On Relationships between Key Concepts of Operational Level Planning

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Abstract

The Australian operational level planning doctrine, Joint Military Appreciation Process (JMAP), comprises four consecutive and iterative steps, namely: Mission Analysis (MA), Course of Action (COA) Development, COA Analysis, and Decision & Execution. All four steps are supported by an integral operational level intelligence function called Joint Intelligence Preparation of the Battlespace (JIPB). During each step of the JMAP, a number of planning objects are produced, leading to the development of an operational plan in its most abstract form: a variety of courses of actions with branches and sequels. The planning objects include a military end-state, centres of gravity (COG) for both the threat and the friendly forces, critical vulnerabilities (CV) and decisive points (DP), properly defined in Operational Art. A course of action is a line of operations that consists of sequenced and coordinated military actions that traverse decisive points, leading to the achievement of the identified military end-state. The desired military actions exploit the threat critical vulnerabilities, while protecting own critical vulnerabilities. The effectiveness of the individual military actions is assessed through their impact on the centres of gravity of both the threat and friendly forces.

This paper develops a modelling framework to elaborate the relationships between key concepts of operational level planning with a focus on deliberate planning. A qualitative analytical model of the concepts is presented to illustrate these relationships. The purpose of this paper is to facilitate course of action development in a systematic manner such that the intermediate and final planning products are amenable to analysis, comparison and reuse. Our goal is to complement Operational Art with a qualitative analytical framework for planning.

1. **Introduction**

Planning is one of the key functions in an operational level Headquarters (HQ). In Australia, the operational level Headquarters is Headquarters Australian Theatre (HQAST). The commander of the Australian theatre (COMAST) is charged with the responsibility of conducting the operational level of war through *planning* and mounting joint and combined forces to achieve national military objectives.

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[1] The authors acknowledge the influence of the trainers from the Australian Defence Force Warfare Centre (ADFWC) on their thoughts on this subject.

Since the establishment of HQAST in 1997, the Australian Defence Force (ADF) has made significant progress in developing an efficient and effective campaign planning process. The most important achievements include the publication of joint operational level planning doctrine, the *Joint Military Appreciation Process (JMAP)* [JMAP 1999], and Australian warfighting concepts, *Decisive Manoeuvre* [HQAST 1997].

1.1 Operational Art and Planning

The foundation of both JMAP and Decisive Manoeuvre is Operational Art, defined as "the skilful employment of military forces to attain strategic goals through the design, organisation, sequencing and direction of campaigns and major operations" Operational art translates military strategy into operational and ultimately tactical actions. According to the definition of Operational Art, the tasks of an operational level commander include (Figure 1):

- Identifying the military conditions or end-state that constitute the strategic objective;
- Deciding the operational objectives that must be achieved to reach the desired end-state;
- Ordering a sequence of actions that leads to fulfilment of the operational objectives; and
- Applying the military resources allocated to sustain the desired sequence of actions

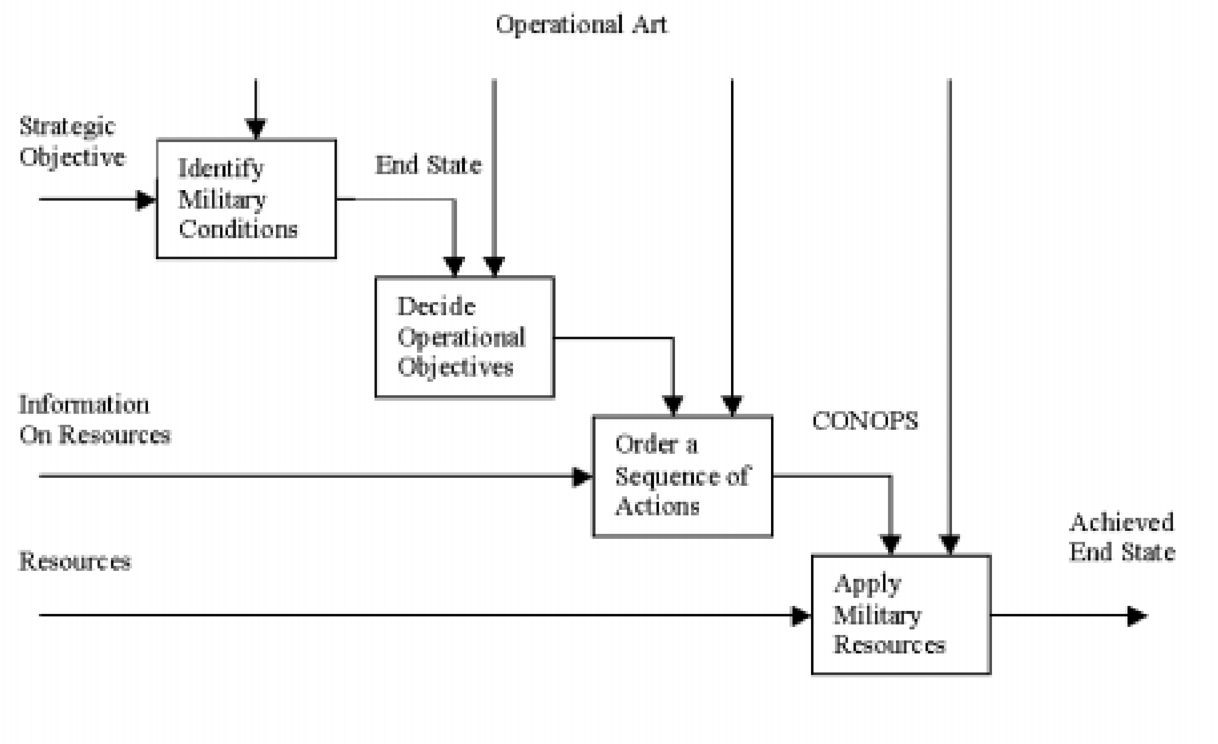

Figure 1 Operational Planning Process using Operational Art

The essence of Operational Art as well as operational level planning is the allocation of military resources to achieve a strategic objective. Like other resource allocation problems, operational level planning can make use of scientific methods such as operations research [Filar *et al*. 1999]. But unlike conventional resource allocation problems, operational level planning is an extremely complex, multiple criteria (some of them inherently unquantifiable) decision making process with a high degree of uncertainty. This means that any planning tool that is to be developed to aid the decision making process in operational level planning will have to take into consideration its limitation in value judging and risk taking. Indeed, much of the effort in providing support to operational level planning has been, so far, focussed on developing information-sharing and voting facilities such as collaborative planning tools and constructing planning-related databases.

In contrast, Wagenhals et al have demonstrated the use of formal modelling methods in COA development and evaluation [Wagenhals *et al*., 1998]. In particular, they propose to use influence nets to model situation assessment and initial development of COA. As the execution of a particular COA involves time-phasing of the actions which can best be modelled by a discrete event dynamic system, Wagenhals et al have developed a method to automatically generate a discrete event dynamic system. This takes the form of an executable coloured Petri net generated from the output file of an influence net that has been constructed through intelligence and initial COA development activities. The resulting coloured Petri net can then be used to simulate the execution of a COA in a scenario. The simulation results can also be used to refine the details of a COA.

This paper aims to explore a modelling framework for course of action development and a concordance of campaign planning concepts to complement Operational Art. It identifies functions in operational level planning where quantitative methods can be applied.

The remainder of this section briefly introduces the JMAP. Section 2 reviews the planning concepts outlined in Operational Art, and discusses their implications in the context of operational level planning. Section 3 puts these concepts back to the JMAP, and proposes a System Engineering approach to the development of planning objects, with a view to establishing a qualitative relationship between the key concepts of operational level planning. Section 4 develops the conceptual relationship one step further. We employ the formalism of Formal Language theory and Finite Automata to define a modelling framework for COA development. The benefit of using formal models in planning is that they provide a means to manage the inherent complexity and uncertainty in a progressive manner. Based on a formal model, appropriate system methods can be applied to address both the logical aspect of COA (ie., Supervisory Control of Discrete Event Systems) and the quantitative aspect (ie., policy analysis). The logical aspect of COA is also discussed in Section 4, and the quantitative aspect is dealt with by Falzon, et al in a companion paper [Falzon, *et al*., 2000]. Section 5 concludes the paper with discussions. These two papers together represent the conceptual stage of our effort in defining requirements for and developing decision support tools in operational level planning.

1.2 ***Joint Military Appreciation Process***

The JMAP process, as illustrated in Figure 2, represents a logical decision making process. In order to make a logical decision or a plan, the planner needs to go through five iterative steps.

- Step 0: gather information (intelligence preparation of the battlespace – IPB)
- Step 1: decide on objectives, available resources and other constraints (Mission Analysis)

- Step 2: develop possible ways to achieve the objectives within the constraints (COA development);
- Step 3: analyse and compare the alternative ways to reach a plan, optimised in regard to the objectives (COA Analysis); and
- Step 4: decide on and execute the plan (Decision and Execution).

The process is iterative in three different ways. Firstly, there are (crude) decision cycles within each step of the process in order to filter out infeasible COA (logistically, for instance). Secondly, the planners may need to revisit their previous steps in the course of planning in response to situational updates. Finally, the measured result of plan execution provides another form of situation update, and hence the planner will need to go through the planning cycle again if execution of the plan has not achieved the objectives. The actual implementation of JMAP in an operational level Headquarters involving organisation and staff allocation is an issue of process modelling, and is dealt with by [Zhang *et al.*, 2000]. In this paper, we focus on the products of the planning process, particularly the deliberate planning process where the planners are assumed to have time to gather information and to apply quantitative methods in decision making.

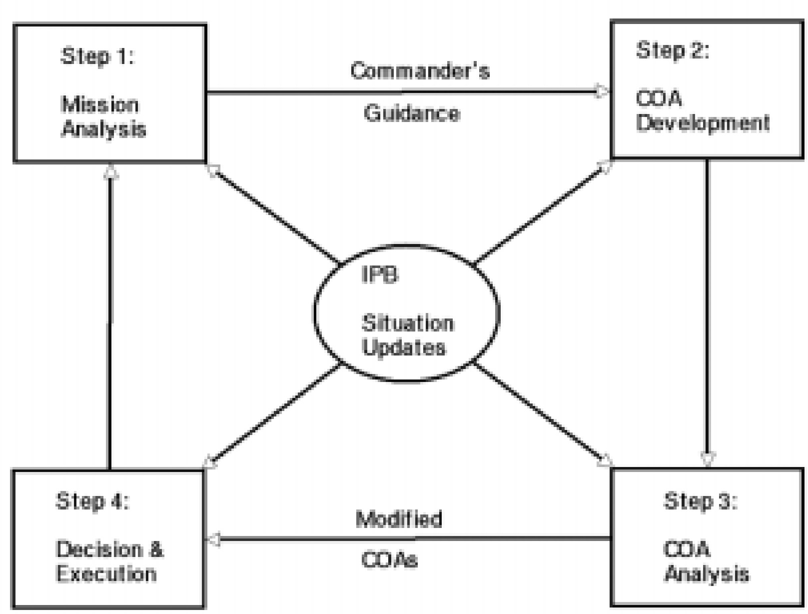

Figure 2 Joint Military Appreciation Process (Source: ADFP 9)

JMAP defines two modes of operational level planning: deliberate and immediate. The deliberate mode is characterised by long planning times, greater freedom for staff to explore a full range of threat and own force options, detailed analysis, thorough deductive reasoning, and maximum staff involvement. It is ideal for use before operations begin or during significant pauses in ongoing operations. The immediate planning mode is designed for use during operations when planning occurs with tight time constraints, is subject to constant change and is used to make quick or immediate decisions. Immediate planning relies on a detailed understanding of the plans that have been produced during deliberate planning and an enhanced situational awareness by commanders and staff.

This paper focuses on operational level *deliberate* planning in the context of the JMAP doctrine. The key concepts of the JMAP doctrine are analysed and then placed in a modelling framework with a view to facilitating the involvement of operational level Joint staff. It should also help quick transitioning of the framework-facilitating tools to operators.

2. **Planning Concepts**

This section introduces elements of operational art that form key concepts of operational level planning. As the elements of operational art reflect centuries of wisdom of military practitioners and theorists, each of the concepts warrants a separate discussion. Examples of such discussions are [Giles and Galvin, 1996] and [Clothier 1998]. As our focus is on the relationships between these concepts, we give a definition to each of the concepts according to military doctrine, followed by a brief discussion for each concept.

2.1 ***End-state***

State is one of the fundamental concepts in (dynamic) system theory. It constitutes the cornerstone of the modelling and analysis of system dynamics. The state of a system at a time instant describes the behaviour of the system at that instant in some measurable way. This information, ie, the description of the system behaviour at that particular instant, is the only information about the system that is required to uniquely determine the future behaviour of the system given some input to the system. In system theory, a state is generally a vector, ie, a set of conditions of the system.

From this definition of *state*, it is straightforward to define *end-state* as a description of certain system behaviour at which point the operation of the system halts. Depending on the perspective, an end-state can be either desired or undesired. In [ADFP6, 1999], the Australian Defence Force defines *end-state* as “the set of conditions which will achieve the strategic objective”. End-state is identified at the national and military levels as follows:

- The national end-state is the set of desired conditions, incorporating the elements of national power, that will achieve the national objectives.
- The military end-state is the set of desired conditions beyond which the use of military force is no longer required to achieve national objectives.

Generally, a national end-state can be defined in terms of social, political, economical, geographical, environmental and military conditions. It is the military conditions that constitute the military end-state. In this sense, a military end-state can be seen as one dimension of a national end-state, although the military dimension is not necessarily orthogonal to other dimensions of the national end-state. In cases when military conditions are not explicitly stated in a national end-state, dependency relationships between the national and military end-states need to be identified. If the achievement of a military end-state does not help the achievement of the national end-state, then either the military end-state is incorrectly identified or the use of military forces is not justified. As our paper focuses on operational level planning, and the determination of a military end-state is a responsibility of the national and strategic commands, it is assumed here that the achievement of a given military end-state would contribute to the achievement of the overarching national end-state. The social, political, economical, and geographic dimensions of the national end-state act as boundary conditions for operational level planning.

End-state is an important concept in military planning. Its importance in strategic planning is discussed in [Clothier 1995]. As this paper concentrates on operational level planning, a military end-state defined by the military strategic level command serves as a qualifier of the mission that is given to the operational level commander. Operational level planners should use the conditions specified in the end-state as measures of the courses of actions developed during the planning process.

2.2 Centre of Gravity

Centre of gravity (COG) is a concept from Newtonian physics. It is defined as the point on an extended body where all the gravitational attraction or weight of the extended body may be considered to be concentrated. When the gravitational field is uniformly distributed, the COG is equivalent to the centre of mass.

The COG concept was introduced to military affairs by Carl von Clausewitz [Giles and Galvin 1996]:

"One must keep the dominant characteristics of both belligerents in mind. Out of these characteristics a certain centre of gravity develops, the hub of all power and movement, upon which everything depends. That is the point against which all our energies should be directed..."

A thorough treatment of COG can be found in [Giles and Galvin 1996], although the model developed is only one of many views of COG, as admitted by the authors themselves, as determination and analysis of COG has been a controversial area for military theorists and practitioners.

In the ADF, centre of gravity is defined as the key 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. The centre of gravity at each level of conflict may consist of a number of key elements [ADFP 6, 1999].

Though we do not intend to join the debate on the meaning and determination of COG, the following observations on COG are made to serve the purpose of developing relationships between the key planning concepts:

- COG exists at both strategic and operational levels. This paper deals with operational COG, but its relevance to strategic COG must be considered in the determination and analysis of operational COG.

- Though the physical meaning of COG is not to be taken literally, it is important to note that the fact of COG being a point holds true for both physical and military systems. In the military domain, COG is a point upon which the opposing force can act, and exploit to achieve the maximum effect. In this sense, to the extent that one can obtain access to and control of his/her enemy's COG, one effectively gains control of the enemy's freedom of action, or the enemy's ability to generate events. In other words, one has fixed the enemy. Whether or not a COG manifests as a characteristic, capability or locality depends on the context within which the COG is to be determined. Analogous to a physical COG that can sometimes be outside the physical body (for instance, is the case of a boomerang), an operational COG can also be distant from the threat that one confronts.

- One must not lose sight of the end-state when considering COG and the effects that one intends to impose on the COG. Will these effects promote the achievement of the end-state? If so, to what extent? Should the COG be negated, degraded, disrupted, or just isolated in order to achieve the maximum effect? Occasionally the total negation of the enemy COG does not necessarily contribute positively to the military or national end-state.

- One must also not neglect the determination and protection of one's own COG during operational level planning, although one may choose to temporarily expose one's COG as a deception measure to achieve tactical advantages.

2.3 Critical Vulnerability

The ADF defines critical vulnerability (CV) as 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. A critical vulnerability is not necessarily a weakness but any source of strength or power that is capable of being attacked or neutralised. A successful attack on a critical vulnerability should aim to achieve a decisive point in an operation or campaign. A force may have a number of critical vulnerabilities [ADFP 6, 1999].

Critical vulnerability is a concept secondary to COG. It is important to note the two qualifiers of a CV: critical and vulnerable. A CV is critical because an action on it may impact significantly on the COG; it is vulnerable because of its susceptibility and accessibility, ie, capable of being exploited, attacked, degraded or neutralised. They form the two key criteria in determining a CV. Though it is stated that a CV is not necessarily a weakness, the feasibility, potential risk and cost of actioning on the CV can be a consideration secondary to the two key criteria.

Due to its accessibility, a CV is inherently more material or physical than a COG. In the case of a simple situation where there is one identified CV that is equivalent to the COG; then an action on the CV becomes a direct approach towards the enemy's COG.

It is necessary during operational level planning that own CV as well as threat CV are identified, and the cost (in terms of own CV) associated with attacking threat CV be appropriately assessed.

As an example, Figure 3 depicts a relationship between the end-state, COG, CV and COA of two opposing forces. The example assumes that the COG of both forces are assessed as their force projection and sustainment capabilities. Courses of action should impact on the CV and COG propagating through to the military end-state.

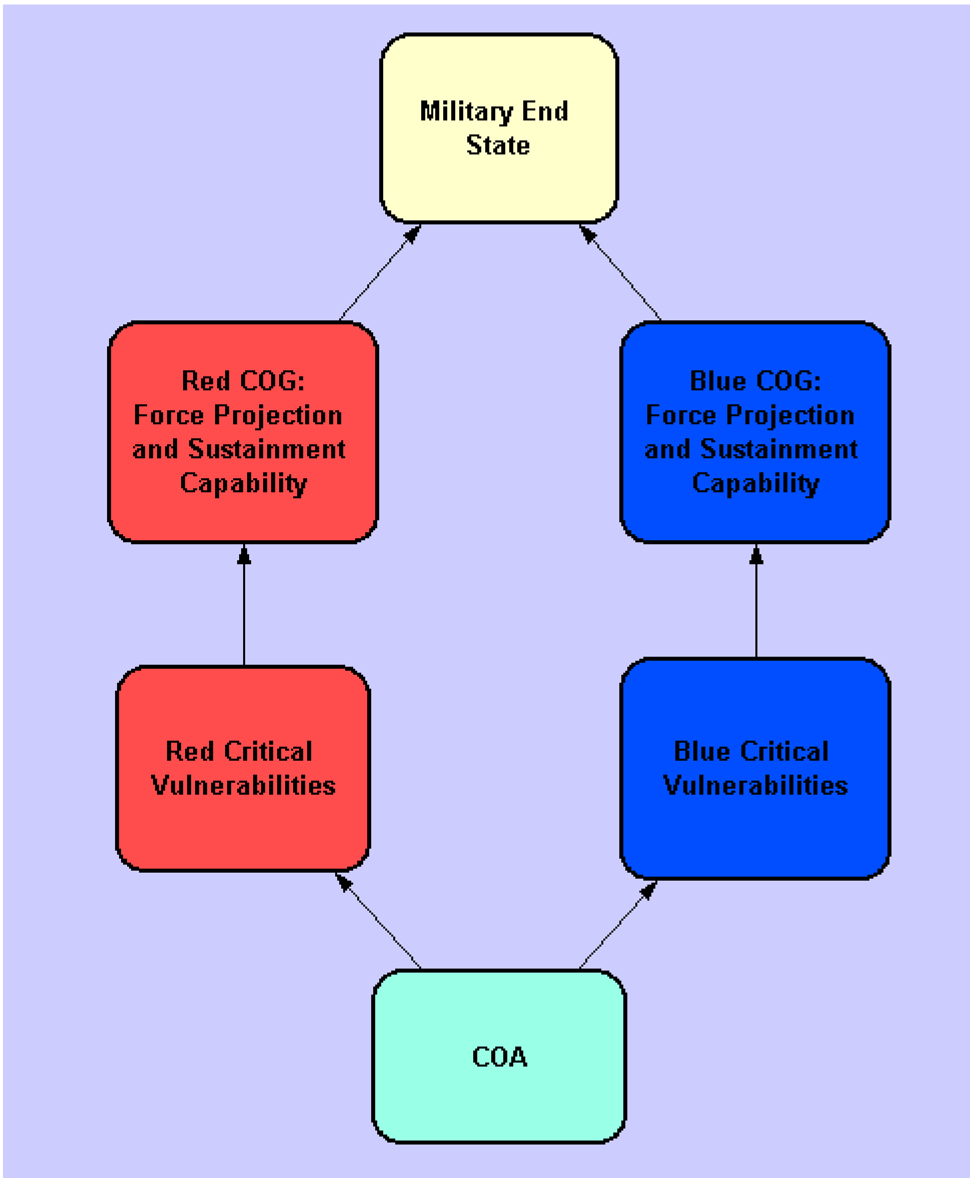

Figure 3 A Conceptual Model for COA Development

2.4 Decisive Points and Lines of Operations

The discussion of *state* and *end-state* in the context of system theory implies that there exist intermediate or transitive states between a current state/situation (or initial state) and an end-state. *Decisive points (DP)* are the most important intermediate states that must be identified for operational planning in order to (1) ensure proper scheduling and coordination of resources; and (2) to set milestones for sequencing operations.

The ADF defines *decisive point* as a major event that is a precondition to the successful disruption or negation of the centre of gravity of either combatant. A decisive point is created normally by successfully attacking or neutralising a critical vulnerability. Operational level planning aims to exploit an enemy's critical vulnerabilities in a sequence or matrix of decisive points known as lines of operation [ADFP 6, 1999].

We wish to make two comments on this definition: (1) we see a DP as a state instead of an event, the difference being that a state (excluding the initial state) is an outcome (or outcomes) of an event; and (2) a DP can be created by a purely one-sided effect (ie, manoeuvre to gain readiness or an advantage over the enemy).

Finally, lines of operations describe how military force is applied in time and space through decisive points on the path to the enemy's centre of gravity. The progress towards the enemy's centre of gravity and the destruction of the enemy's critical vulnerabilities, resulting in a decisive point, may be measured by operational milestones [ADFP 6, 1999].

An example of lines of operations is depicted in Figure 4 where COA connect an initial state to a military end-state traversing decisive points. The branches are the actions taken to achieve decisive points.

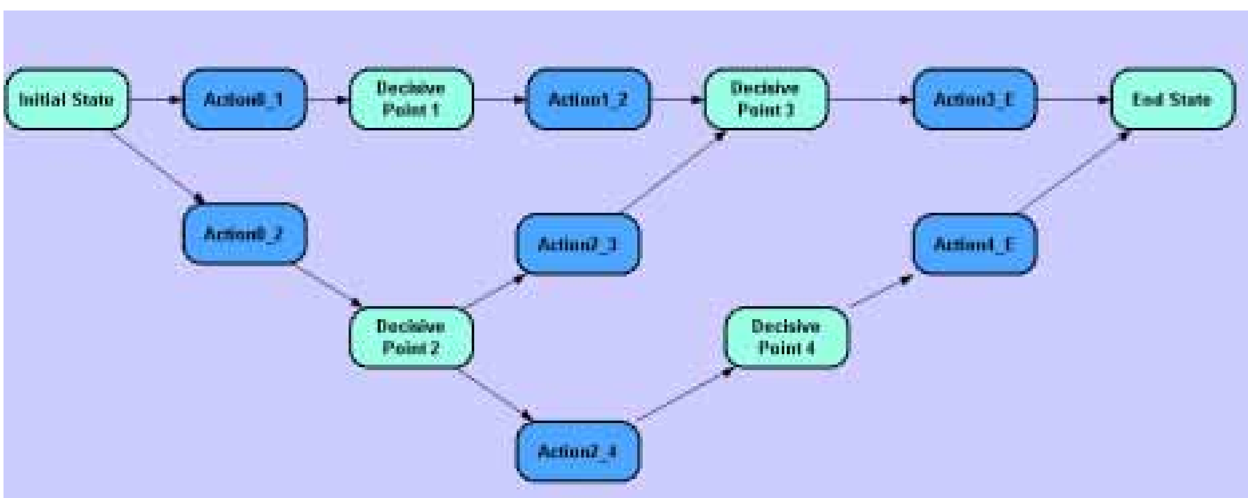

Figure 4 An example of COA representation

The introduction to the key planning concepts in this section establishes a context for the development of a modelling framework for COA. Readers are recommended to read [ADFP 6][Giles and Galvin 1996][Clothier 1995] in order to gain appreciation of the planning concepts introduced.

3. Planning Concepts in JMAP

To understand the importance of the planning concepts in operational level planning, we show in this section how the building blocks of a campaign planning product are based on these concepts. The deliberate planning process is used as an example. An overlay of the planning concepts on the four key steps of the deliberate planning process is shown in Figure 5. The process takes strategic objectives as its input, and produces a campaign plan as its output. In reaching the end product of a campaign plan, a number of intermediate items (underlined in Figure 5) will need to be produced as part of the sub-process outputs. We assume that strategic objectives do not change over a planning period which is a reasonable assumption for deliberate planning. Though the figure does not indicate explicitly the feedback from one step to its previous step(s), it is allowed for in the process model of [Zhang, *et al.*, 2000] to accommodate a dynamic situation.

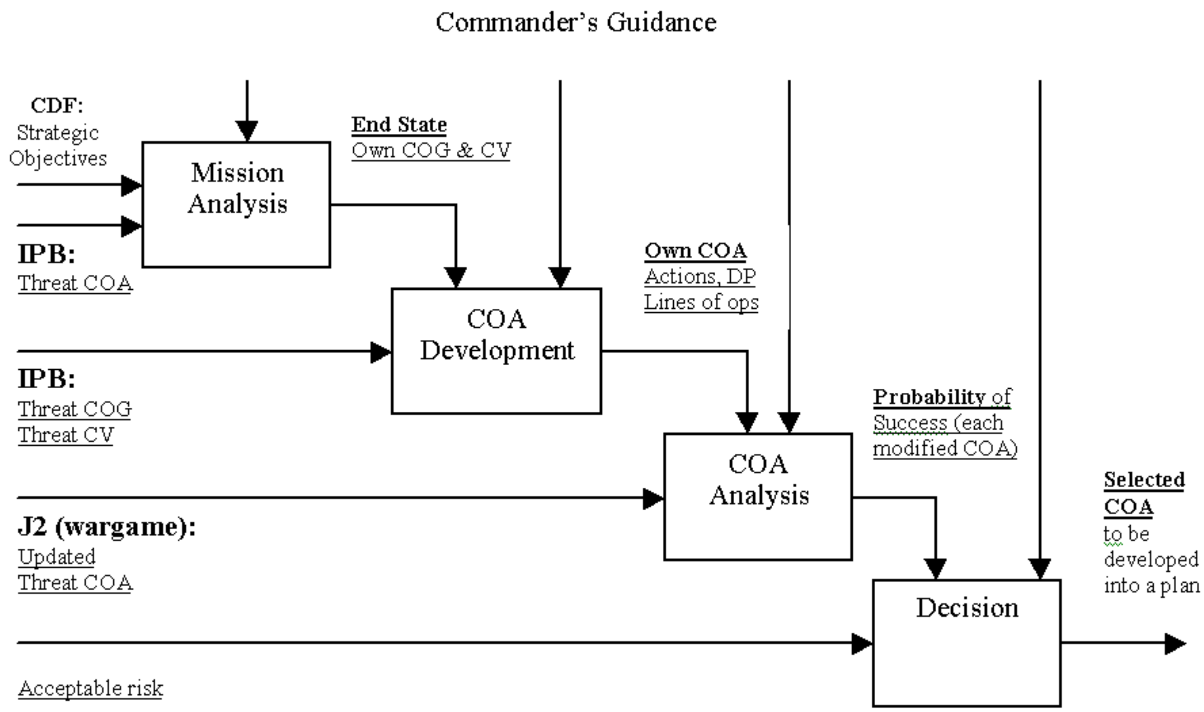

Figure 5 Deliberate Planning Process

It is noted that the four steps depicted in Figure 5 correspond very well to the steps of *Analysis, Synthesis, Evaluation*, and *Decision* from the Systems Engineering approach. More specifically:

– The *Analysis* step should include the specialist intelligence function of Joint Intelligence Preparation of the Battlespace (*JIPB*) as well as the *Mission Analysis* activity. This is because we consider the step of *Analysis* as an activity of constructing the state space of the battlespace for the *Synthesis* step (COA Development). The battlespace is seen as a dynamic system with its boundary defined by the strategic objectives (implicitly perhaps). The military end-state can then be specified as a particular and desired state in the state space. A COA is therefore a path in the state space connecting the initial state (current state) to the end-state. The state space can be constructed as a Cartesian product of the threat and own state spaces. The construction of the threat state space is the responsibility of the theatre intelligence analysts [JMAP 1999][Wagenhals, *et al.*, 1998], and the construction of the own state space is the responsibility of the theatre planning group in conjunction with the administration and logistics planning groups. The granularity of the state space should be proportional to the scale of the operation. The critical vulnerabilities (CV) are the *minimum* set of variables that constitute the state space. The other important concept associated with CV is centre of gravity (COG) which provides a focus for COA development. In the companion paper [Falzon, *et al.*, 2000], we relate COG and CV through influences and conditional probabilities.

– At the *Synthesis* stage, the planners develop sequences of actions (events) to connect the initial state and the end-state though the state space in time and space using the available forces and possibly other means. At the operational level of command, there are two major reasons for sequencing: one is the limitation of available forces; and the other is the desire to assess the effect of initial actions to minimise the chance of excessive use of force. The detailed timing of actions such as the timing of sorties is often left for tactical planners to consider.

  The important concepts at this stage of planning are actions and decisive points. An action is an operational task. A DP is defined as an effect. It is a significant state between the initial state and the end-state in the state space. *Significance* here means that the achievement of such an effect is a precondition to the enablement of future actions and hence achievement of more decisive points that lead to the end-state. An action enables a transition from one decisive point to the next decisive point. An action can be a conventional military operation or an IO campaign, for instance. A COA is a sequence of actions that enable transitions from the initial state to the end-state.

– Conventionally, the *Evaluation* stage is mainly concerned with the conduct of a qualitative assessment of the COA that have been developed at the *Synthesis* stage through seminar wargaming, with a view to improving the COA. Here we propose a quantitative assessment of the COA. To enable a quantitative assessment, actions that constitute COA must have associated metrics such as risk (defined as the probability of failing to effect the desired transition from one DP to another DP), cost (casualty, environmental and financial) and impact (influence on the enemy COG). The end result is the probability of success for each COA, along with other metrics.

– The commander's role in the *Decision* stage is to make a multiple criteria decision on which COA is to be developed into a plan, assisted by the quantities obtained at the *Evaluation* stage. It is also probable that the commander decides to combine a number of COA and make them branches and sequels.

4. A Course of Action Development Model

Based on the discussions in the previous sections regarding the definitions of the key planning concepts, this section presents a qualitative model of COA development that illustrates the relationships between the concepts. We base our model on the formalism of Finite Automata and Formal Languages. A generic definition of Finite Automata is given in Appendix 1. A formal language consists of a set of words made of an alphabet. The language is formal in the sense that certain rules must be followed in the construction of the vocabulary. Here we use an automaton as the generator of a formal language such that the theory of supervisory control [Ramadge and Wonham, 1989] can be applied. In an automaton-generated language, alphabets are the events of the generator. The theory of supervisory control is concerned with constructing a supervisor over a modelled system in order to achieve a set of desired logical behaviour through dynamically disabling certain controllable events. The resulting controlled language, in our case, will form a refined set of COA. Quantitative methods can then be applied to analyse and optimise the COA in terms of key planning criteria.

Assume that there are two opposing forces in the theatre: Red and Blue. We can use the finite automaton (Appendix 1):

$$G = (X_{RED} \times X_{BLUE} \times X_{ENV}, \Sigma_{RED} \cup \Sigma_{BLUE} \cup \Sigma_{ENV}, f, \Sigma_G, x_0, X_{m,RED} \cup X_{m,BLUE}) \quad \textbf{(Equation 1)}$$

where

- X_{RED}, X_{BLUE} and X_{ENV} are the state spaces of the Red force, the Blue force and the environment, respectively. We consider the state space of a military force in the form of a centre of gravity and associated critical vulnerabilities, with the COG representing a qualifier, and CV representing dimensions of the state space. An example state space is given below (also shown in Figure 3):

  $$X_{RED} = (\text{Force Projection Capability} : \text{Operational C2, Supply, C3I Networks, Fighters,...})$$
  (Equation 2)

  The state space for a Blue force can be similarly determined. In [Falzon, *et al* 2000], we constructed the state spaces of the Red and Blue forces, and specified the relationship between the COG and CV through a probabilistic network. An environmental state space comprises factors that may have impact on the planned operation. $X = X_{RED} \times X_{BLUE} \times X_{ENV}$ is a product of the three individual state spaces. It is noted from Figure 5 that the state space (X) is constructed during the stages of Mission Analysis ($X_{BLUE} \times X_{ENV}$) and COA Development (X_{RED}).

- Σ_{RED}, Σ_{BLUE} and Σ_{ENV} are the event sets of the Red force, the Blue force and the environment, respectively. The combined event set $\Sigma = \Sigma_{RED} \cup \Sigma_{BLUE} \cup \Sigma_{ENV}$ comprises the actions that both Red and Blue forces are able to take (Σ_{RED} and Σ_{BLUE} respectively) and the events that the environment generates (Σ_{ENV}).

- The partial transition $f : X \times \Sigma \rightarrow X$ means that an event from $\Sigma(= \Sigma_{RED} \cup \Sigma_{BLUE} \cup \Sigma_{ENV})$ may change the system from one state of $X(= X_{RED} \times X_{BLUE} \times X_{ENV})$ to another. Note that any event may impact on all three sub-spaces of X.

- Given that G is at state x, $\Sigma_G(x)$ represents the active event set: all the events that the forces and the environment can generate (ie, forward basing, strike, …).

- x_0 represents a common starting point for the two forces and the environment.

- $X_{m,RED}$ and $X_{m,BLUE}$ are the military end-states of the Red and Blue forces respectively. There are two sets of end states in this system, the end state from the perspective of the Red force ($X_{m,RED}$) and that of the Blue force ($X_{m,BLUE}$), ie, the campaign halts if either side achieves its perceived end-state. Hence both $X_{m,RED}$ and $X_{m,BLUE}$ are the proper termination conditions. It is important to note that both $X_{m,RED}$ and $X_{m,BLUE}$ are states of $X(= X_{RED} \times X_{BLUE} \times X_{ENV})$ rather than their respective X_{RED} and X_{BLUE}. Therefore our model G is a quasi *parallel composition* of the respective sub-models (finite automata) of the Red force, Blue force and environment, denoted as G_{RED}, G_{BLUE} and G_{ENV}, respectively.

Once G is constructed during Mission Analysis and the early phase of COA development, execution of G will generate a language $L(G)$, consisting of a set of ordered event sequences (words). The sequences that end with states from $X_{m,RED} \cup X_{m,BLUE}$ form the marked language $L_m(G)$, representing all the likely sequences of events from the current state x_0 to one of the (marked) end-state.

Clearly $L_m(G)$ consists of all the possible COA (given the modelled scenario G). The sequences (or paths) that lead to $X_{m,RED}$ are the undesired ones and therefore can be deleted from the languages. For this reason, G can simplified as

$$G = (X_{RED} \times X_{BLUE} \times X_{ENV}, \Sigma_{RED} \cup \Sigma_{BLUE} \cup \Sigma_{ENV}, f, \Sigma_G, x_0, X_{m,BLUE}) \quad \textbf{(Equation 3)}$$

Occasionally, a full automaton of G is retained for the planners and intelligence analysts to understand the enemy's perspective.

Even after the trimming of the undesired COA leading to $X_{m,RED}$, there can still be too many COA for the planners to examine more closely. In order to reduce the number of COA into a manageable size, one can apply a set of logical constraints to the language $L_m(G)$. Assume that the constraints can be modelled as languages K_i, $i = 0,1,\cdots,I$ (often defined by set properties rather than listing a set); then the logically refined COA set, K, is represented as

$$K = L_m(G) \cap \left(\bigcap_{i=0}^{I} K_i \right)$$ **(Equation 4)**

There is a branch of Discrete Event System (DES) theory that addresses the implementation of Equation 4: Supervisory Control of DES [Ramadge and Wonham, 1989]. The idea is to construct a supervisor S that controls the automaton G such that the language generated by the controlled automaton $L_m(S/G)$ satisfies the logical constraints. Supervisory Control acknowledges that there are certain events of G that cannot be controlled, for example, in the context of operational planning, the events that may be generated by the Red force or the environment. We partition the alphabet Σ into two subsets: uncontrollable events $\Sigma_{uc} = \Sigma_{RED} \cup \Sigma_{ENV}$ and controllable events $\Sigma_c = \Sigma_{BLUE}$. During execution, the supervisor S disables certain controllable events to generate the controlled language K. The resulting language K represents a logically refined set of COA that meet the predefined constraints.

An example representation of the resulting COA set is illustrated in Figure 4. Each COA is represented as a viable path (eg., a legal word satisfying all the qualitative constraint requirements) from the initial state to a number of decisive points (transitive states) and through to the desired end-state. The trellis representation of courses of action also enables quantitative analysis of COA [Falzon, *et al.*, 2000].

5. Discussion

This paper presents a modelling framework for key concepts that are used for the development of operational plans in the ADF. This framework is used to guide the development of decision support tools for operational level planning as well as to enhance understanding of the planning process.

Appendix 1. A Generic Definition of Finite Automata and Formal Languages Generated by Automata [Cassadras 1993]

Consider a finite automaton $G = (X, \Sigma, f, \Sigma_G, x_0, X_m)$ where

- X is the set of states of G.
- Σ is the set of events (alphabets) associated with the transitions in G.
- $f : X \times \Sigma \rightarrow X$ is the partial transition of G: $f(x,e) = x'$ means that there is a transition labelled by event e from state x to state x'.
- $\Sigma_G : X \rightarrow 2^{\Sigma}$ is the active event function (or feasible event function): $\Sigma_G(x)$ is the set of all events e for which $f(x,e)$ is defined. $\Sigma_G(x)$ is called the active event set (or feasible event set) of G at x.
- x_0 is the initial state of G.
- $X_m \subseteq X$ is the set of marked states of X.

The language generated by G, denoted $L(G)$, is $L(G) = \{s \in \Sigma^* : f(x_0, s) \text{ is defined}\}$ where

- Σ^* is the set of all finite sequences of events (referred to as traces, strings or words) from Σ.
- $f(x,s)$ is an extension of $f(x,e)$ from domain $X \times \Sigma$ to domain $X \times \Sigma^*$ through the following recursion:

  $$f(x,\varepsilon) = x$$
  $$f(x, s\sigma) = f(f(x,s), \sigma) \text{ for } s \in \Sigma^* \text{ and } \sigma \in \Sigma$$

  given that ε denotes the empty string of Σ^*.

The marked language by G, denoted $L_m(G)$ (where $L_m(G) \subseteq L(G)$), is $L_m(G) = \{s \in \Sigma^* : f(x_0, s) \in X_m\}$.

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