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A Centre of Gravity Analysis Tool to Support Operational Planning

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Abstract

The Australian Defence Science and Technology Organisation (DSTO) is developing a centre of gravity (COG) analysis tool, intended to support operational planning in the Australian Defence Force (ADF). This tool provides a visual representation of the COG causal structure and an impact and later effects-based analysis capability, which facilitates the determination of the critical vulnerabilities that have to be degraded or negated to influence the COG. Furthermore it provides a framework, which can serve as a knowledge base representing generic causal relationships to aid knowledge reuse and knowledge transfer. In this paper we describe the COG Network Effects Tool (COGNET) suite, its underlying generic capability-models database and steps towards integrating the tool into the ADF joint planning process.

1. Introduction

The Australian Defence Science and Technology Organisation (DSTO) is developing an integrated modelling and simulation suite to support the Australian Defence Force (ADF) in operational-level planning. The ADF uses a mature planning process to provide Courses of Action (COA) to the operational-level commander. The process is a four step formal construct and is called the Joint Military Appreciation Process (JMAP), doctrine for which is developed and maintained by the ADF Warfare Centre (ADFWC). Planning outcomes include a military end-state and identification of the centres of gravity (COG) for the threat and friendly forces, critical capabilities (CC), critical requirements (CR), critical vulnerabilities (CV) and decisive points (DP). The initial stage of any operational-level planning process typically includes some form of mission analysis. This involves identifying and analysing the superior commander's intent in order to ensure that commanders and staff can determine which tasks are essential to achieve the operational objective. Correct assessment of the objective is deemed to be crucial to success at the operational level ([ADFP 9], Chapter 4). Mission analysis relies heavily on input from the joint intelligence preparation of the battlespace (JIPB), in particular intelligence on the enemy centre of gravity (COG) and the likely enemy COA. The COG, a key concept of operational art, is defined as *that characteristic, capability or locality from which a military force, nation or* *alliance derives its freedom of action, strength or will to fight at that level of conflict* [ADFP 9].

Once the enemy COG has been determined, planners generate suitable COA (a COA is judged suitable if it meets the objectives as detailed in the mission analysis step). Since directly targeting the enemy COG is not usually feasible a critical capability analysis is conducted at this stage of the planning process. A critical capability is defined to be *a characteristic or key element of a force that if destroyed, captured or neutralised will significantly undermine the fighting capability of the force and its centre of gravity* [ADFP 9]. Critical capabilities are then further decomposed into associated critical requirements. These requirements are further analysed and may be judged to be critical vulnerabilities; i.e. elements that are potentially vulnerable ([ADFP 9], Chapter 8). The idea behind critical capability analysis is to identify which aspects of the threat critical requirements can be targeted in order to influence the enemy critical capabilities and hence the COG.

A good understanding of the key concepts of operational art is as essential for military operational planners as it is for developers of planning support tools. Previous work has investigated the qualitative relationship between these planning concepts [Falzon *et al.*, 2000, Zhang *et al.*, 2000]. COGNET is being developed to facilitate a more rigorous and systematic approach to COG analysis. The concepts underlying COGNET, which uses Bayesian (or causal probabilistic) networks, which reflect the relationships between the CC's and CR's, has been described previously [Falzon *et al.*, 2001] and only a brief description will be given here. In this paper we describe the COGNET tool suite, the generic capability-models database and steps towards integrating the tool into the ADF joint planning process.

JMAP is a complex multi-path problem-solving tool. Previous observations have identified a logical disconnect between COG analysis and development of the COA within the process. COGNET reinforces the logical link between these two steps. In addition COGNET automates certain parts of the process thereby allowing the planners more time to apply intellectual rigour to alternative COA. COGNET provides a rigorous and consistent framework for COG representation and analysis.

2. Description of the tool: COGNET

2.1. Overview

Late in 1999 the Systems Simulation and Assessment Group of DSTO attended the Joint operational planning course at the ADFWC with the objective of developing modelling & analysis tools to support operational-level planning. It was observed that the identification, representation and analysis of centres of gravity were a key component of the course. With the ADF's increasing emphasis on developing and applying operational art in the planning and conduct of military campaigns, it was considered useful to develop a knowledge-based system support tool that can complement and incorporate operational art in order to facilitate the process of COG identification, representation and analysis. COGNET, which uses a Bayesian engine (see the following section) to investigate COG/CC/CR/CV relationship structures, is being developed in support of the ADF. COGNET provides a visual representation of the COG causal structure and an effects-based analysis capability, which facilitates the determination of the critical vulnerabilities that have to be degraded or negated to influence the COG. Furthermore it provides a framework and database structure, which can serve as a knowledge base representing generic causal relationships to aid knowledge reuse and knowledge transfer. In addition, COGNET includes:

- An underlying database for the flexible management of COG element categorisation;
- A higher-level user interface that aids model construction, data maintenance and interaction;
- Software utilities for impact and later effects based analysis; and
- A choice of tailored conditional probability table generation software.

2.2 Bayesian Engine

Bayesian networks (BN) are graphical representations of causal relations in a particular domain. They are typically used to model a domain that has inherent uncertainty due to a combination of incomplete knowledge of the domain and randomness in the environment [Jensen, 1996]. The network may be represented by a directed acyclic graph whose nodes correspond to random variables, which can take on two or more values, and which are linked by causal dependencies. The causal direction is represented by the direction of the arcs in the graph. Nodes that have arcs directed towards them are called destination (or children) nodes while nodes with arcs directed away from them are known as origin (or parent) nodes. Internal nodes are both origin and destination nodes (or parent and children), whereas the nodes at the edge of the network are either root nodes (they only have arcs directed away from them) or terminal nodes (purely destination nodes). Figure 1 shows an example Bayesian network model produced in HUGIN [www.hugin.com], a software tool for building Bayesian networks, which forms the Bayesian engine for COGNET. The net depicted represents a critical capability (in this case Air Defence (AD)), which for logical convenience, has been further decomposed into critical requirements to ensure that root nodes represent possible critical vulnerabilities.

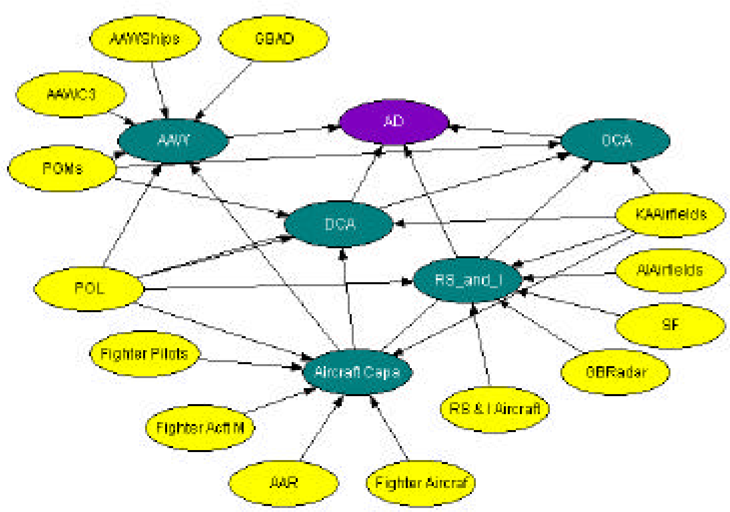


Figure 1: Simple Bayesian Network capability model

The strength of the causal relationship is expressed as a conditional probability. Each node has a set of two or more potential values or states. In the examples presented here each node can take on two values, called strong and weak, which describe the current belief in the operational state of the capability or requirement corresponding to that node. The probability of being in each particular state is conditioned on the state of each of its neighbouring parent nodes. The probability distribution of a Bayesian net is specified by assigning to each root node an initial probability of being in each state and assigning conditional probabilities (conditional on all possible combinations of the states of all neighbouring origin nodes) to all other nodes in the network. As Pearl [Pearl, 1988] points out, the advantage of this graphical representation is that it allows a specification of direct dependencies representing the fundamental qualitative relationships. The network structure then augments these relationships with a consistent set of induced indirect dependencies, which are stable and independent of the numerical probability estimates. It is then possible to calculate the probabilities of the states of the terminal nodes each time the probability values of the root nodes change.

AAW	DCA	OCA	RS & I	Likelihood of AD being Strong	Likelihood of AD being Weak
Strong	Strong	Strong	Strong	0.99	0.01
Strong	Strong	Strong	Weak	0.70	0.3
Strong	Strong	Weak	Strong	0.75	0.25
Strong	Strong	Weak	Weak	0.5	0.5
Strong	Weak	Strong	Strong	0.75	0.25
Strong	Weak	Strong	Weak	0.5	0.5
Strong	Weak	Weak	Strong	0.5	0.5
Strong	Weak	Weak	Weak	0.25	0.75
Weak	Strong	Strong	Strong	0.75	0.25
Weak	Strong	Strong	Weak	0.5	0.5
Weak	Strong	Weak	Strong	0.5	0.5
Weak	Strong	Weak	Weak	0.25	0.75
Weak	Weak	Strong	Strong	0.5	0.5
Weak	Weak	Strong	Weak	0.25	0.75
Weak	Weak	Weak	Strong	0.25	0.75
Weak	Weak	Weak	Weak	0.01	0.99

Figure 2: Conditional probability for Air Defence capability

The probabilities required for a Bayesian network are normally elicited from a subject matter expert. They may be completely subjective estimates of the likelihood of an event. However, in Bayesian formalism the measures must obey the fundamental axioms of probability theory, which allows us to determine whether the model is complete and consistent. Another advantage of using Bayesian nets is that determining context-dependent probabilities is much more compatible with human reasoning than estimating absolute probabilities. In the statement “the probability of A given B”, B serves as a context for the belief attributed to A and is much easier to determine than “the probability of A and B”. Probabilities provide the means for drawing inferences from causal connections and the relative strengths of these connections. However, obtaining these probabilities can sometimes be problematic due to the cognitive demand placed on the domain expert. For example in Figure 1 the probability that the AD capability is in a strong state is conditioned on whether Anti Air Warfare (AAW), Defensive Counter Air (DCA), Offensive Counter Air (OCA) and Reconnaissance, Surveillance and Intelligence (RS & I) are in a strong or weak state. The Conditional Probability Table (CPT) is shown in Figure 2. As can be seen this requires specifying sixteen probabilities. The number of probabilities to be assigned can become excessively large in situations where the number of requirements for a capability increases above five. For example, the aircraft capability of Figure 1 has six critical requirements, which equates to the assignment of sixty-four conditional probabilities. Systems for overcoming this problem are discussed later in this paper but it must be stressed that the ability to specify the CPT directly, if required, is an important feature of the COGNET design.

2.3 Generic Models

During the course of the development of COGNET the need for a modular knowledge representation framework became evident. Deliberate (long-term) planning at the operational level aims at developing plans that can be adapted when a conflict or situation arises, to meet the objectives set out by strategic guidance. While the COG for a particular force may change according to circumstance, a relatively fixed causal network can reflect the current force structure and capabilities over a fixed set of critical capabilities depending on a fixed set of requirements. The network structure would be invariant for a range of problems but the causal strengths may vary with respect to the specific COG being considered.

A knowledge representation framework expressing the invariant causal relationships is being constructed for each specific operational capability. This serves as a knowledge base expressing generic causal relationships with probabilistic strengths integrated into the model to tailor it to a particular situation. The generic framework is built on the basis of categorisation of operational-level capabilities. Model construction uses generic military categories such as Command & Control, Protection, Deployment etc and their underlying requirements, organised in hierarchies of subnetworks, which can be combined as required for each specific scenario. In order to ensure that the generic model is sufficiently extensive and consistent, a hierarchically organised reference system such as a Joint Task List (JTL) [UJTL, 1996] is used as a basis. Task areas at the top level of the hierarchy are mapped to military capabilities, while subtasks at the lower levels are mapped to critical requirements wherever possible. The structure of a JTL is such that any task can be traced through the hierarchy to determine its contribution to higher-level tasks. In the same way our generic model can help determine which of the requirements are critical for threat (or own) capability. Such a comprehensive Bayesian net can be large and complex but may be built from a library of modular subnets reflecting the hierarchical structure and capturing the stable patterns of probabilistic relationships. This generic framework has been constructed in COGNET and is based upon a relational database system, which stores relevant entity data of capability models and is discussed in the next section.

2.4 The COGNET User Interface

The COGNET application consists of a user interface and relational database system. Figure 3 depicts the COGNET system. Upon entry into COGNET a user is presented with a choice of several data-sources that may be opened, each of which may have been created and managed by different headquarters (HQ) or organisations. A data-source contains appropriate capability models and generic model-frameworks for the particular HQ or organisation. Each data-source selected consists of three main sets of tables defining entities, types and scenarios. The entity tables contain the list of entities and their relationships to one another according to the generic capability models developed. Development of the generic database is still ongoing. The types tables contain the standard nomenclature data used to populate the entity tables. For specific situations or scenarios, data can be generated from the relevant entity tables to create scenario specific data tables.

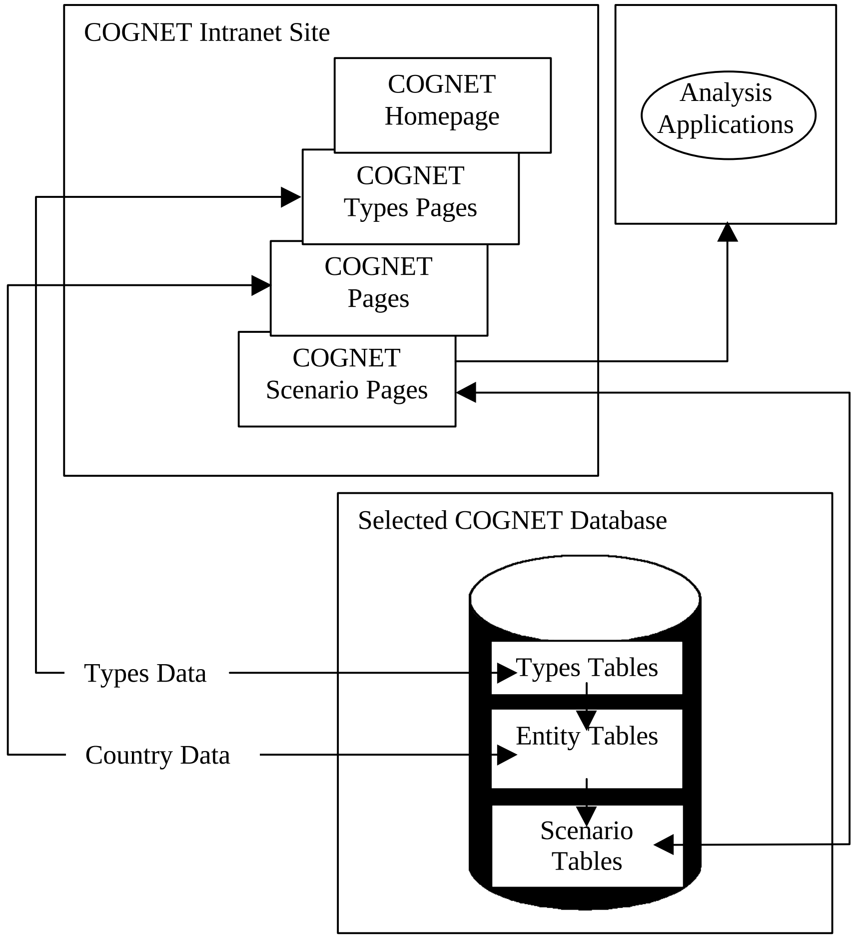
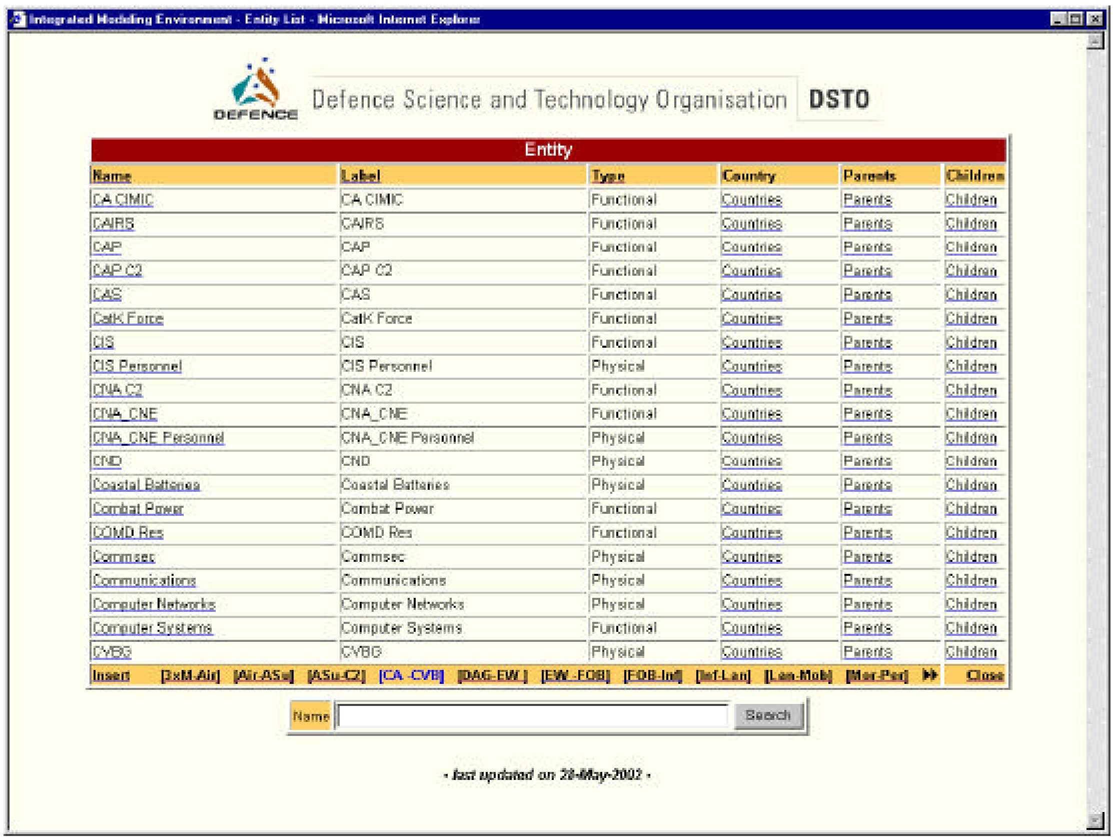


Figure 3: COGNET interface block diagram

Figure 4 shows a typical screen shot from the COGNET generic capability database, which is the centrepiece of the development of COGNET. The generic capability database is built on the basis of operational-level capability categorisation. These capability databases range from standard warfare capabilities such as Combat Air Patrol (CAP) (shown later in Figure 5) to Information Operations (IO). Each capability model has been constructed using generic military categories such as Deployment, Protection, Sustainment, Command & Control, etc.

The relationships between entities needed to form BN capability models are stored within the database in the form of parent and children associations. In addition, country associations can be added to entities or capabilities in the database. For example, a country (or countries) that exists within the database can have CAP (and its appropriate entities) associated with it if it has that capability. The ability to tag individual entities with a country association also allows the removal (or addition) of entities from a capability model for that particular country. As an example let us consider two countries A and B that are in a situation that requires CAP. Let us also consider in this situation that country A has Air-to-Air Refuelling (AAR) available and country B does not. (AAR, a force (or capability) multiplier, allows CAP to be used in situations where its operating base is a significant distance from the Area of Operations (AO) and hence is an important element of CAP.) The remaining entities required for CAP are the same for both countries. In COGNET this is implemented by tagging the CAP entity with countries A and B, and tagging each of its sub-elements with A and B, with the exception of AAR, which is only tagged with country A. The ability to associate countries with entities in this manner allows several country capability models to be generated from a single generic 'catch all' model.

The generic capability database can then be used in the development of a scenario dependent COG model.


Integrated Modelling Environment - Entity List - Microsoft Internet Explorer

DEFENCE Defence Science and Technology Organisation DSTO

Entity

Name	Label	Type	Country	Parents	Children
CA CIMIC	CA CIMIC	Functional	Countries	Parents	Children
CAIRS	CAIRS	Functional	Countries	Parents	Children
CAP	CAP	Functional	Countries	Parents	Children
CAP C2	CAP C2	Functional	Countries	Parents	Children
CAS	CAS	Functional	Countries	Parents	Children
CatK Force	CatK Force	Functional	Countries	Parents	Children
CIS	CIS	Functional	Countries	Parents	Children
CIS Personnel	CIS Personnel	Physical	Countries	Parents	Children
CNA C2	CNA C2	Functional	Countries	Parents	Children
CNA_CNE	CNA_CNE	Functional	Countries	Parents	Children
CNA_CNE Personnel	CNA_CNE Personnel	Physical	Countries	Parents	Children
CND	CND	Physical	Countries	Parents	Children
Coastal Batteries	Coastal Batteries	Physical	Countries	Parents	Children
Combat Power	Combat Power	Functional	Countries	Parents	Children
COMD Res	COMD Res	Functional	Countries	Parents	Children
Commsec	Commsec	Physical	Countries	Parents	Children
Communications	Communications	Physical	Countries	Parents	Children
Computer Networks	Computer Networks	Physical	Countries	Parents	Children
Computer Systems	Computer Systems	Functional	Countries	Parents	Children
CVBG	CVBG	Physical	Countries	Parents	Children

Insert [3xM-Air] [Air-ASu] [ASu-C2] [CA -CVB] [DAG-EW] [EW -FOB] [FOB-Inf] [Inf-Lan] [Lan-Mob] [Mar-Per] Close

Name Search

- last updated on 28-May-2002 -

Figure 4: Example interface to COGNET generic capability database

2.4.1 Scenario Development

It is conceivable that for a particular force the COG changes according to the circumstances or type of conflict. The current force structure for a particular force will, however, remain the same. This can be represented by a relatively fixed causal network, in which only the causal strengths vary according to the scenario. Using COGNET it is possible to tailor models to a particular situation using the generic framework. For a particular situation with a specific COG the user can create a new scenario table and import countries and their associated entities from the generic database of models. The network then consists of a subnet of capabilities and requirements from the generic database of models for that country. Entities that are irrelevant for a specific scenario, or COG, are simply deleted or 'desensitised' along with any entities that were only influenced by those deleted entities. The probabilistic interrelationships among relevant entities and capabilities can then be re-examined in light of the specific problem at hand, including the critical capabilities for the defined COG. Part of the re-examination can be facilitated by way of the CPT generation utility.

2.5 The Conditional Probability Table Generation Utility

Acquiring the probabilities for a Bayesian network can be difficult due to the cognitive load placed on the subject matter expert. We adopt a Bayesian or subjective interpretation of probability as opposed to an empirical or relative frequency interpretation. While the Bayesian interpretation describes the probability of the occurrence of an event A, *P(A)*, as a measure of our uncertainty about the occurrence, the Frequentist defines *P*(*A*) as the frequency of *A* in a large sequence of *actual* trials. There is no historical data from which these probabilities can be determined and conducting realistic trials for the purpose of collecting this type of data is impractical. Since this alternative is not available probabilities are assigned on the basis of experience, beliefs and intuition. The subjective approach capitalises on the experience of subject matter experts.

Let us consider the nature of the cognitive load problem by way of the CAP capability example. CAP is dependent on six parent entities as shown in Figure 5. If each of these entities has two possible states (strong and weak), then sixty-four conditional probabilities must be specified for the likelihoods associated with CAP. In situations where there are more parent entities, and possibly more entity states, there are a large number of distributions to be subjectively assigned by the user. Hence the problem is now one of high *cognitive load* requiring a considerable amount of time. Research into this problem at DSTO has focussed on the development of a utility with a high-level user interface and built-in algorithms that generate a CPT with much less cognitive effort, but without loss of mathematical rigour, in cases in which time is constrained. Several algorithms are being investigated for use in COGNET.

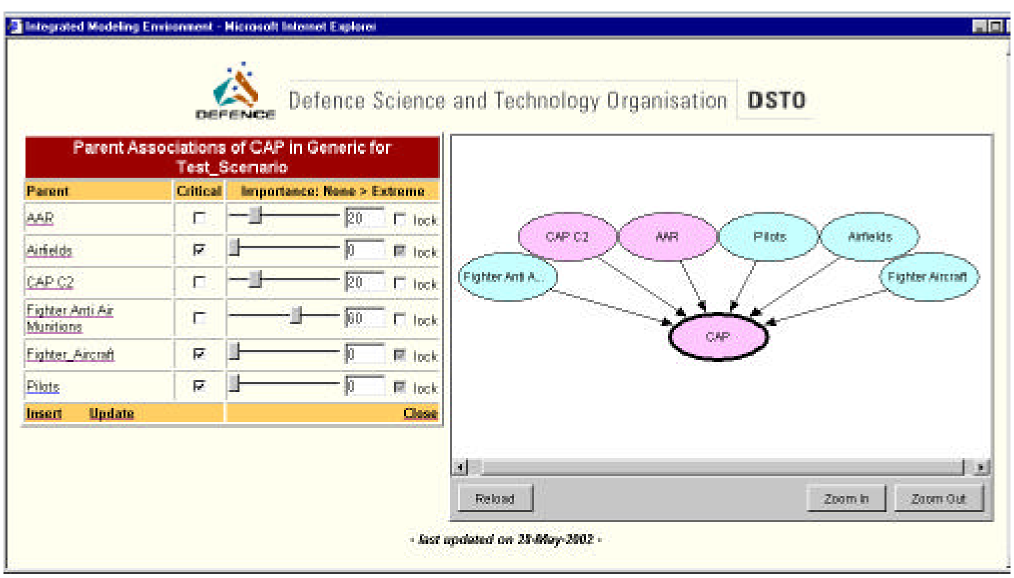


Figure 5: Example of COGNET generic capability database

The algorithm adopted here implements a weighted sum technique and is fully described in a separate paper [Das, 2002]. This algorithm reduces the cognitive load required to generate the CPT by allowing the user to consider the effects on the child node for each parent node in-turn, thus reducing the number of probability distributions to be specified. This constitutes the first step in CPT generation. Next, the user is asked to consider the intensity of the importance of each parent node on the child node in terms of relative weights. Thus, if a critical requirement A is considered to be twice as important to capability C as critical requirement B it is assigned twice the weight. The weighted sum algorithm can now be used to fully populate the CPT. For example, if a node has six parent nodes the algorithm reduces the number of probabilities that need to be specified from 64 (2^6) to 12 (2×6) by automatically generating 64 probabilities from the six weights and the twelve probability distributions assigned. Figure 5 shows how the weights for the parent nodes of CAP are entered. The user considers, in the context of the scenario, the importance of all relative entities that make up CAP. The user also specifies whether an entity is critical to the capability. An entity is defined to be critical to a capability if the latter is totally dependent on it. In this example AAR is not considered to be critical to the CAP capability, but airfields, aircraft and pilots are. It must be stressed again that the CPT can be specified or modified directly if required.

Once the complete scenario COG model has been constructed and populated it can be further analysed.

2.6 The Impact Analysis Utility

Impact analysis facilitates the ability to identify which of the threat requirements are critical and to investigate the potential impact they have on the enemy COG. It is conducted in HUGIN by changing the initial probabilities of the states of the initial nodes and observing the propagated effect on the COG. This analysis has been automated in COGNET such that a user can generate a list of initial nodes ordered by the potential effect on the COG.

Let us demonstrate a Bayesian Network representation of a typical critical capability analysis. The network shown in Figure 6 represents a COG analysis exercise observed by the authors at the ADFWC Joint Operations Planning Course. It is based upon a fictitious scenario used for training purposes in which the perceived threat was an imminent invasion of an island belonging to an ally. The threat COG was assessed as the ability of the enemy to project force, which was subsequently broken down into its associated critical capabilities and requirements. The root nodes represent critical elements that are potential targets and hence vulnerable.

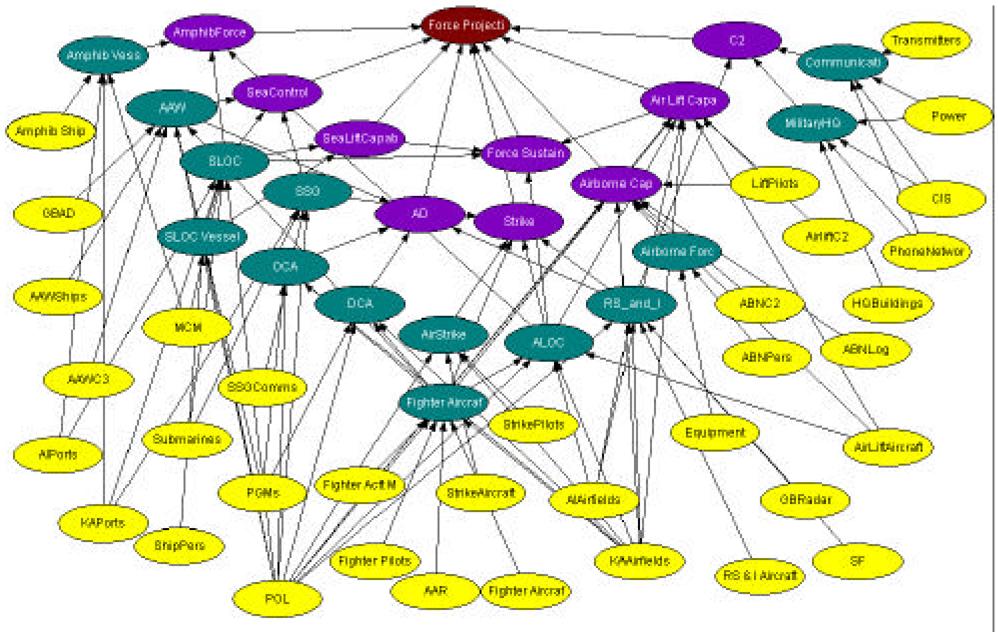


Figure 6: An example threat COG network

Figure 7 shows the initial probability distribution assigned to the network. Each root node is assigned a probability of being in each state, independent of the status of all other nodes. All remaining nodes have a conditional probability table defining the probability of being in each state conditioned on the states of its neighbouring origin nodes.

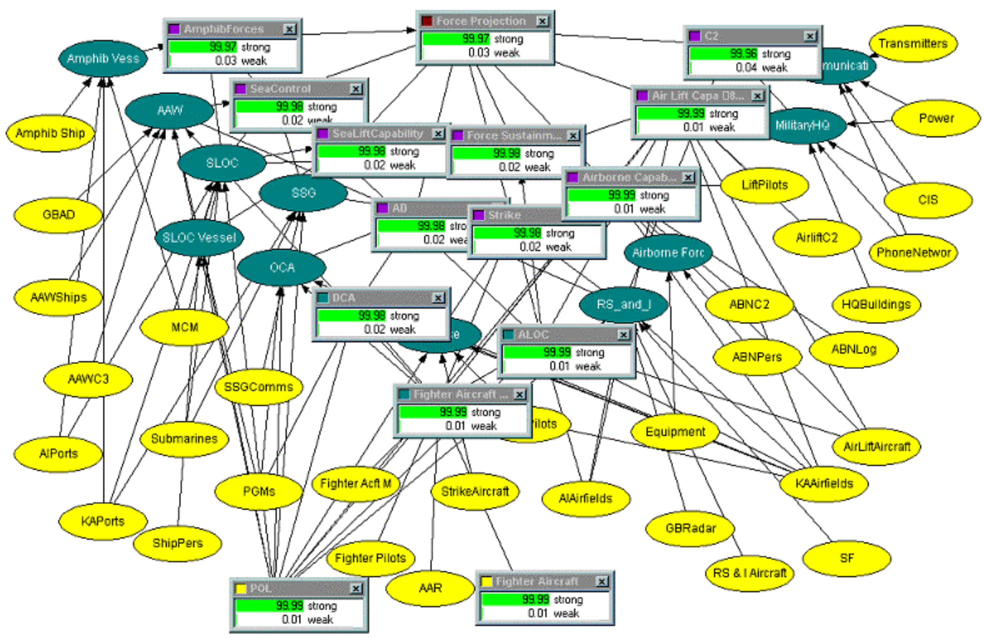


Figure 7: Initial probability distributions - base case of analysis

As can be seen from Figure 7 the initial probability distribution for all root nodes has been set to 99.9% probability of being in a strong state. This is as one might expect at the start of a conflict. As the probabilities propagate up to the COG the probability of the COG being in a strong state is calculated as 99.97%. This is therefore our base case of analysis.

We are now in a position to do some basic impact analysis, that is, to answer some "what if" questions. In Figure 8 the effects of targeting the enemy's Petroleum, Oils and Lubricants (POL) stocks and fighter aircraft such that they are considered to be in a weak state are seen. The probability that the COG is in a strong state has now reduced to 53.08%, given that the probability distributions of the target requirements are as shown. POL and fighter aircraft have a marked effect on intermediate nodes such as DCA and Airborne capability due to criticalities in the relationships.

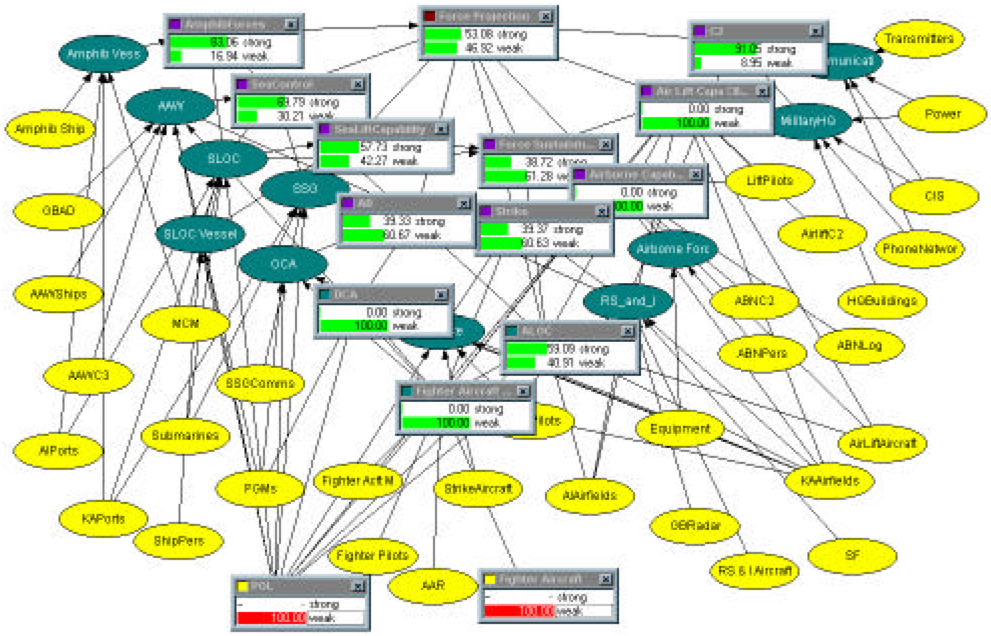


Figure 8: The effects of targeting certain critical requirements

This system allows the operator to investigate the effect of targeting a single or set of root nodes. However, a manual analysis of all combinations would be quite laborious. To facilitate a complete analysis of the network an automated impact analysis utility, which utilises the Bayesian engine, has been constructed. The impact analysis utility allows the user to investigate the impact that all critical requirements (some of which may be critical vulnerabilities) have on the COG. Again, impact on CR here means rendering weak. Analysis can be done singularly or in multiple configurations of root nodes, thus allowing the user to construct a possible set of critical vulnerabilities to target. Figure 9 shows the impact analysis utility and results when used upon the COG construct. The bar chart to the right of Figure 9 shows the root nodes that have the greatest effect on the COG. The operator, after analysis, has the option of saving the results to file for presentation.

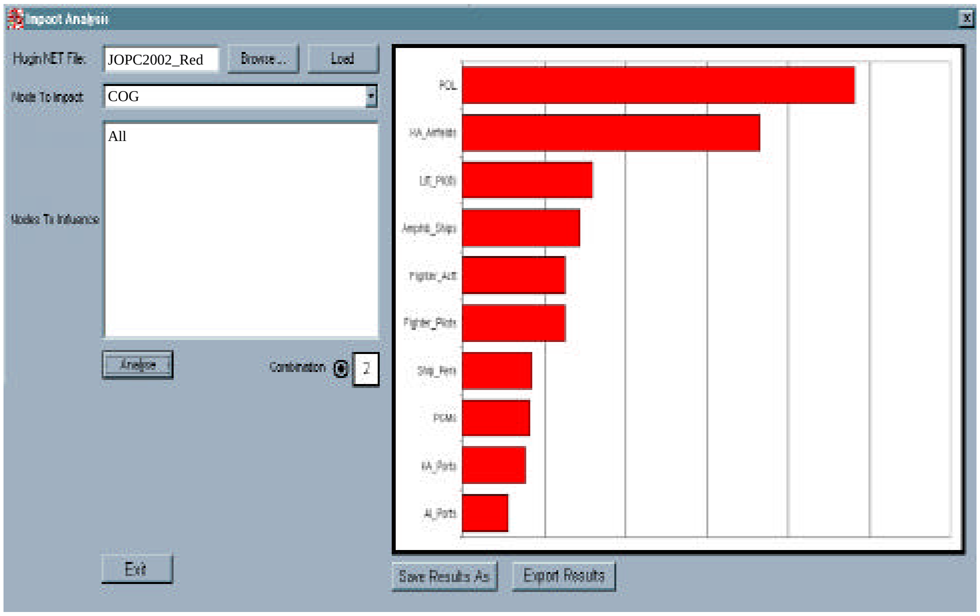


Figure 9: The effects of targeting certain critical requirements

3. COGNET integration into JMAP training

An important aspect of this work is integrating COGNET into the ADF planning process. This will only succeed if the tool is seen to save time and effort and/or improves the quality of planning products. Since the inception of COGNET the developers have involved operational planning instructors at the ADF Warfare Centre in the conceptual development in order to ensure that the philosophy underlying the models is compatible with ADF doctrine and the planning process. The instructors have also formed a major part of our domain expert pool, and so have contributed to populating the generic models. In addition to this constant interaction with the instructors we have also been given the opportunity to introduce the tool to operational planning students during week-long planning exercises, which are a crucial part of the training. Apart from the obvious benefit of having future planning officers become familiar with COGNET, trials of the tool also provide us with instant feedback of the performance and utility of the tool in realistic conditions.

The strategy adopted so far in our trials of COGNET in the planning course has been to adopt a non-intrusive approach. During the COG analysis step of the planning exercise, analysts only observe the derivation of COG-CC-CR determined by the students. This is normally recorded in tabular form and a cursory analysis is conducted to determine which enemy requirements should be targeted in the planned course of action. Based on this the analysts quickly produce a Bayesian net reflecting the structure of the COG table produced by the students. The net is populated by means of the CPT generation software based on weights elicited from the students. A more rigorous analysis is subsequently demonstrated to the students using the impact analysis software.

Observations from recent COGNET trials conducted during a planning course at ADFWC were very positive. The students were able to validate their analysis and review their lines of operation obtained through the JMAP process. The graphic demonstration of the tools flexibility and the reinforcement of the requirement to maintain the link between centres of gravity and course of action development demonstrate the practicality of the tool in one showing. One of the major uses for the tool will be to reduce the amount of time to produce outcomes in the COA development step of JMAP. With the generic database providing a valid start point for operational level planning, novice members of planning teams will be able to contribute in a positive manner without the requirement of a complete knowledge base. It is anticipated that the use of COGNET will result in a reduction in time to complete the JMAP and possibly alleviate the requirement for subject matter experts to attend planning groups. COGNET fosters greater rigour and consistency within the planning process.

4. Future work

ADFWC in collaboration with DSTO will continue to populate the generic database with specialist information, including electronic warfare, communication, logistics and health data. A major task will be the maintenance and validation of the models in the generic database. Continued participation in operational level planning courses is necessary for feedback to shape ongoing development. Introduction of COGNET to real-world planning groups is programmed once the usefulness of the tool is validated over time.

5. Acknowledgements

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