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A Combined Bayesian Belief Network Analysis and Systems Architectural Approach to analyse an Amphibious C4ISR System

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Abstract: As an amphibious operation encompasses the land, air and sea domains, it is a Joint Operation, involving all three services. More than any other military operation, the success of an amphibious mission requires the extensive synchronisation of both physical and informational assets across the joint force. Vital to this synchronisation is an effective and reliable Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) system. Consequently, in supporting the development of the ADF's amphibious capability, the Defence Science and Technology Organisation (DSTO) was involved in modelling the operational effectiveness of this joint amphibious capability with a focus on the impact of C4ISR. In this paper, we describe our staged approach to develop a C4ISR focused Bayesian Belief Network (BBN) model of amphibious operations via a higher level cause-effect concept map and a BBN.

BBNs were selected as they provide a means to both graphically represent the cause and effect relationship between various elements within a scenario as well as to quantify their likely impact on the outcome. As part of this approach, we propose a methodology to link BBNs with discrete information exchange requirements as a means of capturing the operational impacts of C4ISR. Such an approach can potentially provide both the detail on the availability of information products during various tactical phases of an operation as well as the probable operational impact of any deficiencies. Consequently, it is possible that both commanders and capability developers can make more informed decisions and trade-offs under conditions of uncertainty.

Keywords: *Bayesian Belief Network, System Architecture, Defence, C4ISR*

1. INTRODUCTION

The core requirement of the Australian Defence Force (ADF's ADF) amphibious warfare capability (AWC) is the delivery of joint forces to a land objective simultaneously by air and surface from an amphibious task force (ADFWC, 2009). Once delivered, these forces will be reliant on physical and informational support from the amphibious task force. This implies that the amphibious capability will have a high dependence on the performance of a sea based Command, Control, Communications, Computer Networking, Intelligence, Surveillance and Reconnaissance (C4ISR) system.

This paper describes our approach to developing a cause-effect concept map that is based on key amphibious concept documents and our efforts to convert this concept map into a C4ISR focused Bayesian Belief Network (BBN) model. A BBN model is a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed acyclic graph. The nodes of the graph represent random variables or events. Each variable consists of a finite set of mutually exclusive states. It is possible for variables to have a continuous state, representing a numerical value such as velocity, but there are a number of limitations on their use, so we consider only variables with a finite number of states. It is usually simple to convert a continuous state to a set of finite states, so this is only a minor limitation. The directed links between variables in the graph represent causal relationships. The practical applications of Bayesian network analysis are not new. They have been used successfully for many years in the fields of medical diagnosis, artificial intelligence and environmental problems (Jensen, 1996) and (Pourret et al., 2008), but to date their use in defence problems has been limited (Das, 2000). Part of the reason for this is that it is quite difficult to collect the large amounts of data and calculations involved with complex systems in the defence environment.

A crucial problem in this work was accounting for the uncertainty in both the delivery of information as well as the impact of information deficiencies. Here we propose a methodology to link a BBN of the given amphibious operation scenario to a Department of Defense Architecture Framework (DoDAF) compliant database (DoD, 2010), via discrete information exchange requirements, in order to map likely information deficiencies to probable operational impacts. The DoDAF database structure was extended to capture SME knowledge on amphibious C2 processes and information exchange within a relevant scenario context. The database follows the structure of who (the major Actors in a scenario), what (the activities being carried out by the actors), where (the geographical location of the actors), when (the time specified by operational phases in which the activities were performed) and why (the purposes of the operations). This information was captured from interviews of multiple SMEs who were involved in an amphibious exercise.

2. MODELLING C4ISR IMPACTS ON OPERATIONAL OUTCOMES

This paper will detail our efforts to link C4ISR informational effects with AWC operational outcomes through the construction of a preliminary BBN. In supporting the development of the AWC, a key challenge for the Defence Science and Technology Organisation (DSTO) was to develop a means to assess the impact of the sea based C4ISR system on the amphibious operation, for different system configurations and tactical situations. With such a tool, the overall operational benefits of a proposed C4ISR change could be systematically and coherently assessed, therefore informing key trade-off decisions on the future of the capability. The first challenge was to identify a suitable modelling technique.

The North Atlantic Treaty Organisation (NATO RTO, 2012) identified five key benefits of conducting modelling in the investigation of complex defence questions such as amphibious C4ISR. They can be summarised as: **organising** a representation of the problem; **presenting** large quantities of data; **understanding** the key factors that influence a problem; enabling the **investigation** of decision options; and supporting '**what if**' analysis. These benefits were used as a guide in selecting a modelling approach for this problem. Bayesian Belief Modelling (BBN) was selected as it provides a means to:

- **organise** the problem situation in terms of causal (concept) map as the front end of the model;
- **understand** the key factors that influenced the impact of C4ISR on the amphibious operation via the cause and effect map;
- capture and **present** the 'so what' of a great deal of SME qualitative data within the BBN structure; and
- **investigate** decision options and conduct a '**what if**' analysis by varying the inputs to the BBN.

There are generally three key steps involved in building a BBN (Cain, 2001a). In step 1 the analyst must develop the network structure which is essentially a causal model representing how key concepts and capabilities relate to each other in terms of cause and effect so as to produce a desired higher level goal(s). In this case the goal was **enhanced amphibious land tactical operations**. In the second step, the analyst must define nodes in the structure as BBN nodes by identifying the possible states that the node may hold. In step 3, the analyst must elicit the associated conditional probabilities (Cain, 2001a) though consultation and interviews with SME. This requires substantial effort by the analyst to reduce the burden of data elicitation (Evans and Olson, 2003).

In applying BBNs to study the impact of changes to C4ISR, step 3 of this process will remain unchanged. That is, SME will be consulted to elicit conditional probability assessments. However it is less clear whether the complex and highly technical informational effects of C4ISR can be effectively captured in steps 1 and 2 in order to identify the network structure and define BBN nodes. Complex systems such as the AWC C4ISR system are notoriously difficult to deconstruct and therefore analyse (Ryan, 2007). Even dedicated technical assessment frameworks have struggled to capture the wide range of key performance impacts that arise from changes to command and control systems (Armenis et al., 2010). The key challenge for this study is therefore to identify and link the technically focused informational products produced within the C4ISR system to outcomes (‘so what’) in an operationally focused BBN.

Given the challenges involved in linking C4ISR effects with an operationally focused BBN it was decided to undertake a two staged approach.

Stage 1
In stage 1 of this approach, an operationally focused BBN is constructed that captures the causal relationships between relevant concepts and capabilities. In this map, the impact of C4ISR is considered only at an abstract level in which the specific mechanism for the impact of C4ISR changes on operational outcomes is deliberately obscured. This enabled an initial operational focus on amphibious operations within a BBN structure and provided an opportunity to investigate whether amphibious operations were likely to be found to be sensitive to C4ISR changes within a BBN.

Stage 2
Stage 2 of this approach then focused on removing the abstraction of C4ISR from the BBN by explicitly identifying the mechanism linking C4ISR with operational outcomes within the BBN. Noting that the role of the C4ISR system is essentially to collect, process and disseminate information products (Hayes, 2001) for the amphibious force, the method proposed to identify C4ISR mechanisms for influencing operational outcomes via information exchange requirements (IERs).

IERs, which are compiled using an architectural analytic framework based on the Department of Defence Architecture Framework (DODAF), have a database that conforms to the following structure: who (the major actors in a scenario); what (the activities being carried out by the actors); where (the geographical location of the actors); when (the time specified by operational phases in which activities were performed); and why (the purposes of the operations). A set of IER data can be constructed based on an Activity Based Methodology (ABM) approach (Pang et al., 2011). Subject matter experts (SMEs), who have deep understanding of the military doctrine and concept of operations of a system, were interviewed in order to extract data in the above format. A subset of the extracted IER data, which is constructed through the use of scenario based activity modelling, is used to provide the context for subsequent analysis such as C3 and C4ISR capability analysis.

3. BBN WITH ABSTRACTED C4ISR

In this section we follow the stage 1 approach to develop a BBN model with abstracted C4ISR. This required the following actions:

- *Developing a Causal Concept Map;*
- *Converting the Causal Concept Map to a BBN Model;*
- *Eliciting Conditional Probabilities; and*
- *Analysing the resulting BBN.*

Developing a Causal Concept Map
There are two key factors in developing a cause-effect concept map. First the various cause/effect nodes relevant to the area being studied (in this case, the concepts and capabilities relevant to the conduct of an

amphibious mission) are identified and defined. Second, these nodes are linked together in cause and effect arguments (Nadkarni and Shenoy, 2004). Both of these can be accomplished through consultation with SME and/or through analysis of authoritative textual sources (Coutts, 2013a).

A causal map for a generic amphibious operation was developed from relevant defence doctrine, including (ADFWC, 2009). In applying this method, causal relationships were first identified in the texts using a method similar to (Nadkarni, et al., 2004). An example of how this method was applied is provided in Table 1.

Table 1: Example of identifying causal relationships in textual sources[1]

Source	Original Reference	Summary of Causal Relationship	Causal Phrase	Interpreted Causal Connector	Effect Phrase
ADDP 3.2 p 1-9	" Sea basing is also intended to reduce the operational pause associated with the build-up of combat power ashore prior to the break out to secure objectives."	Sea Basing reduces operational pause of entry operations	Sea Basing	**increases (+ weak)**	Tempo
ADDP 3.2 p 1-8	"projection of force by both surface and air means directly to the objective from the sea, to dislocate the adversary in time and space"	Simultaneous entry by air and sea dislocates enemy	Simultaneous Insertion Capability	**leads to (+ weak)**	Generate Dilemma for the Enemy
ADDP 3.2 p 1-10	"[Components of amphibious task force conducting simultaneous entry operations]must be sufficiently networked to ensure a high degree of situational awareness combined with mission appropriate C2 arrangements"	Simultaneous operations require high degree of support from Networked C2.	Interoperable C2	**Support (+ Strong)**	Simultaneous Insertion Capability

The table shows how phrases are first identified from the text because they contain some reference to a causal relationship. For example, the first phrase listed in the original reference column was identified because it associated sea basing with reducing operational delay. The phrase was then summarised to clarify the main points relevant to the causal argument and then causal nodes, causal connectors and effect nodes were identified and recorded. A preliminary assessment of the direction of the likely strength of the causal link on the effect node was also made and recorded in brackets with the causal connector. In determining the likely strength of a causal link, it was first important to identify the type of mission the Amphibious Task Force (ATF) (ADFWC, 2009) was engaged in for the scenario. In this case the mission was a relatively low threat evacuation operation in the context of an uncertain environment and enemy intent.

Causal and effect nodes[2] were then recorded and defined separately (see Table 2). As new causal relationships were identified, this existing list of nodes was examined in order to determine if similar nodes had been previously identified. In the interests of model clarity and efficiency it was important to reuse these nodes wherever appropriate.

Table 2:- Causal Concept Map Variables with Possible States

Node / Variable	Description	Possible States
Air Assault	Ability to conduct assault by air	Degraded, Good
Air Space Management	Ability of ATF to coordinate air, ground operations in the Area of Operation (AO).	Degraded, Good
Combat Assets	Level of joint enablers supporting land operations	Degraded, Good

[1] The intent was to provide an example of how the causal relationships were captured. The full set of data identifying causal relationships would have been too large for the constraints of the paper.

[2] A node can be both a causal and an effect node in the overall map depending on the causal relationships.

Complexity of Terrain	Net effect on friendly force operations resulting from the human, informational and physical complexity of the AO.	Low, Medium, High
Control and Coord	Ability to control and coordinate friendly force operations.	Degraded, Good
Data Services	Ability to access and create C2 related electronic information.	Degraded, Good
Enemy Course of Action	Willingness of the enemy to aggressively oppose friendly force operations.	Most Likely, Most Dangerous
Force Multiplier	Combined effect of multiple operational and tactical enablers on friendly force operations	Low, Medium, High
Friendly Mitigators	Combined effects of actions taken to mitigate operational threats in the AO.	Low, Medium, High
Generate Dilemma for Enemy	Effect on Enemy decision cycle arising from uncertainty on which course of action may be employed by the friendly force (more Course Of Action (COA) available to friendly force leads to greater dilemma)	Degraded, Good
Generate Surprise	Ability to surprise the enemy and therefore restricting their ability to react.	Degraded, Good
Information Collection Support	Ability to coordinate and conduct information collection operations on behalf of friendly force requirements.	Degraded, Good
Information Fusion Support	Ability to fuse information from diverse sources in order to support friendly force operations.	Low, Medium, High
Interoperable C2	Ability to provide interoperable command control to support friendly force operations.	Degraded, Good
Joint Fires Support	Ability to provide lethal joint fires support	Low, Medium, High
Joint Organisation external to ATF	Impact of whole of government actions to set conditions for friendly force operations.	Degraded, Good
Logistics Support	Ability to provide sustainment to the land force operation.	Low, Medium, High
Medical Capability	Ability to provide medical support to friendly force operations.	Degraded, Good
Mobility	Ability of the friendly force to move throughout the AO in conducting operations.	Low, Medium, High
Networks	Ability to access and create electronic data and voice services within the friendly force in support of Land Operations.	None, Degraded, Adequate
Operational Threats	Net impact on friendly force Operations arising from all threat sources.	Low, Medium
RW Support	Ability to provide airmobile support to friendly force operations.	Low, Medium, High
Sea Basing	Ability to support Land Force Operations from afloat.	Low, Medium, High
Shaping and Deception OPS	Enabling Effect of Whole of Government pre-entry operations.	Low, Medium, High

Simultaneous Insertion Capability	Ability to conduct simultaneous insertions by multiple means (surface and air).	Degraded, Good
Landing Craft Support (Small boat support)	Ability to provide sea mobile support to friendly force operations.	Low, Medium, High
Surface Assault	Ability to conduct assault by sea.	Degraded, Good
Tactical Flexibility	Ability of the friendly force to adopt multiple responses to tactical situations.	Degraded, Good
Tactical Land Force Operations	Ability to conduct Land Force Mission	Low, Medium, High
Tempo	Speed of decision cycle able to be generated in support friendly force operations.	Low, Medium, High
Voice Services	Ability to access voice services in support of Land Force Operations.	Degraded, Good

The resulting map (Figure 1) provides a cause-effect or 'means-ends' analysis[3] of how amphibious relevant concepts and capabilities combine to deliver operational effect on land in an uncertain but low threat scenario, albeit with C4ISR effects abstracted.

The majority of influences between concepts in Figure 1 are positive and are depicted with black arrows. For example, when *Simultaneous Insertion Capability* is in a "good" state, it will influence *Tactical Flexibility* toward a good state. Influences that have a negative influence are depicted with red arrows. The relative strength of the influence (based on SMA input) is indicated by the size of the associated arrow.

Figure 1 indicates that the ship to shore connectors of the ATF, as represented by *RW Support* and *Landing Craft Support*, contribute to the mission outcome through two paths. First they enable ATF *Mobility* which in turn supports increased *Tempo.* Second, they provide the means to conduct *Surface* and *Air Assault* simultaneously[4]. This simultaneity contributes key warfighting effects as *Force Multipliers* via the ability to both surprise and generate a dilemma for the enemy. The ability to support both *Air* and *Surface Assault* enables *Tactical Flexibility* that provides the commander the ability to respond to and reduce *Operational Threats*. In this case *Operational Threats* are largely dominated by *Environmental Complexity* rather than the *Enemy*.

The level of *Logistics Support* is largely determined by the level of mobility within the ATF and the level of *Interoperable C2*. *Logistics Support* in turn greatly influences the *Force Multipliers* supporting *Tactical Land Force Operations*. However the major direct influences on *Tactical Land Force Operations* are via the level of *Interoperable C2* and the level of *Combat Assets* available within ATF

Force Multipliers and *Operational Threats* also directly influence *Tactical Land Force Operations* but they are less influential in this scenario. While the map indicates that *Joint Fires Support* acts to reduce the *Enemy* effect, and thereby reduce *Operational Threats*, the nature of the enemy, the human terrain and the tactics employed by the enemy precluded any employment of joint fires in this scenario

[3] In a 'means-ends' analysis, 'ends' concepts are defined by their contributing/enabling means concepts. In a concept map, the direction of the arrows goes from 'means' to 'ends' concepts.

[4] Arguably, *Interoperable C2* is also required to coordinate *RW* and *Landing Craft Support* activities independent of *Simultaneous Insertion*. As the Bayesian data was collected based on the map with this omission, it has not been corrected here. Instead this will be addressed in future versions of the map.

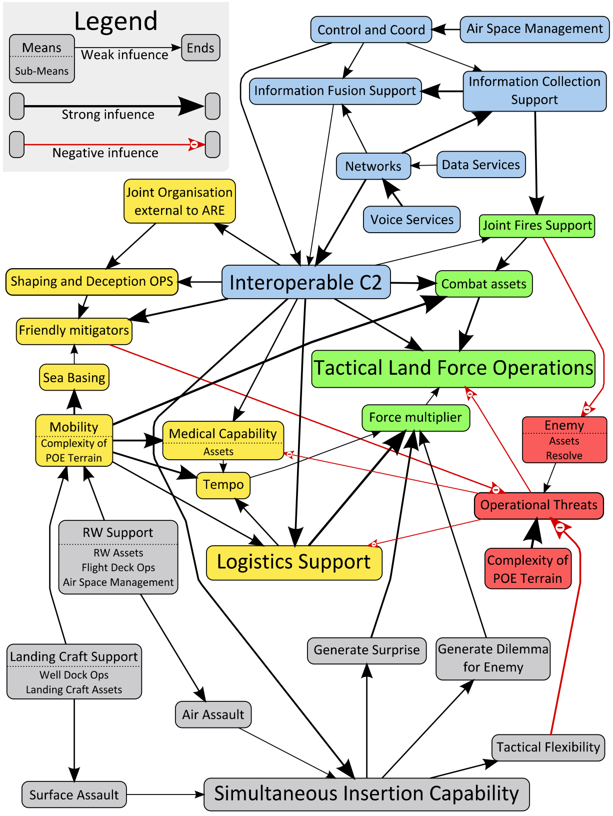

Figure 1: - Concept map based on a generic low threat amphibious scenario

Converting the Causal Concept Map to a BBN Model

Individual nodes in the causal map were then converted to Bayesian nodes by identifying the possible states that these nodes could hold within a BBN model. In identifying these states, Cain (2001a) suggests that the analyst should first describe the state the node is normally in, then the likely extreme state the node could reach and finally any useful intermediate states. These states were initially defined by analysts interpreting available doctrine however these states were later confirmed with SMEs. Care was taken to ensure that the selected states fitted in with the overall logic of the BBN (Cain, 2001a). Node states are listed with the node definitions in Table 2.

Eliciting Conditional Probabilities

Conditional probabilities for the BBN nodes were elicited by interview with amphibious SME as part of an amphibious capability development wargame in 2012. Eliciting conditional probabilities from busy decision makers and military commanders is difficult and potentially tedious (Jensen, 1996) depending on the scale and complexity of the BBN. Consequently there are a number of strategies that can be employed to reduce the elicitation burden placed on the SME, without which BBNs would be infeasible for this role[5]. The primary strategy employed to reduce the data elicitation burden for this activity was to reduce the complexity of Figure 1[6].

Validating the Model

BBN model validation was distributed throughout the modelling process and included a level of conceptual and logical validation through exposing the causal map to amphibious operations SME through interviews. The interviews also provided a level of confidence in the data (data validation) in that groups of SME were consulted to make probability assessments. Additionally a very limited form of operational validation was attempted via SME review. In no way could this be considered to be a complete or satisfactory model validation, however it was considered sufficient to continue to this next step of the modelling process.

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[5] The experience of data elicitation in this study provided the motivation for (Coutts, 2013b) which provides an overview of four strategies to reduce the data elicitation burden and a data collection framework in which to employ them for related situations.

[6] Primarily by ‘divorcing’ causal (parent) nodes from effect (child) nodes (Cain, 2001b).

Analysing the resulting BBN

On completion of data elicitation, probabilistic inferences were calculated based on the resulting conditional probabilities and propagated through the BBN to provide a distribution of outcomes for the highest level node: *Tactical Land Force Operations*. In analysing the BBN, the key question to be addressed was: "how sensitive is *Tactical Land Force Operations* to the state of the supporting interoperable C2 networks?". Previously it was identified that rotary wing and landing craft assets were core enablers to the simultaneous insertion capability. Consequently we decided to compare the impact on tactical landing force operations of degrading interoperable C2 performance against degrading both the RW and landing craft capabilities. The results are displayed in Figure 2. In each case, the impact of enemy action was considered with the enemy COA variable[7], which reflects whether the enemy opted to undertake a more aggressive (MD) or passive (ML) course of action noting that overall this was a low threat scenario.

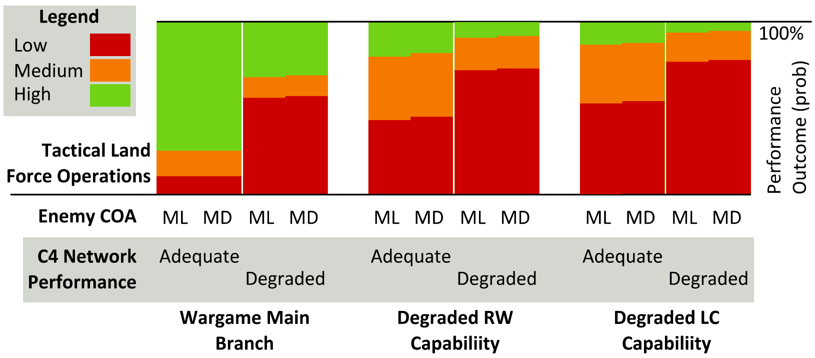

Figure 2 - Outcomes of modifying variables on Tactical Land Force Operations

Figure 2 shows that, based on this Bayesian model:

- C4 *Networks* performance is generally more influential than enemy COA on the Tactical Land Force Operations (mission performance).
- Degradation of *Landing Craft Support* has slightly more impact on the conduct of the operation than degradation of the *Rotary Wing Support*.
- The enemy COA has little effect on outcome in this low threat scenario essentially because of their relatively low capabilities.

4. BBN WITH EXPLICIT C4ISR MECHANISMS

In this section, we describe our proposed stage 2 approach to 'expose the C4ISR mechanisms' that were abstracted in the BBN developed in previous section. The approach adopted to achieve this involves linking the BBN with IERs relevant to amphibious operations in order to map likely information deficiencies to probable operational impacts.

Argument for IERs with BBNs

The precondition for this approach is to have access to amphibious operationally relevant IERs that apply to the key functional areas within the AWC. These IERs should provide sufficient detail to link types of information exchange with the performance of different functional areas and/or the effects they generate.

When analysing military systems it cannot be assumed that such operationally relevant IERs exist and this constrains the applicability of the proposed method. However, in this case, a parallel activity captured IERs for the AWC in a relevant amphibious scenario. The IER data, which was generated by using the ABM approach, was extended to include scenario phases and events. As mentioned before, the IER data has the structure: Who; What; When; Where; and Why. An example set of IER matrix is as shown in Table 3.

Table 3 describes each IER in the following terms:

- Description: a basic summary of the context/operational relevance of the IER
- From/To: Information on the originator/receiver of the information exchange
    - Node: The name of the node originating the exchange

[7] Note that the Enemy node in Figure 1 represents the Enemy COA variable defined in Table 2.

  - Activity: The operational activity that the originating node is engaged in at the time of the exchange
  - Location: Sufficient location information to assess possible communication options and performance
- Required Latency: The time in which the exchange must occur for the information to be operationally useful
- Information Category: The purpose of the information exchanged, e.g. friendly locations (Blue Location); enemy locations (Red Locations); and information on how to conduct a mission (Orders and Control Measures).

Table 3: Example of information exchange

Description	From			To			Required	Information
	Node	Activity	Location	Node	Activity	Location	Latency	Category
Mission Orders	Amphibious Operations Officer	Planning Amphibious Operation	Amphibious Ship Command Centre	RW Platform (Crew)	Prepare for RW Mission	Amphibious Ship	Near Real Time	Control Information
Pre-Flight Briefing on Enemy	Amphibious Operations Officer	Process Intelligence	Amphibious Ship	RW Platform (Crew)	Prepare for RW Mission	Amphibious Ship	Real Time	Red Information
Provide location of RW platofrm during mission	RW Platform	Conduct RW Mission	Beach Landing Site	Amphibious Operations Officer	Command Landing Operations	20 km from BLS	Near Real Time	Blue Location

IERs as Causal Inferences
In order to incorporate IERs into a BBN they must be recast as causal statements. This is facilitated by considering that the data in Table 3 could be interpreted as a causal statement. For example, the first IER in Table 3 could be restated as:

The amphibious operations officer (From Node) *delivers control information to the RW platform* (To Node) *in order to provide mission orders* (IER Description) *to initiate a RW mission*.

This can be recorded as a causal relationship as shown in the RW1 entry in Table 4.

Similarly, the third IER could be stated as:

The RW platform (From Node) *delivers blue location information to the RW operations officer* (To Node) *in order to provide location of RW platform during mission* (description)

This is recorded in the Table 4 as RW 3 IER.

However, this information alone is insufficient to describe the impact of the C4ISR system on the exchange of the information. Additional information captured with each IER (refer to Table 3) can imply other necessary but lower level causal relationships. For example, given that there is a value associated with required latency for the RW 3 IER, this could be interpreted as the following causal statement:

There is a specified Latency (From Node) *required for the delivery of the Blue Location Information* (To Node) *to be useful* (Description)

This is added as causal reference RW3a. Similarly, information on the ability of the communication bearer available to deliver the information given the distance between from and to nodes can be similarly coded as a causal statement (RW3b).

Applying IERs to the BBN
Unfortunately, in applying the causal links generated by the IERs our BBN model becomes very large and unwieldy. This degrades its usefulness as a means to organise information and aide decision makers to understand a situation (NATO RTO, 2012). However, the IER based causal links assume a hierarchical structure (see Figure 4), resulting in several variables being strongly connected with each other and only weakly connected with the rest of the model. For example – *RW Support*, *Landing Craft Support*, and *Logistic Support* may be three almost autonomous subsystems that can be connected with each other through a small number of links and their information exchanges. These nodes are single nodes in Figure 1, but

linking each node with IER data create separate sub-systems. A decision maker may want to examine each of these subsystems in detail, but may also want to have a global view of the operational impact of information exchange in amphibious operations without unnecessary detail.

Table 4: Example of information exchange for RW Support

Source	Original Reference	Summary of Causal Relationship	Causal Phrase	Interpreted Causal Connector	Effect Phrase
IER RW 1	The amphibious operations officer (From Node) delivers control information to the RW platform (To Node) in order to provide mission orders (IER Description) to initiate a RW mission	Control information required to initiate RW mission	Control Information	**required by (+, strength unknown)**	RW Mission Planning (Process)
IER RW 3	The RW platform (From Node) delivers blue location information to the RW operations officer (To Node) in order to provide location of RW platform during mission (description)	Blue location information required to control RW mission	Blue Location Information	**required by (+, strength unknown)**	RW Operations Officer
IER RW 3 a	There is a specified Latency (From Node) required for the delivery of the Blue Location Information (To Node) to be useful (Description	Specified latency required for delivered blue information	(Sepecified) Latency	**Required for delivery of (+, strength unknown)**	Blue Location Information
IER RW 3 b	Delivery of the Blue Location Information must be possible within the constraints of distance and communication bearer capabilities	Communication connectivity required to deliver blue location information	Ability to Deliver Information	**Required by (+, strength unknown)**	Blue Location Information

We adapt a sub-modelling approach proposed in (Zagorecki and Druzdzel, 2006). Sub-models are special types of nodes that host sub-graphs of the entire graph and make the graph view structured almost hierarchically. Sub-modelling facilitates modularity in large models. The internals of a sub-model along with its structure can be examined in separation from the entire model. The concept map in Figure 1 is now restructured with the sub-modelling approach as shown in Figure 3. It is shown in Figure 3 that highly connected and similarly functioning nodes are grouped into sub-models, where rectangular nodes representing sub-models. Note that a sub-model is a collection of nodes, while arcs in Figure 3 indicate linking between nodes in each sub-model. Therefore, two way relationships between sub-models and loops appear in Figure 3 but not between nodes.

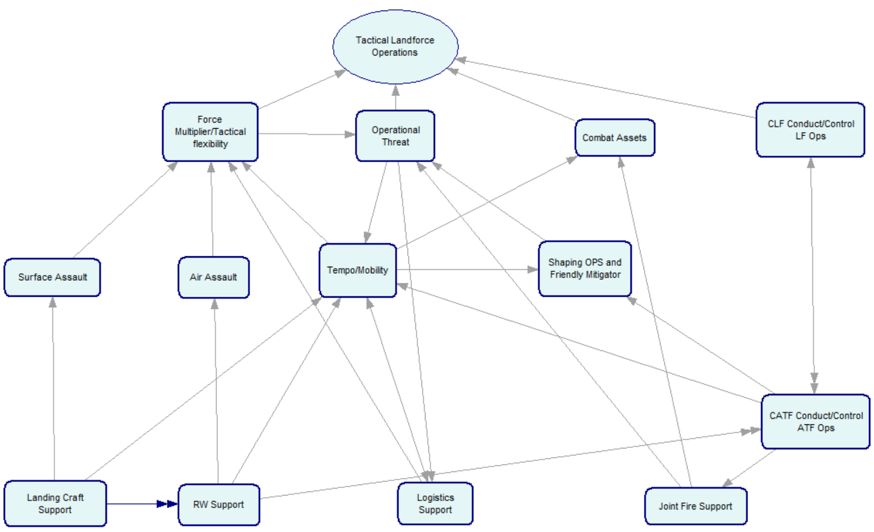

Figure 3: Amphibious concept map with sub-modeling approach

A RW support sub-model that incorporates information exchange links is shown in Figure 4. A review of the sub-model suggests that IERs provide a promising means to capture C4ISR impacts on amphibious capabilities, as they:

- provide a tangible means to represent C4ISR effects at the tactical levels
- directly capture operational effects and measures relevant to the quality and delivery of C4ISR products
- facilitate data elicitation from operational SME (e.g. "How likely is it that your knowledge of friendly (blue) locations be in a high state given that useful information was provided but delayed".)

However, linking information exchange data to BBN will significantly increase the number of nodes and arcs, and this will lead to exponentially increasing number of conditional probability assessments. There are several approaches to reduce the number of conditional probability assessments. Amongst the most promising is the Noisy-OR model, originally introduced in (Kim and Pearl, 1983). The Noisy-OR model reduces the number of probabilities to be specified by making additional assumptions about the underlying causal structure of the variables. For the Noisy-OR model, the number of probabilities needed to determine the full CPT is linear in the number of conditioning variables, rather than exponential. Although this can mean a huge reduction in elicitation effort, the assumptions necessary are strong and all the variables in the noisy-OR model need to be binary, which strongly limits the applicability of the method. The Noisy-MAX model (Dıez, 1993) can be seen as the extension of the Noisy-OR to multi-valued variables. In this model the CPT is derived from 'marginal conditional' distributions specified for each parent: for each parent the probabilities conditional on this parent node are specified and subsequently the full CPT is derived from these conditional probabilities using the max function. The influences of each of the parent nodes are treated in this model as independent. So the joint influence that the parent nodes exercise is fully determined by their marginal influence and a fixed function. While some evidence exists that suggests that the Noisy-Max assumptions may be broadly applicable (Zagorecki, 2010) research in this area and its applicability to the information exchange BBN model requires further investigation.

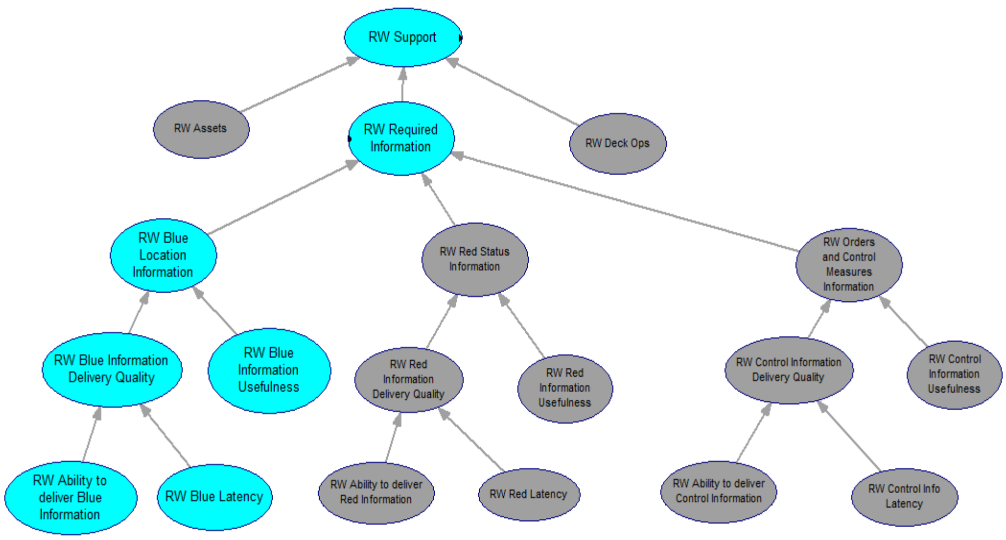

Figure 4: Information exchange RW support sub-model, blue nodes indicate data presented in Table 4.

5. CONCLUSION

The driving force behind this work has been a desire to find suitable tools to model uncertainties in amphibious C4ISR systems and to analyse the impact of these systems on amphibious operations. The graphical techniques of Bayesian networks, as we have demonstrated, potentially provide a rich tool to comprehend and analyse these uncertainties. The pictorial display of the model as a graph facilitates easy understanding and therefore would be of great help in rapid model development. The framework of Bayesian networks divides the model development process into two parts decoupling the qualitative aspects from the quantitative ones. This enables the user to first concentrate on building the causal structure of the network without worrying about the probabilistic aspects. The incorporation of IERs into a Bayesian Network appears to be a promising method with potential to represent lower level C4ISR effects in a way that can be understood by operational SMEs. However, challenges remain in the viability of data elicitation due to the exceptionally high numbers of conditional probability assessments that must be made with SMEs. In the section dealing with information exchange we have advocated that further research in reducing the number of elicited conditional probability is needed to be pursued. One of key weaknesses of BBN is its acyclic graph structure that cannot model feedback processes which occur very commonly in C4ISR. As a side effect of this weakness, BBN represented a relatively steady state of the operation rather than a dynamic process in which time could be critical issues. This problem could be overcome by extending existing BBN to the temporal dimension. The temporal extension of BBN does not mean that the network structure or parameters changes dynamically, but that a dynamic C4ISR system is modelled. A dynamic BBN is a directed, acyclic graphical model of a stochastic process. It consists of time-slices (or time-steps), with each time-slice containing its own variables. However, this approach will significantly increase the scale of our problem; it is worth investigating the feasibility of dynamic BBN for modelling C4ISR system in our future work.

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