A Policy Analysis Approach to Operational Level Course of Action Analysis

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Abstract

Our aim is to develop a relational model between the operational art concepts of *end-state*, *centre of gravity*, *critical vulnerabilities* and *decisive points* as currently used by planners in course of action (COA) development. It is motivated by a need for a methodology for COA analysis based on the concepts underlying military COA development but with a theoretical underpinning derived from policy analysis. In this paper we describe a modelling framework based on the relationships among the planning concepts listed above. We then use this framework as a basis for an influence model to support COA development and a quantitative analysis model to support COA analysis.

Functional decomposition is used to identify the elements that influence a centre of gravity and to categorise them into a six-layer hierarchy: centre of gravity, capabilities (environmental), abstract functions, general functions, processes and physical systems. The models facilitate the determination of the set of actions required to influence the centre of gravity. The kind of complex decision problems under consideration here have multiple dimensions of cost and impact associated with an outcome. We take the systems analysis approach of disaggregating the problem systematically and evaluating the expected risks, costs and impacts associated with each action.

1. **Introduction**

Policy analysis attempts to "evaluate, order and structure incomplete knowledge so as to allow decisions to be made with as complete an understanding as possible of the current state of knowledge, its limitations and implications" [Morgan and Henrion, 1990]. This description ties in very well with military command and control, described by Levis and Athans [Levis and Athans, 1987] as an endless quest for a reduction in uncertainty. They subscribe to the military historian M.Van Creveld's view that "The history of command in war consists essentially of an endless quest for certainty about the state, activities and intentions of enemy forces, about the … environment and about the state, activities and intentions of one's own forces". In this context uncertainty is defined as the difference between the knowledge required to accomplish a mission and the knowledge a decision maker has at that time. Hence uncertainty is inversely proportional to the decision-maker's level of understanding of the current state.

Policy analysis is normally performed with some decision-making criteria in mind. One category of criteria is based on the valuation of outcomes such as benefits and costs. Another focuses on reduction or elimination of risks, independent of costs and benefits. The criteria to be adopted in the analysis should be explicitly declared. Uncertainties about quantities or

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about the appropriate model structure should also be declared explicitly and a systematic sensitivity and uncertainty analysis should be conducted in order to determine the effect that changes and uncertainties in input values and models have on the concluding analysis [Morgan and Henrion, 1990]. Sensitivity analysis can also be used to check the sensitivity of the model to changes in subjective values. In complex decision problems, in which multiple criteria might influence a decision, an arbitrary weighted index of utility can be used. In these cases it is imperative to evaluate the sensitivity to changes in utility values, importance weights and combination rules [Barclay *et al.*, 1977].

Operations Research techniques such as dynamic programming, stochastic modelling and optimisation are commonly used for decision analysis. Decision analysis provides a systematic method for structuring a complex decision problem. Barclay et al. present a methodology [Barclay *et al.*, 1977] which is based on four elements: a set of initial courses of action, a set of possible consequences for each initial act, the value of each act in terms of money, utility or some other unit and the likelihood that a particular act will result in a particular consequence. We will show below that the first two elements are an integral part of Course of Action (COA) development in military operational level planning. The last two elements should form the basis of a systematic COA analysis as demonstrated in Filar et al. [Filar *et al.*, 1999]. They propose a task network model to perform quantitative comparison of candidate courses of action in a generic combat situation. Each course of action is modelled as a sequence of tasks that need to be accomplished. The task sequences are represented by directed paths of a graph, in which each node corresponds to a task and each arc represents the implementation of the task corresponding to the destination node. The performance criteria on which the analysis is based include cost, impact on the enemy and risk of failure.

In this paper we present COA development and analysis models based on the concepts underlying military COA development but with a theoretical underpinning derived from policy analysis.

2. Systematic decision making

The kind of complex decision problems under consideration here have multiple dimensions of cost and impact associated with an outcome. Often the dimensions of value are qualitative and very subjective. The systems analysis approach of disaggregating the problem systematically and evaluating the expected utilities associated with multiple attributes (including inherent risk) provides a way around this problem. In this way individual domain experts can make a judgement in their own area of expertise rather than an overall judgement in a complex domain. Judgements about values are by nature subjective and vary among individuals. In order to solve a complex decision problem we need a structure which models the components within the system and the causal influences and effects among the components so that it enables us to elicit judgements and represent them quantitatively. In the approach advocated by Saaty [Saaty, 96], judgement is based on paired comparisons relative to a common criterion or goal. Similarly, probabilistic modelling techniques, such as Bayesian belief networks and influence diagrams, rely on the ability of probability theory to process context-sensitive beliefs [Pearl, 97]. These models are populated with conditional probabilities (the probability that A is true given the context, C) which are easier to estimate than absolute probabilities.

An added advantage gained by disaggregating the problem and modelling the causal influences is the link between the overall effectiveness of the COA to measures of utility that

are traceable and subject to scrutiny. It is an attempt at scaling the decision-makers' subjective preferences for particular consequences, their attitude towards risk, and judgements about uncertainties. In this section we describe some of the techniques used in quantitative policy analysis for modelling decisions under uncertainty.

2.1 *Bayesian networks and influence diagrams*

A Bayesian network is used to model a domain that has inherent uncertainty due to a combination of incomplete knowledge of the domain and randomness in the environment. The network may be represented by a directed acyclic graph whose nodes correspond to random variables linked by causal dependencies. The causal direction is represented by the direction of the arcs in the graph. Each node has associated with it a set of potential states. Nodes that have arcs directed towards them are called destination nodes while nodes with arcs directed away from them are known as origin nodes. We will call origin nodes that have no arcs directed towards them *initial* nodes and destination nodes that are not origin nodes, *root* nodes. Each destination node has associated with it a conditional probability of the node being in a specified state given the states of the origin nodes linked to it. Each initial node must have associated with it a likelihood of being in each of its potential states.

Making a decision can be considered as choosing a set of decision variables in a Bayesian network and fixing their values unambiguously [Pearl, 1997]. This would alter the probability distribution of the consequences of the decisions and determine the expected utility associated with the decision chosen. Influence diagrams are often used to model decisions and their consequences. These diagrams are simply Bayesian nets extended with decision nodes, representing the choices available to the decision-maker, utility nodes, representing the utilities to be optimised and chance nodes, representing (uncontrollable) random variables. Arcs pointing to utility and chance nodes represent functional dependence whereas arcs pointing to decision nodes show which variables will be known to the decision-maker before the decision is made, implying time precedence. The value of each decision variable is imposed from the outside to meet some objective.

2.2 *The Analytic Hierarchy Process [Saaty, 1994]*

The Analytic Hierarchy Process (AHP) derives ratio scales of relative magnitudes of a set of elements by making paired comparisons with respect to importance, preference or likelihood of a property they have in common. Decision making with the AHP is based on ranking activities in terms of relative ratio scales.

The various elements of a decision problem are organised into a multiple-level hierarchy. Each level has multiple nodes with respect to which the alternatives on the next level are compared. The first step in the analysis is to compare the elements in each level in pairs according to their contribution to the parent node in the level above. A pairwise scale of relative priorities is derived from the pairwise comparisons for the group. This is repeated for all groups on all levels. A weighting process uses these priorities to rank the overall importance of the criteria.

Judgements for comparing the criteria of a particular level can be represented by a reciprocal (ie a[ij] = 1/a[ji]) square matrix whose elements reflect the intensity of dominance of the criterion represented by the row over the criterion represented by the column. The components of the eigenvector of the matrix, termed the priorities vector, represents the

conversion of the pairwise comparison of the criteria into a ratio scale (the sum of these numbers must be one). The principle eigenvalue gives a measure of the consistency of the judgements. The procedure is repeated for every criterion. The subcriteria under each criterion are compared with respect to that criterion to obtain their local priorities. The importance of each subcriterion is weighted (multiplied) by the priority of the parent criterion to obtain its global priority. At the lowest level the global priorities are summed to obtain the overall priorities.

The AHP can be extended to an Analytic Network Process (ANP) to incorporate dependencies and feedback [Saaty, 1996]. While hierarchies are concerned with the extent of a quality among the elements being compared, a network is concerned with the extent of influence of elements on some element with respect to a given quality. A network is well suited to modelling dependence relations among components. It makes it possible to represent and analyse interactions and to synthesise their mutual effects by a single logical procedure.

A, so-called, supermatrix, describing the interaction between the components of the system is constructed from the priority vectors. It can be used to assess the results of feedback. Each of the columns is an eigenvector that represents the impact of all the elements in the *i*th component on each of the elements in the *j*th component. Interaction in the supermatrix is measured according to several possible criteria whose priorities and relations are represented in a control hierarchy. A different supermatrix of impacts is developed for each criterion. The components are compared according to their relative impact on each other component, thus developing priorities to weight the eigenvector columns in the supermatrix.

The ANP can be structured so that it represents a Bayesian network. Prior probabilities are linked with the probabilities of outcomes as follows. Consider a three-level hierarchy: the goal, the current states and the outcomes. Let the column vector of prior probabilities coincide with the priorities of the current states under the goal in the hierarchy. Let the matrix of likelihoods coincide with the priorities of outcomes according to the current states. Hierarchic composition yields priorities of the outcomes that coincide with the probabilities of the outcomes as determined by conditional probability.

A feedback network, representing the dependence of causes on outcomes and the dependence of outcomes on other outcomes, is constructed by inverting the hierarchy in order to evaluate the current states in terms of outcomes. It is easy to write down the supermatrix corresponding to this network. The mathematical machinery developed for the supermatrix can then be used to derive the matrix form of Bayes Theorem.

2.3 ***Markov decision processes***

Markov decision processes use the fundamental properties of Markov processes to arrive at decisions using dynamic programming techniques. In essence the decision-maker observes the current state and must choose among a finite set of possible actions incurring a possible cost (or reward) for each action chosen. The costs and state transition probabilities are functions only of the last state and subsequent action. The set of rules by which the decision-maker chooses alternatives at each stage of the process is called a policy. The theory enables the decision-maker to determine the optimal policy according to some set of criteria, for example, maximising the expected aggregate reward.

In Bayesian decision theory, the underlying Markov process has uncertain transition probabilities and rewards. It uses the Bayesian theory of probability to characterise degrees of uncertainty in terms of subjective probabilities. The decision-maker can update information about the current state by performing experiments.

3. **COA development and analysis**

COA development is Step 2 in the Joint Military Appreciation Process (JMAP) which has been adopted as the basis for operational level planning in the ADF. It involves identifying a number of courses of action that will accomplish the mission according to the commander's intent. Each COA must target the enemy centre of gravity (COG), a key element of operational art [ADFP 9, Chapter 4]. The COG 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*. Another key element of operational art is critical vulnerability (CV), *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*. Related to these two concepts is the notion of a decisive point (DP): *a major event that is a precondition to the successful disruption or negation of a COG of either combatant and is created normally by successfully attacking or neutralising a critical vulnerability*. A successful attack on a CV should aim to achieve a DP in an operation.

Each COA developed in this step must target the enemy COG by exploiting the enemy's critical vulnerabilities in a sequence of actions known as a line of operation. Decisive points are milestones that can be represented as transitive states of the COA along the lines of operation. Operational tasks or actions, such as strike or sea control, enable transitions from one DP to the next so that the whole course of action is a sequence of transitions from the initial state to the military end-state [Zhang *et al*., 2000]. The planners must also identify critical vulnerabilities and decisive points from the enemy's perspective, that is, related to the friendly COG. In summary, this step of the JMAP should identify the enemy's COG, a number of approaches to undermine and neutralise it, the decisive points and lines of operation for each of these approaches and the critical vulnerabilities contributing to each decisive point. In addition the planners should determine their own force's COG and related decisive points and critical vulnerabilities.

It is also stipulated that "throughout COA development the staff must consider the 'cost-benefit' that results in apportioning capabilities and rates of effort to achieve objectives and tasks", and they should also "identify and analyse the consequences of potential risks and how they may impact on own and higher missions" [ADFP9, 8.24]. All four elements of Barclay's methodology defined above are thus represented. Our contention is that what is missing is a systematic comparative assessment based on the costs, benefits and risks of each COA, broken down into its component actions. A comparative assessment is done in Step 4 of JMAP, the Decision and Execution step. The decision criteria used in this step are derived from the war game analysis in Step 3 (COA analysis). They are measured over the whole COA rather than over each action in the lines of operations, which is what we propose. This type of decision-making is categorised as a wholistic decision rule in the literature. Sage [Sage, 1981] describes it as reasoning by intuitive affect and typically absorbing information by looking at the situation as a whole rather than disaggregating it into its component parts. We are not advocating that the wholistic thought process should be abandoned in favour of an analytical one, rather that the two approaches are complementary and compatible and that both types of assessment should be encouraged.

Simulation-based war gaming is a time consuming exercise owing to the complexity involved in populating the models for each COA. Performing preliminary analytical assessment prior to the war gaming stage of COA analysis might obviate the need to consider some courses of action in this stage and focus investment of effort.

Before we introduce our COA analysis model let us consider potential costs, impacts and risks associated with military courses of action.

3.1 *Possible COA measurements*

Selecting a particular course of action involves a set of (possibly implicit) decision rules in order to permit some prioritisation of alternatives. In order to do this a planner needs a set of possible alternatives that achieve the objectives as well as a measure of the cost, impact and risk associated with each alternative.

Some of the potential costs include loss of capability, sustainability, loss of personnel, effect on the environment, and humanitarian and social implications. The costs can often be determined from own critical vulnerabilities, for example, loss of personnel and sustainability. Similarly potential impacts may be determined from the enemy critical vulnerabilities. These include disruption, degradation or destruction of enemy capabilities and factors that affect this loss of capability.

Risk is defined as the probability of exposure to injury or loss from a hazard. When assessing the risk of hazards in operations, decision-makers must assess two kinds of risk, tactical and accident risk. The former is associated with hazards that exist due to the presence of the enemy on the battlefield. The latter is associated with equipment readiness, inadequate training and environmental conditions. During COA development and analysis possible hazards must be defined and assessed, and controls for each hazard must be developed until the residual risk is either at an acceptable level or cannot practically be further reduced. The level of residual risk might result in a COA being rejected.

Possible decision-making criteria for comparative assessment include decision superiority, innovation, moral authority, effective interoperability, force preparation, timely force projection and robust security.

4. Modelling courses of action using key concept relationships

Our aim is to develop a relational model between the key concepts currently used by operational planners in COA development: end-state, centre of gravity, critical vulnerabilities, decisive points and lines of operation. It is motivated by a need for a rigorous methodology for COA analysis based on these concepts. In [Zhang *et al.*, 2000] we draw out these relationships and apply them to develop a modelling framework. In this section we use this framework as a basis for an influence model to support COA development and a quantitative analysis model to support COA analysis. The models are built using influence diagrams that reflect the relationships among the planning concepts detailed above.

4.1 *COA development model*

At the COA development stage, the planners develop sequences of actions to connect the initial and military end-state through time and space using available means

[Zhang *et al.*, 2000]. To do this they must first determine ways to influence the operational centre of gravity, directly or indirectly. It is important at this stage to keep the COG in mind. As explained in [Giles and Galvin, 1996], “exploiting weaknesses and vulnerabilities are clearly important considerations; however, doing so will not cause the deteriorating effect desired unless it influences the centre of gravity".

The relational model we present here aims to support this activity. It represents the COG and all the elements that influence it. Functional decomposition [Rasmussen *et al*., 1994] of the centre of gravity is used to identify the influencing elements and to categorise them into a six-layer hierarchy: COG, capabilities (environmental), abstract functions, general functions, processes and physical systems. As we will see below, such a decomposition ensures that the direction of influence travels up the hierarchy. In other words, targeting a physical system produces an effect on all related elements higher up in the hierarchy.

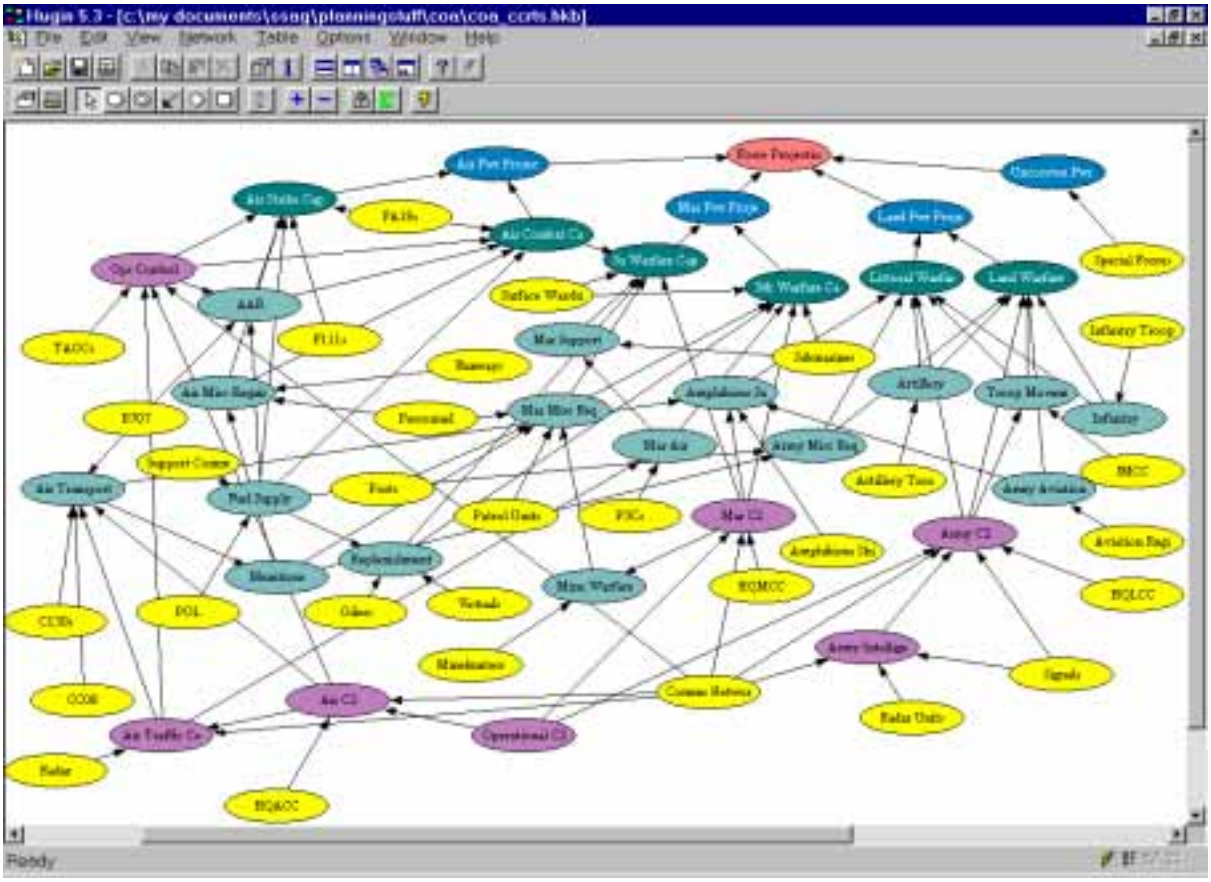

Figure 1: COG influence model

The influence diagram in Figure 1 shows an example of a COA influence model developed using Hugin, a Bayesian network and analysis software package. The nodes represent elements of the functional decomposition of the COG, which, for this example is chosen to be force projection capability, represented by the root node. Each node is described by two states: weak and strong. The arrows represent the direction of influence among the elements. Each of the initial nodes (eg POL, Communications Network, Radar etc) have an absolute probability measure assigned to each state and the states of all destination nodes have been assigned a conditional probability measure conditioned on the state of each of the origin nodes to which they are linked.

The node colours identify the classification of the element represented by the node. The colour-mapping scheme is shown in Figure 2.

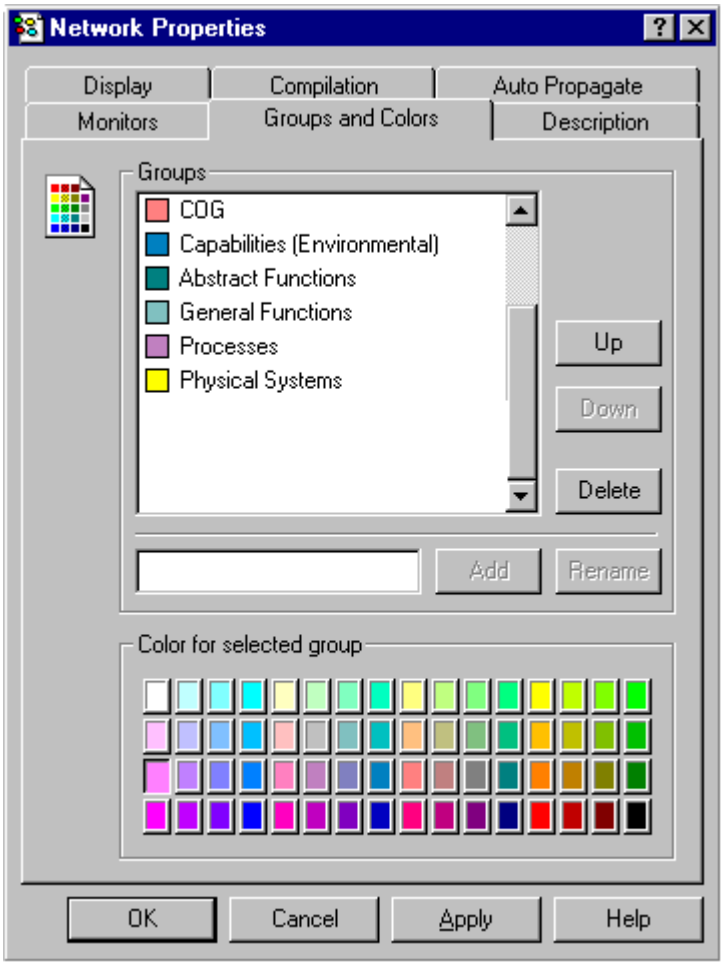

Figure 2: Node colours and the element types they represent

The model calculates the probability that the enemy COG is in a particular state given the states of various influential entities. We assume that initially all elements have a high probability (99%) of being in a strong state. By adjusting the state probabilities of various elements it is possible to determine the critical vulnerabilities that should be targeted for maximum effect. Figure 3 shows the probabilities associated with the capabilities and abstract functions related to the COG. Air, maritime, land and unconventional power projection capabilities are further decomposed into air strike, air combat, surface (su) and sub-surface (sub) warfare, littoral and land warfare capabilities. In this case we have chosen to negate littoral warfare capability. The effect is propagated through the net resulting in a significant weakening of the enemy COG, from an initial 79 % probability of being in a strong state, down to 37.48%.

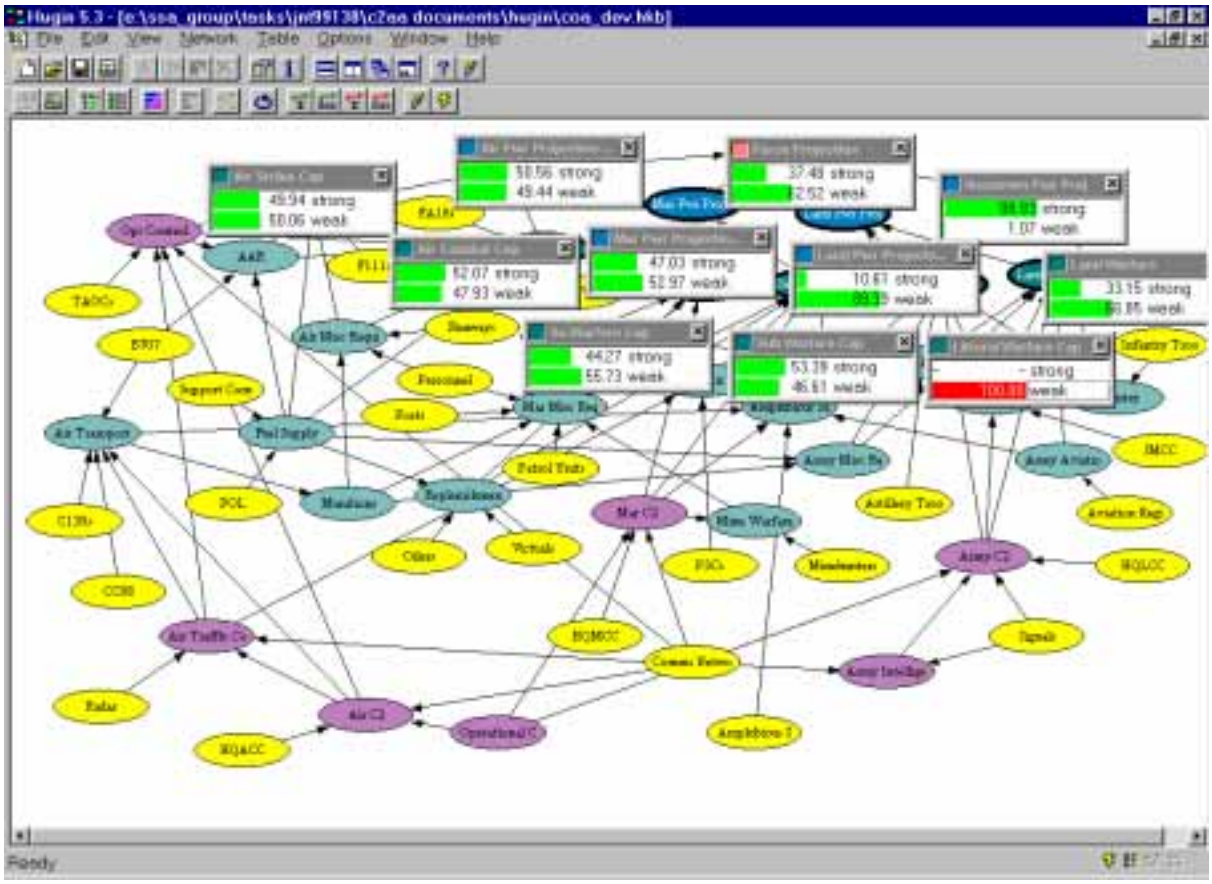

Figure 3: The effect of negating littoral warfare capability

Figure 4 shows how low fuel supplies influence air strike and air combat directly and how this effect propagates through to air power projection capability and in turn to force projection capability.

Using this model it is possible to investigate the effect that a set of actions has on the enemy centre of gravity. The model facilitates the drafting of a COA and determination of the decisive points required to influence the COG by identifying the critical vulnerabilities that have to be degraded or negated in order to arrive at the decisive points. It is also important to model the friendly COG and its dependencies in the same way in order to ensure proper protection against the enemy and due consideration of cost.

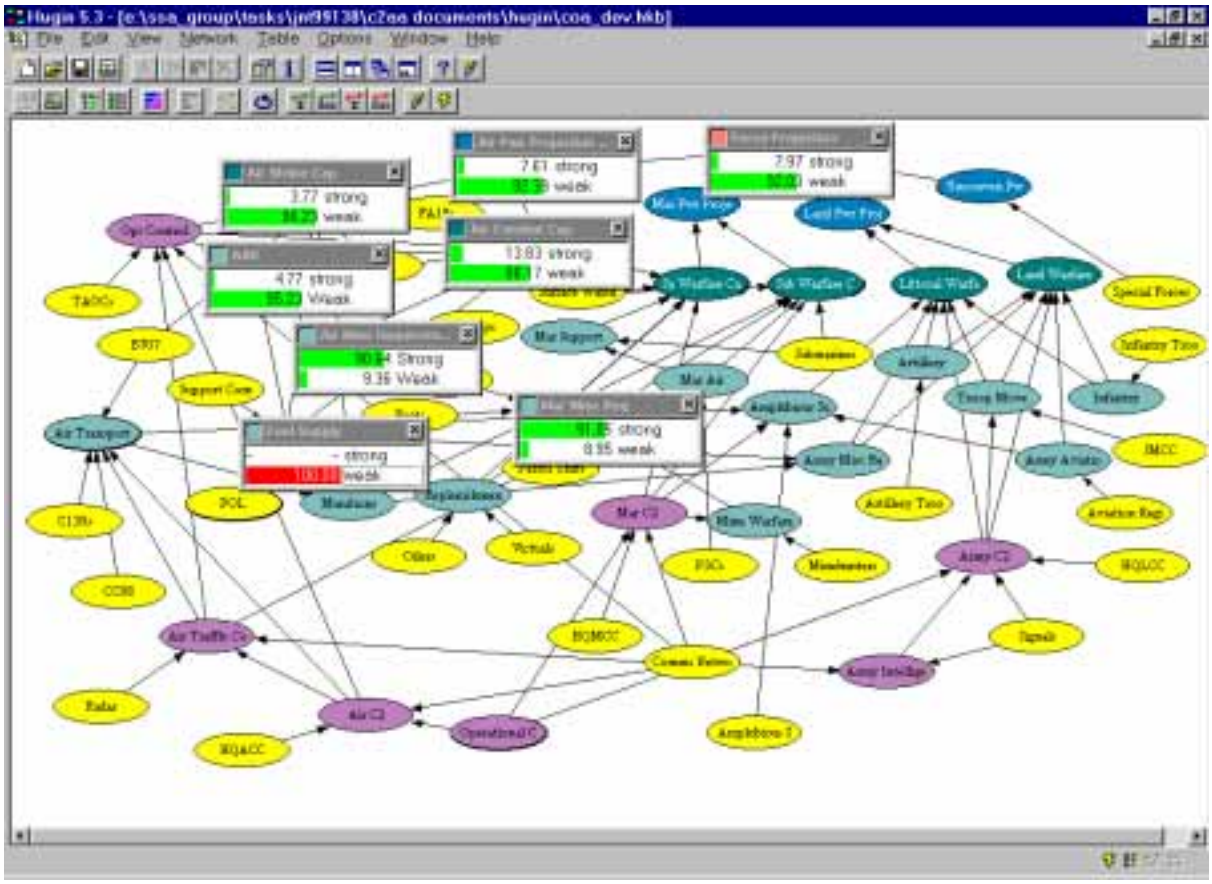

Figure 4: The effect of a highly depleted fuel supply

4.2 *COA analysis*

Having selected the courses of action that are likely to achieve the military end-state, the planners must now perform an analysis of the costs and risks associated with each COA. In this section we describe an approach towards a quantitative analysis model based on the concepts discussed above.

Analytica is a software package used to develop decision support systems. It employs influence diagrams as a modelling paradigm. Influence diagrams were developed for representing policy and risk analysis models in such a way as to facilitate communication with domain experts and enable them to express their objectives and uncertainties [Morgan and Henrion, 1990]. They offer a visual representation of a decision problem by displaying the causal relationships among the essential elements or dependencies among the variables. Nodes connected by influence arrows represent decisions, objectives and variables, both deterministic and stochastic. Influence diagrams are easily understood and help the modeller and the decision-maker understand which factors need to be included in the model and how they relate to each other. They provide a simple intuitive representation for communicating the qualitative structure that reflects the underlying quantitative representations.

Figure 5 shows a high-level influence model of the key concepts involved in COA development. The model, which was developed in Analytica, illustrates the possible relationships which can be derived among own and threat critical vulnerabilities, and how they impact on both centres of gravity. Such relationships would mirror those of the Hugin

model (described in Section 4.1) but in this case are quantified. An indicative COA consisting of a number of branches and sequels, with associated DPs and actions, is also shown. In our model a DP is defined as a significant state in the trajectory between the initial and end states. An action (leading to achievement of a DP) enables the transition between two such states. It can impact on a number of adversary CVs and incur costs through multiple own CVs. Impact and cost, along with risk, are quantified for each action and facilitate a comparative assessment of each COA.

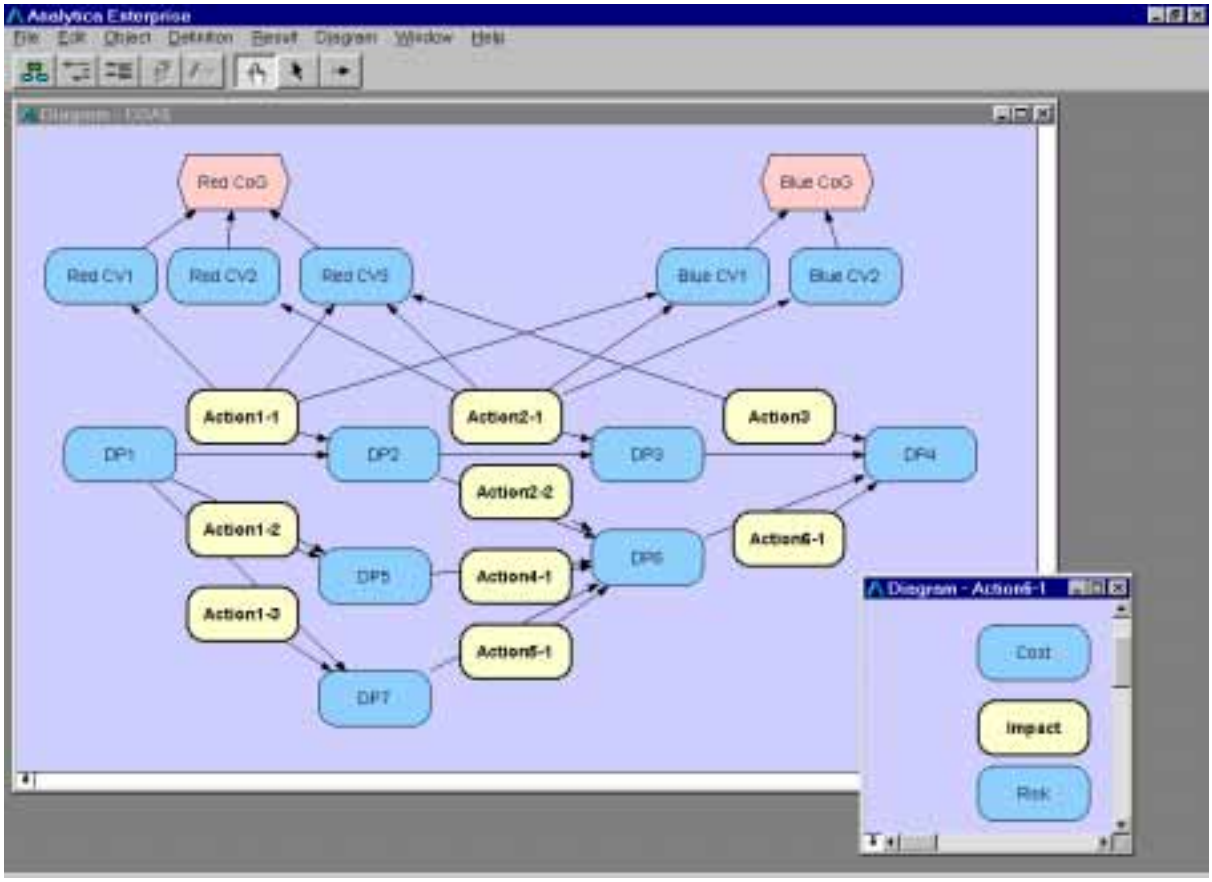

Figure 5: A high-level COA model

This model provides a quantitative structure which models the dependencies among the key components of a course of action. It is now possible to elicit judgements on the cost, impact and risk associated with each action and use the relational structure to evaluate each course of action.

5. Discussion

A different approach to COA analysis is presented in [Wagenhals *et al*., 1998]. They develop an influence net model of a COA using Situational Influence Assessment Module (SIAM). Influence nets are similar to Bayesian nets but assume independence of causal influence in order to simplify knowledge elicitation and inferencing. SIAM generates a user interface logic that requires a relatively small number of probability assignments and whose inference logic is understandable and meaningful to the user. The influence net models are used to identify the set of actionable events that collectively have maximal positive influence on the objectives modelled. In this sense the model is similar to the COA development relational

model we describe above except that we consider capabilities, functions, processes and physical systems rather than actionable events. Wagenhals'analysis is performed by converting the information contained in the influence net into a timed executable model of a COA. This enables a temporal analysis of the set of timed sequences to support dynamic planning decisions.

We have presented our approach to systematic COA modelling based on the concepts underlying military COA development but with a theoretical underpinning derived from policy analysis. Using functional decomposition we developed a relational model to support COA development. Our analysis models use influence diagrams that reflect the relationships among the key planning concepts. The models take uncertainty and risk into account as well as the costs and benefits associated with each action. They demonstrate the relative importance of uncertain variables and how different actions might contribute to them. Time has not been incorporated into the models as yet. To this end future models will incorporate aspects of discrete event dynamic system theory as outlined in [Zhang *et al*., 2000].

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