crises, and finally to contribute to international stability. The proper execution of the missions entrusted to the armed forces supposes the mastery of the four main strategic functions as defined by The Joint Maritime Operations Publication, which are deterrence, prevention, projection, and protection. (JP 3-32, 2018). In the Navy and U.S Air Force, the word "requirements" is interpreted as capabilities or conditions controlled by a system to attain an objective (Blickstein et al. 2016). The reference guide for Navy Planning, Programming, Budgeting, and Execution categorized it in two groups: "to achieve military objectives identified in a mission, campaign, or capabilities-based assessment or (2) the operational performance attributes at a system-level necessary for the acquisition community to design a proposed system and establish a program baseline. This type of requirement is also often referred to as a "warfighting" or "operational" requirement" (Blickstein et al. 2016). According to the Basic Military Requirements (BMR), the function of the U.S Navy are Sea Control which refers to the total management of air control, sea movement and subsurface areas, and the second function is the power projection that stands for the usage of sea power. From a capability standpoint and within a DoD perspective we extracted and synthesized factors from U.S Navy functions and capabilities that represent a base of the developed complex systems Requirements Model. Those factors are defined as follow:

• Assault support: Defined by The Basic School Marine Corps Training Command as: "Assault support operations are defined as the tactical movements of Marines, weapons, and material by assault support aircraft to support the ground tactical plan." (USMC, B2C0355XQ). It relies on a permanent organization of command and on operational forces, whose posture, adaptable to the situations, permanently guarantees a strike capacity, whatever the circumstances. An environment of conventional means, including in particular very reliable information and telecommunications systems, supports this system.

• Air warfare: This factor takes into consideration offensive air support, and electronic warfare, Anti-air warfare, which consists of Air defense, and Offensive Antiair Warfare, as supported by the fundamentals of the U.S. Navy/U.S. Marine Corps. Anti-air warfare is a term used to indicate that action required to destroy or reduce to an acceptable level the enemy air and missile threat. It assimilates all offensive and defensive actions against enemy aircraft, surface-to-air weapons (DOD, 2020). Offensive Anti-air warfare is responsible for minimizing or defusing the enemy's air and missile threat, while the Air Defense includes all the defensive measures to destroy attacking enemy aircraft or missiles (DOD, 2020).

• Control, on the other hand, represents the ability to direct a system and to maintain it in a state allowing concrete and defined action, by integrating all the functions of the U.S Navy. It aims, in particular, to control, even suppress change, and organize the system by fighting entropy. It refers to three complementary dimensions. The first is informative, giving measurement values of the state of the controlled system, or elements of the system. The second dimension is preventive, anticipating the possibilities of drift and preventing deviations from expectations or that do not correspond to the desired objective. The third is an incentive, of a positive nature, by promoting the desired possibilities, and by promoting their implementation, their development and their expression according to the objectives ordered. The control aims in particular to reduce the uncertainty in the system (Green et al. 1988; Burton, 2020).

• Surveillance: It involves utilizing information, telecommunications and intelligence systems, reliable, protected and interoperable, to search for, use and disseminate information at the different command and operational management levels (strategic, operational levels and tactics). Using sensors and radars that support the intelligence warfighting. The three types of air reconnaissance are visual, multi-sensors imagery, and electronic (Rielage, 2019).

2.5 The developed Bayesian Network model

Based on the factors precised and defined in the previous section, the base model is as follows;

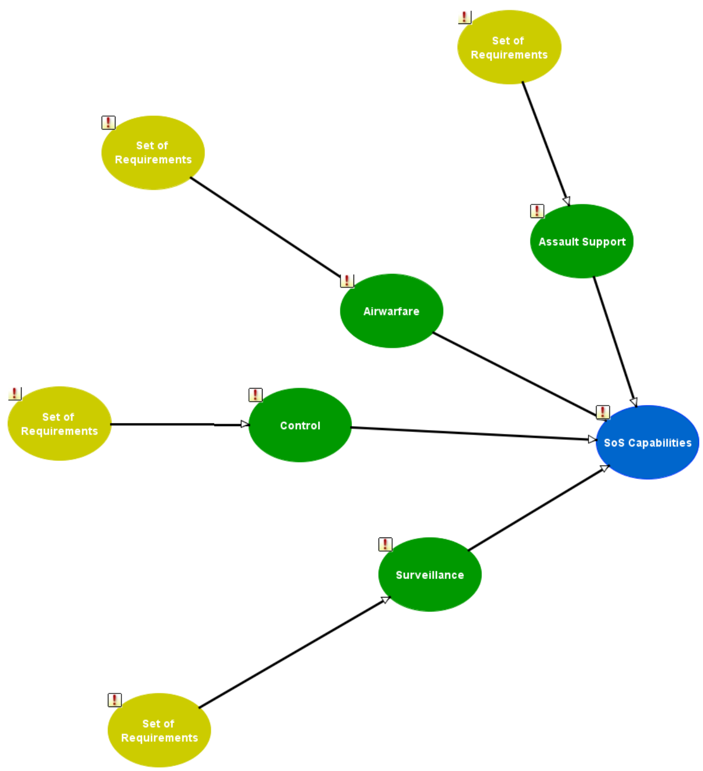

Figure 2.3: The developed Bayesian Network Model

CHAPTER 3

CASE STUDY- FFG(X)

3.1 Case study description

The United States of America is a maritime nation. For more than two centuries, the Navy, the Marine Corps, and the Coast Guards have operated around the world to protect American citizens and defend national interests by responding to crises and, when you must, fighting wars. The naval forces must defend the interests of the United States in a global security context characterized by precariousness, instability, complexity and interdependencies, a context marked by geopolitical changes and military challenges.

The U.S Navy maritime strategy reaffirms two fundamental principles. The first is that the advanced naval presence of the United States is essential to accomplish the following naval missions: defend the national territory, prevent conflicts, respond to crises, defeat aggressors, protect the maritime area of interest, strengthen partnerships and provide humanitarian and disaster relief assistance. The second principle is that the power of naval forces increases when they act together and in concert with allies and partners.

Coastal combat ships, “frigates” (FF), are an example of the ability of modular platforms, which saves time and money. By maximizing the capabilities and robustness of this concept, the U.S Navy could be responsive to any evolving threats in the blue water and littoral maritime environment. The U.S Navy intended to build 20 guided-missile frigates

(FFGs) to address the threats, the ships intend to support combatant and fleet commanders during the conflict and providing high/low mix of fleet capabilities. (O'Rourke, 2017) In the program designation FFG(X), FF means frigate, G means guided-missile ship (indicating a ship equipped with an area-defense AAW system), and (X) indicates that the specific design of the ship has not yet been determined.

As part of this frigate's capabilities, the ship needs to be multi-mission capable of conducting Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), Antisubmarine Warfare (ASW), and Electromagnetic Warfare (EMW) operations. The FFG(X) is larger in terms of displacement, more heavily armed, and more expensive to produce than any other frigate concept. The issue resides in the cost and capabilities tradeoff, whereas, an imbalance in between these two variables could lead to an increased risk of cost growth in the program (CBO 31, GAO 32). As a case study, we will be evaluating FFG(X) capabilities using the Bayesian Network with respect to the factors that we proposed and the categorization of the capabilities that we put in place.

3.2 Proposed framework

In this thesis, the sub-factors of the proposed model were selected from the literature and validated by an expert within the defense industry. This step is detrimental in the design of the Bayesian model. The sub-factors are presented below;

• Electromagnetic Maneuver Warfare: is the concept of creating an electromagnetic battle management system that consists of sensing and exploitation, whereas data is collected on enemy signals to deceive or jam the adversary by including electronic attack, directed energy, and electromagnetic-enabled cyberspace attack (JP 3-32. 2018).

• Radars: Navy ships could be equipped with different types of radars that provide multiple detection options by combining different radars that includes air traffic control radars, air dominance radars, surveillance radars, ballistic missile defense radars, and integrated air and missile defense radars (Radar Systems. n.d).

• SONAR: (Sound Navigation and Ranging) a device for detecting and identifying objects underwater by means of sound waves sent out to be reflected by the objects measuring distance. They use specialized transducers (underwater microphones) that converts the sound into electrical signals. There are two different sonars, Passive, which does not emit sounds into the water and only allows to detect objects without giving away the position, and Active sonars are the most effective form of sonars, by locating objects that are too quit to be detected (Fleet Environmental: USFF. n.d.).

• Sensors: are in different forms of technologies and devices from the most basic ones like thermometers to weather imaging systems. Any communication between the sensor and its nearby physical condition brings about some kind of information, either the physical, chemical or the biological state of the outside world. Sensors are passive and active, whereas the first simply measure and report on the local environment, the second one stimulates the environment by producing signals that interact with the environment and reflect to the sensor system (Board, et al. 1997; Rielage, 2019).

• C4I CMS: Command, Control, Communication, Computers, and Intelligence Computer Management System, is a combat system software that encompasses satellite communication, transmission data, and computer security services (Buntha, 2005; Raytheon, n.d).

- Anti-Submarine: assisting in establishing a maritime superiority by defying enemy submarine power with active and passive undersea sensors.in a certain area by having the right mean to detect, identify, track, and engage enemy submarines (JP. 3-32, 2018).
- Air warfare Guns: autonomous combat system that searches, detects, tracks (radar and electro-optic), and engages threats. Categorized with stability, effective range, lethality, and nighttime capability (U.S Navy, 2017). Anti-Ship Cruise Ballistic Missiles: Delivers defense against anti-ship missiles and high-speed aircraft by providing expanded defense against unequal threats such as small, fast surface craft, slow-flying aircraft, and unmanned aerial vehicles (U.S Navy, 2017).
- Helicopters: they are vital to the execution of numerous Navy missions. It serves as a force multiplier for air-defense capable destroyers escorting logistics ships. Watercraft: It provides a means to perform ship to shore, ship to ship, and humanitarian operations.
- Guns: ranges from lightweight to heavyweight, and different in ranges, lethal-ness, automatic and semi-automatic, and accuracy (O'Rourke, 2010).
- Missiles: Class destroyers to provide precision, volume, and sustained fires (U.S Navy program 2017).

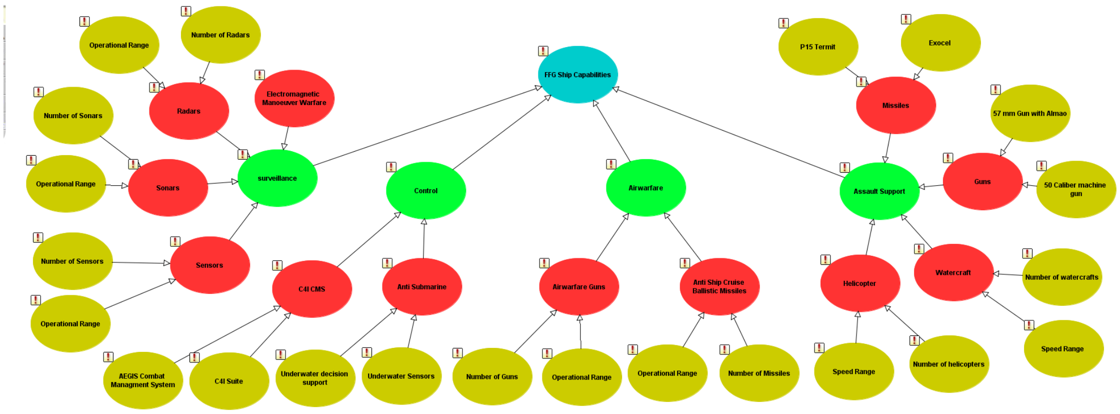

Figure 3.1: Completed Framework

3.3 Quantification of factors

Based on the identified factors and sub-factors of FFG ship. A BN model was developed through the quantification of each node. In this section, we present the quantification process of the different variables composing the proposed BN. The simulation was run using the simulation software AgenaRisk. After collecting the data ad filtering it, it has been found out that there is three types of variables presented as follows:

1. Boolean variables: refer to variables that are composed of two responses. These responses are presented in form of two cases “True” and ”False” to depict the positive and negative results. The outcome of the cases can be changed according the case study scenario. According the base model, the node Exocel which shows that there is a chance of 90% it would increase assault support level, while there is 10% chance it would not. Same logic came be used to explain all the other Boolean nodes.

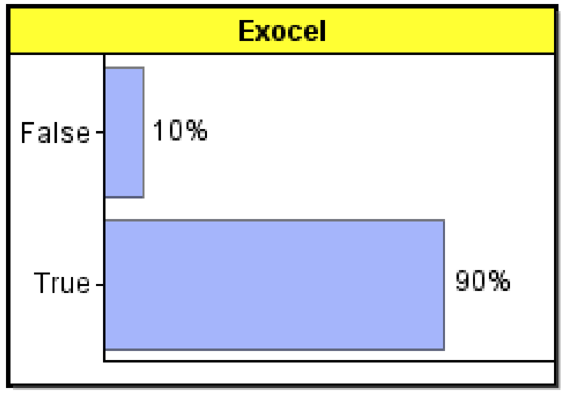

Figure 3.2: Boolean Variable

2. Continuous variables: stand for the quantitative variables used to express measurable data. Hossain et al. (2019) defined CV as "variables that can take continuous values via a probability distribution of random variables". In the base model, the continuous variables are implemented using a truncated normal distribution known as TNORM. This distribution is a known model of randomness that provides somehow an accurate result. The truncated normal distribution is presented by same parameters as normal distribution: mean, standard deviation, lower value, and upper value. As depicted in the base model, the "Muzzle velocity" node is a continuous variable characterized by a mean value of 3200m/s, lower value of 3199m/s and upper value of 3200.7m/s. All the other Boolean nodes in the base model are assessed based on the same logic.

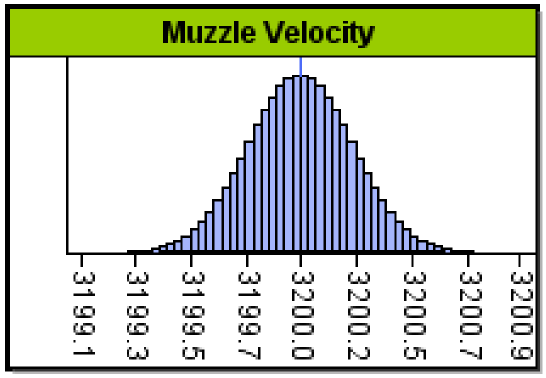

Figure 3.3: Continuous Variable

Qualitative variables: they are variables described with set of labels and set of cases. To evaluate the probability of FFG ship, a qualitative node called "weight" is created describing the weightage of each of four main factors (control, surveillance, assault support, air warfare), which is 25%. For instance, Figure 3.4 refers to the weight node.

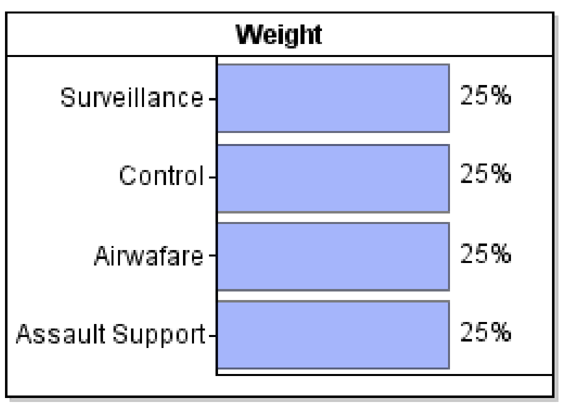

Figure 3.4: Qualitative Variable

3.4 Base model

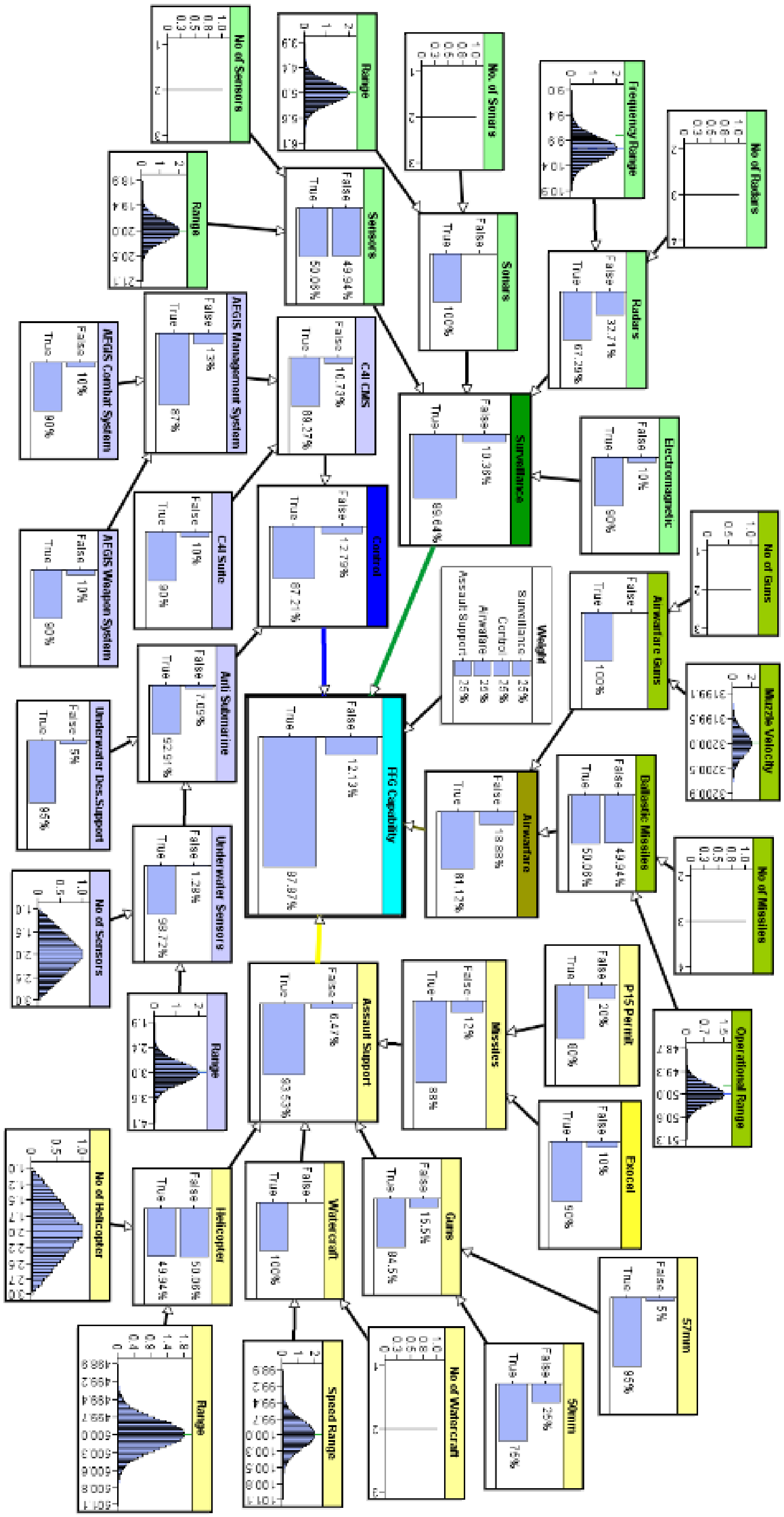

Figure 3.5: Base model of the Bayesian network

CHAPTER 4

ANALYSIS AND RESULTS

This chapter focuses on the propagation analysis performed to allow the decision makers to develop a different kind of observations in the base model in order to draw a better managerial insight and predict requirements. The belief propagation analysis is known as message-passing analysis (Montanari et al. 2007). In this analysis, message, i.e. variable, is introduced from hidden node X and transmitted to its child node Y, and vice versa. Message can be imparted from any direction, which means it can be initiated at any node of the model. In other words, the belief propagation reflects the effect of the evidence on the developed model. It is one of the main features of the Bayesian Network; it allows a flow of information. It calculates the marginal distribution of each "unobserved" node conditioned on the observed nodes. There are two types of propagation: forward and backward can be conducted in the underlying BN model. Forward propagation, which allows observations on causes to be made to determine the effect, whereas backward propagation permits observations to be inserted on effects and propagates backwards to arrive at conclusions regarding the causes (Fenton and Neil, 2012). In this study, we suffice on running a forward propagation to compare the results with the proposed base case of the Bayesian model. During the propagation analysis, the probability distribution for any event is predicted based on contributing factors Mi = 1 to n. Each factor used as input function into BN model, creating the probability distribution of N in the following way

$$P(N = Q_k) = \sum_{1}^{m^r} P(N = S_k | M_1 = m_l, M_2 = m_l, ..., M_r = m_l) \times P(M_1 = m_l, M_2 = m_l, ..., M_r = m_l) \quad (4.1)$$

Where r refers to the number of parent nodes and m_1 is the lth state of the parent node. Q_k is the k^{th} state of the leaf node where $k = 1$ to t. $P(N = Q_k | M_1 = m_l, M_2 = m_l, ..., M_n = m_l)$ is the conditional probability distribution when $N = Q_k$

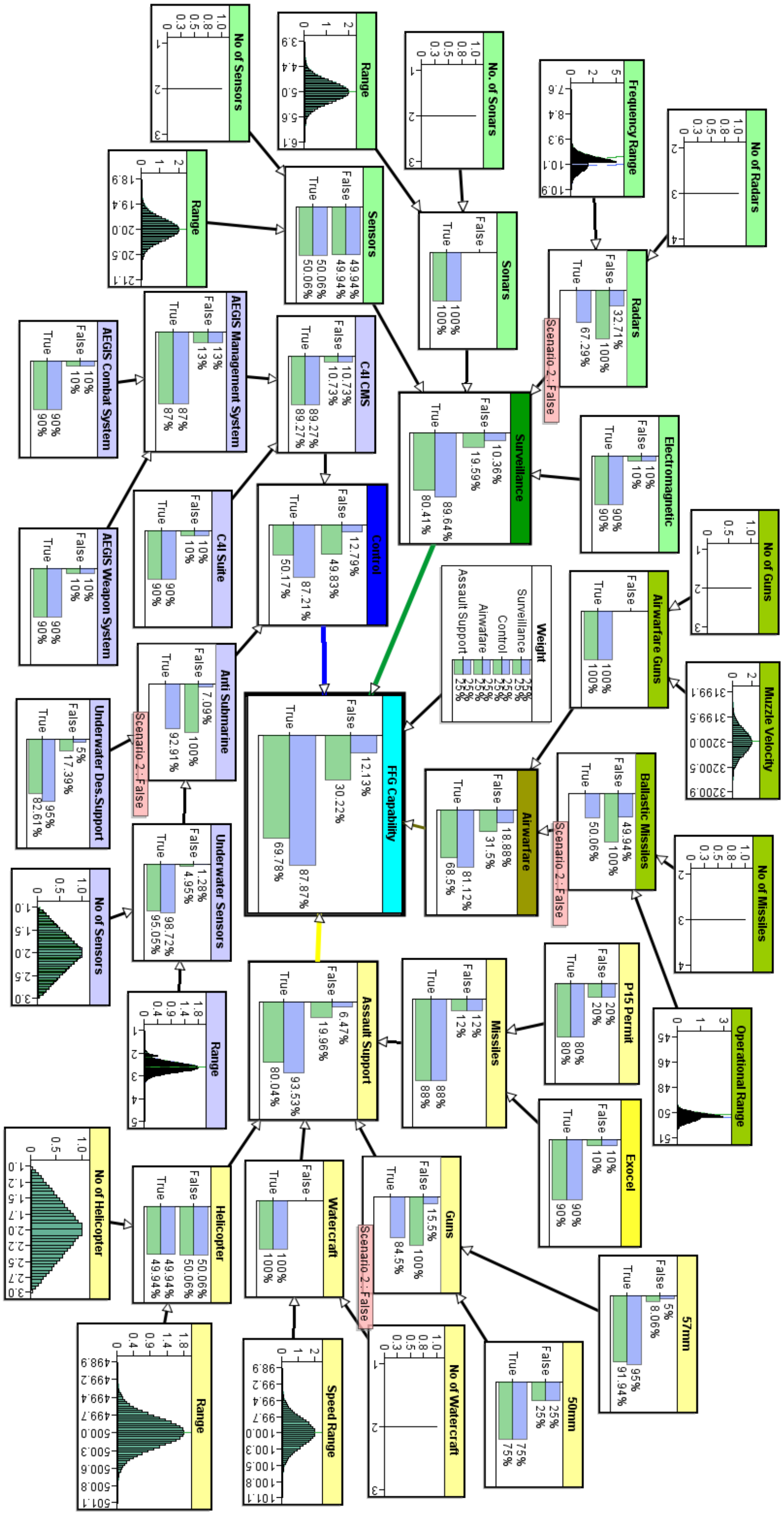

Figure 4.1: Base model of the Bayesian network

Table 4.1: A Comparison of the of the Base Scenario and Worst-Case Scenario

Scenario	Guns	Ballistic Missiles	Anti-Submarine	Radar	FFG(X) Capability
Scenario 1 (Base Case)	84.5% (effective)	50.05% (effective)	30.4% (effective)	67.29% (effective)	87.87%
Scenario 2 (Pessimistic Case)	Fail	Fail	Fail	Fail	69.78%

In this study, a pessimistic scenario has been developed. The scenario is based on failing the performance of four sub-requirements: 1) Guns, 2) Ballistic missiles, 3) Anti-submarine, 4) Radar. The choice of these four sub-requirements originates from the expert opinion and literature review (Thomas et al., 2001; Tompkins et al., 2018). Table 4.1 depicts the results obtained from the propagation analysis. Results showed that the failure of guns, ballistic missibles, anti-submarine, and radars highly affect the FFG(X) capability percentage: it drops from 87.87% to 69.78%. This emphasized the importance and main role of these requirements in FFG(X) capability.

By comparing the results to real-world scenario, it can be noticed that they seem consistent. According to the literature, there are some case studies in which the significance of combat system features for warships has been illustrated (Thomas et al., 2001; Tompkins et al., 2018). Obviously, the surveillance ability has the highest priority for warships. This ability ensures the safety of navigation by detecting potential threats. Another significant capability is the control. In general, control of situation is considered as best approach to succeed. The study intent is to predict the cited requirements as well as illustrating the usefulness of Bayesian network in decision making as a support. A study conducted by Yeasin et al. (2019) was based on Bayesian network and aimed to provide decisions approval all over the project life cycle. However, no study has offered a requirements engineering prediction tool throughout the project lifecycle.

CHAPTER 5

CONCLUSION

In this thesis, Bayesian network has been used as a requirements engineering tool to predict the defined requirements. Based on the literature the impacting factors on a DoD capabilities were identified. A case study of a warship, named FFG(X), has been employed to work on and relate the study to real-life scenario. Upon the case study, set of requirements were determined and data were extracted. To predict requirements and validate the developed model, propagation analysis has been used. The novelty of this study are highlighted as follows:

- A framework (BN) for predicting the requirements engineering was developed.
- To relate the proposed framework to real-life cases, a case study has been used to establish and expand the BN model.
- The paramount important requirements have been identified and validated based on an expert opinion and propagation analysis.

This study can serve as a requirements engineering tool to predict requirements as well as supporting in making decisions. The work developed in this thesis can be more extended in term of sub-requirements and use of more analytical techniques such as sensitivity analysis to test the uncertainty in our model.

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