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# Modelling Operational Level Planning Processes with Coloured Petri Nets

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**Abstract**

This paper presents a Coloured Petri Net (CPN) model of the Australian Defence Force (ADF) operational level planning process. The use of CPNs as a formal modelling tool in the study of an operational planning process enables the analysis of structural and behavioural properties of the process and performance evaluation. As the model is executable, steps and sub-steps of the planning process can be followed with an animated token game that is useful for education and training. When the CPN model was populated with the data collected during a Headquarters planning exercise, valuable information about the process was obtained through state-space analysis of the populated process model.

## 1. Introduction

Structured planning at the operational level is a recent concept for the Australian Defence Force (ADF). The first Australian Joint operational level Headquarters, Headquarters Australian Theatre (HQAST) was created in 1997 with the responsibility for conducting operational level planning and mounting of joint and combined forces to achieve national military objectives. Headquarters staff adopted the Joint Military Appreciation Process (JMAP) [ADF, 1999] to facilitate operational planning. As the JMAP evolved, a need was identified to refine the process to improve its efficiency. Discussions between staff from the Australian Defence Force Warfare Centre (ADFWC) and scientists from the Defence Science and Technology Organisation (DSTO) identified a number of problems that contributed to the complexity in operational level planning. The main problem is seen to be a lack of clear understanding of the application of JMAP.

In order to rectify the problems identified, a formal representation of the planning process is required. It was envisaged that the use of formalism in the modelling of the ADF operational planning process would have a number of benefits. Firstly, formal models are logical and therefore assist in reducing ambiguity and inefficiency in the process. Informal graphical models of processes are useful for the visualisation and documentation of processes, but they do not enable the verification of consistency in the modelled processes. This is because informal graphic models do not follow a close set of defined rules that are consistent themselves. Secondly, formal executable models can generate behaviours that are amenable to both structured and unstructured analysis. Finally, formal specification of business processes such as military planning is useful in the development and instrumentation of workflow automation and management.

A project was carried out by DSTO in collaboration with ADFWC to develop a formal model of JMAP. The objectives of the project included:

- Improving the efficiency of the current operational planning process. This will be achieved through identifying and removing bottlenecks, and facilitating concurrent activities.
- Enhancing the understanding of the JMAP by staff and researchers through rich representation of the process.
- Developing a capability of evaluating the performance of operational level planning processes.
- Providing feedback to the development of Joint operational planning doctrine and subsequent training.

In this paper, we present the resulting JMAP process model in the form of CPNs. A Petri net is a network of interconnected locations and activities with rules that determine when an activity can occur, and specify how its occurrence changes the states of the locations associated with it [Jensen, 1994]. CPNs are a graphically oriented modelling language capable of expressing concurrency, non-determinism, and system concepts at different levels of abstraction. CPNs combine Petri Nets and functional programming languages within the same mathematical framework. Petri Nets are used to model concurrency, synchronisation, and resource sharing and allocation, whereas a functional programming language is used to model data manipulation and to create compact and parameterised models. A software package, Design/CPN [CPN Group, 1996], supports the modelling, simulation and analysis of CPNs. CPNs and Design/CPN have a wide range of application areas such as data networks and communication protocols, hardware design, embedded systems and decision-making organisations. The choice of CPNs for modelling the process is based on the following reasons.

- CPNs are a formal modelling method which is mathematically rigorous. It is possible to use formal analysis methods that are associated with CPNs to verify the structural consistency of a process model.
- CPN models are executable. Computer simulation can be carried out to evaluate the performance of particular designs of the planning process, which may lead to better procedures for planning.
- There is a sophisticated computer tool “Design/CPN” that supports CPNs not only in formal analysis and simulation of the models but also in visualising the flow of information and use of resources. The tool can be used in training to improve the application of the process.

The paper is organized as follows. Section 2 gives background information on the JMAP. Section 3 briefly introduces CPN terminologies that are used in this paper. Section 4 describes our modelling approach and the method of data collection. Section 5 presents the constructed CPN model of JMAP with selected representative steps and sub-steps of the process. Section 6 gives examples of analysis results that can be obtained. Finally, Section 7 presents the conclusions.

## 2. The JMAP Planning Process

This section provides an overview of JMAP which is the doctrine giving the principles for Joint operational level planning in the ADF. JMAP comprises four consecutive and iterative steps as illustrated in Figure 1. The four steps are: Mission Analysis (MA), Course of Action (COA) Development, COA Analysis, and Decision & Execution. All four steps are supported by an integral and ongoing Joint intelligence acquisition and analysis function called the Joint Intelligence Preparation of the Battlespace (JIPB).

Prior to the formal initiation of JMAP, an operational level HQ will normally conduct some form of Preliminary Scoping. The commander orientates the planning staff to the “big picture” with his understanding of the higher headquarters mission, superior commander’s intent and initial guidance. Additionally, the planning timeline is established and planning responsibilities allocated. The format and detail covered during this activity will differ in each HQ as per Standing Operating Procedures (SOP).

JMAP is a complex multi-path problem-solving tool. The main outcome of the planning process is the creation of an operational plan. For this purpose, the doctrine requires planners to go through the following consecutive and iterative steps.

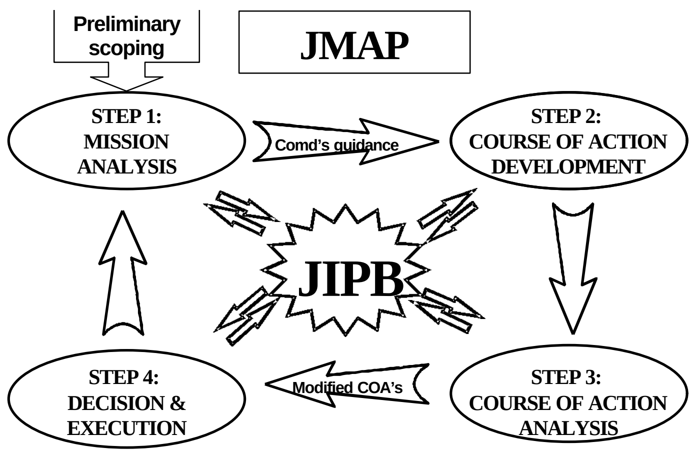



Figure 1 Joint Military Appreciation Process

**Step 1**: Decide on the objectives, available resources, and other constraints. This step is referred to as MA. An important part of MA is to determine and analyse the Centres of Gravity (COG) that are to be affected by the operational plan.

**Step 2**: Develop possible ways to achieve the objectives within the constraints. This step is referred to as COA Development. An important aspect of COA Development is to devise a strategy for influencing the COG determined in Step 1.

**Step 3**: Analyse and compare the alternative courses of actions to reach a desired end state, optimised in regard to the objectives. This is referred to as COA Analysis.

**Step 4**: Decide on and execute the plan. This step is referred to as Decision & Execution (D&E).

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 unachievable 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 planners will need to go through the planning cycle again if execution of the plan has not achieved the objectives.

## 3. **CPN Preliminaries**

This section gives an informal introduction to CPN constructs that are used in this paper. A formal definition of CPNs can be found in [Jensen 1994].

A CPN can be described in terms of a *net structure*, *colorsets* (e.g. data types), *initial markings*, and enabling and occurrence rules. The schema of a simple CPN is shown in Figure 2.

There are three components in a CPN *structure*: *places*, *transitions* and *arcs*, depicted in Figure 2 as ellipses, boxes and arrows, respectively. *Places* can hold *tokens* that model the states of a CPN. *Transitions* represent actions that can be executed to change CPN states. *Arcs* connect places and transitions.

Tokens in a place represent data. The types of data that a place can hold are specified by a set of *colours* (e.g. a CPN *colorset*). The *marking* of a CPN place specifies the numbers and colours of tokens in that place. A *CPN marking* includes markings of all places. A CPN marking in a particular instant represents the state of the net in that instant. An *initial marking* represents the initial state of a CPN.

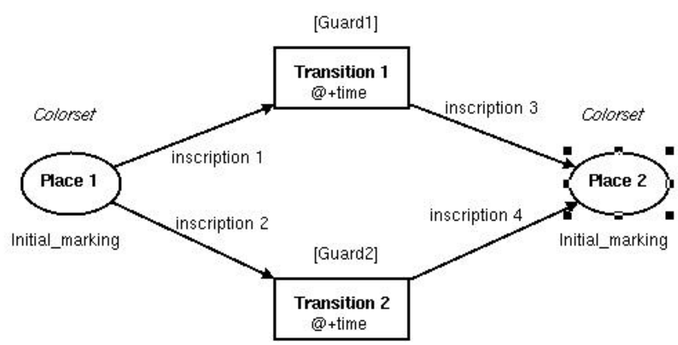



Figure 2 Schematic diagram of a CPN example

Given a CPN net structure and an initial marking, the dynamics of a CPN is determined by the enabling and occurrence rules, modelled by *arc inscriptions* and *guards* of transitions. There are two types of arcs in respect to transitions: incoming arcs and outgoing arcs. Incoming arcs connect from *input places* to a transition, and outgoing arcs connect from a transition to *output places*. Inscriptions on incoming arcs specify the numbers and colours of tokens from the input places that must be present in order for a transition to be enabled; and, once the transition occurs, to be consumed. Inscriptions on outgoing arcs specify tokens that are produced by the occurrence of a transition; the tokens are then put into the output places.

Transition guards are optional, and if present, impose additional conditions for transitions to be enabled and to occur. Enabled transitions can occur either concurrently or sequentially, and in various orders, depending on the numbers of available tokens in places. It is also possible that the occurrence of some transitions changes the state of a net such that the conditions of other enabled transitions are no longer met.

The occurrence of a transition may take time. The duration of a transition is prefixed by the CPN symbol "@+", as shown in Figure 2. A CPN that also models time is known as a *timed CPN*.

## 4. **The Modelling Approach**

This section describes the approach that we have adopted to JMAP modelling and data collection. The doctrine stipulates that each of the JMAP steps, e.g. *Mission Analysis*, comprises a number of sub-steps (or activities), e.g. Review situation, Analyse superior commander's intent and our mission, etc. A more detailed representation of the JMAP principle is shown in Figure 3. The hierarchical nature of the JMAP was exploited in the development of the process model.

Figure 3 also shows that a JMAP step (e.g. COA Development) depends on information (e.g. Commander's Guidance) produced by its preceding step (e.g. Mission Analysis) as well as improved situation awareness. Similarly, the input/output relationship can be explored between sub-steps and activities.

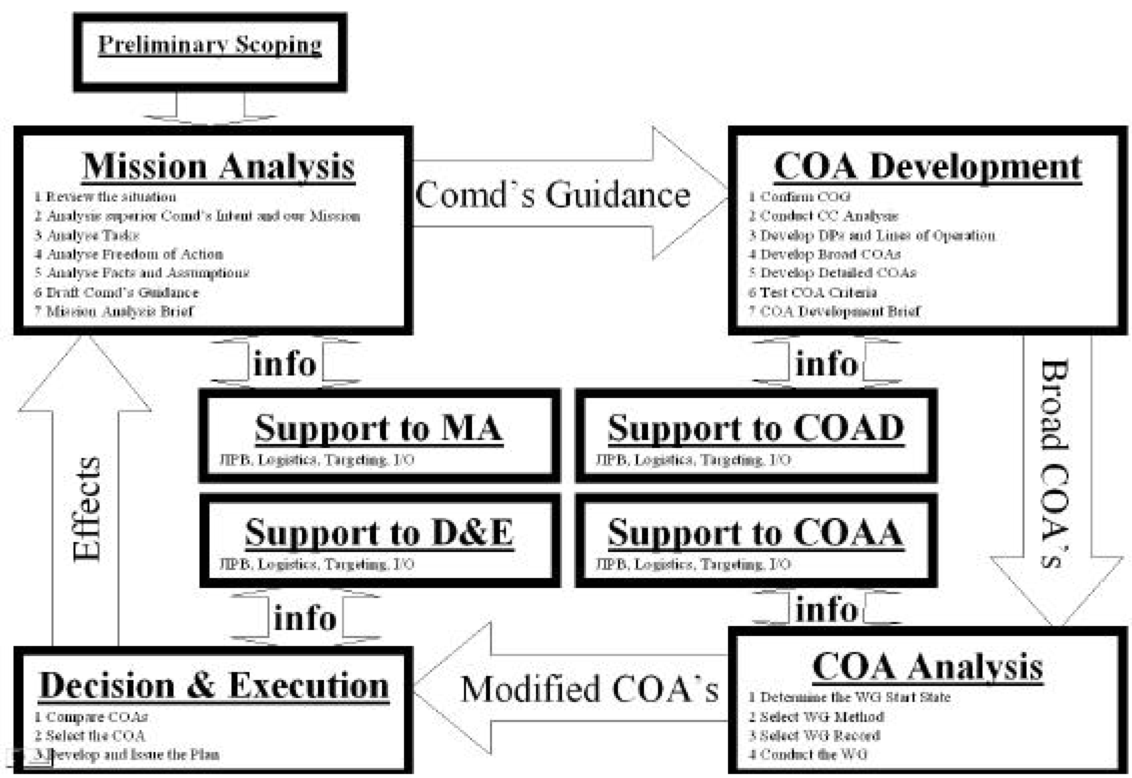



Figure 3 JMAP Steps and Activities

Figure 4 shows the schema that was used in the development of the JMAP model. A planning activity requires input information and planning staff, and produces output information. There are cases when input/output relationship between activities is implicit, i.e. without the involvement of information in the form of a document, e.g. where an understanding is achieved between the commander and planning staff in an activity that is essential for another activity. The concept of "Prior Activities" is introduced for this purpose. Definitions of the components in the activity schema are given as follows.

- **INPUT Information**: Information that *must* be available before the activity can occur. This information is usually passed electronically (e.g. in Word, Excel, PowerPoint), verbally, or hand written. Note that there are two types of input information: information from *external* sources and information produced as an output of another activity *internal* to JMAP.
- **OUTPUT Information**: Information that is *produced* by the activity. This information can be used in other activities in the JMAP.
- **PRIOR Activities**: Activities that *must* be completed before the activity can occur. Sometimes activities do not produce a specific output, but discussions held in one activity are important to another activity.
- **STAFF**: Staff groups that are involved in the activity.
- **DURATION**: The *expected* length of the activity in minutes.

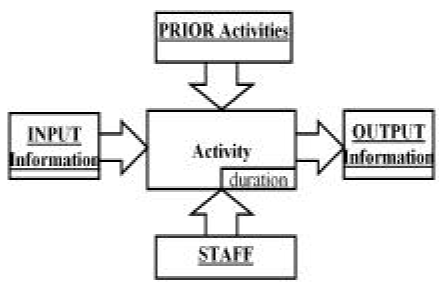


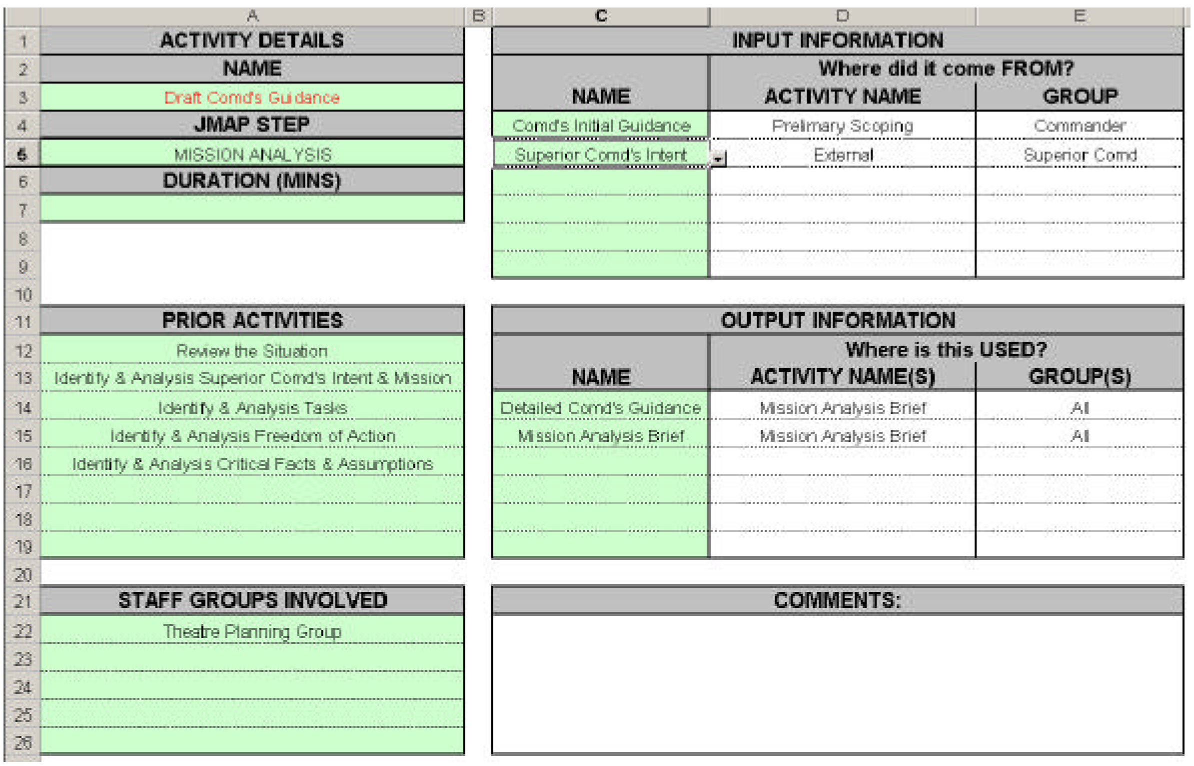

Figure 4 Schematic Diagram of a JMAP activity

The modelling schema shown in Figure 4 is then developed into a data collection form (Figure 5) for subject matter experts to fill in data in order to develop the JMAP model. This same form was used in the observation of an ADF planning exercise. Figure 5 shows an example of the populated data sheet. The entries of the form are explained as follows.

- **Name**: Name of the activity as it appears in the doctrine
- **JMAP step**: Where does this activity occur? It may be part of a JMAP step (MA, COAD, COAA, D&E) or part of the support to JMAP (e.g. JIPB).
- **Duration**: What is the expected duration of the activity in minutes?
- **Prior activities**: What activities must be completed before this activity can occur?
- **Staff groups involved**: What Staff groups are involved during the activity?
- **Input information**: What input information is required before the activity can commence? Select this from drop down list. This information must be an output from another activity or from an external source. If it is from an external source, it must be defined on the *Validation Data* sheet which is separately designed from the data collection form for the purpose of ensuring consistency of the information used by and produced in the process.

- o **Name**: Name of the document that is produced by the activity.
- o **Where does it come from**: What activity produced this information?
  - Activity name: Hame of the activity that produced the information. If it is from an external source, then write “External” in the cell.
  - Group: What group/branch produced this information?

- **Output information**: What information does this activity produce?
  - o **Name**: Name of the document that is produced.
  - o **Where is this used**: What activities make use of this information?
    - **Activity name**: Names of the activities that used the information.
    - **Groups**: What groups use this information?
- **Comments**: What occurred in this activity? What extra comments can be provided to help understand the data entered?



| | A |
|---|---|
| 1 | ACTIVITY DETAILS |
| 2 | NAME |
| 3 | Draft Comd's Guidance |
| 4 | JMAP STEP |
| 5 | MISSION ANALYSIS |
| 6 | DURATION (MINS) |
| 7 | |
| 11 | PRIOR ACTIVITIES |
| 12 | Review the Situation |
| 13 | Identify & Analysis Superior Comd's Intent & Mission |
| 14 | Identify & Analysis Tasks |
| 15 | Identify & Analysis Freedom of Action |
| 16 | Identify & Analysis Critical Facts & Assumptions |
| 21 | STAFF GROUPS INVOLVED |
| 22 | Theatre Planning Group |

| INPUT INFORMATION | | |
|---|---|---|
| | Where did it come FROM? | |
| NAME | ACTIVITY NAME | GROUP |
| Comd's Initial Guidance | Prelimary Scoping | Commander |
| Superior Comd's Intent | External | Superior Comd |

| OUTPUT INFORMATION | | |
|---|---|---|
| | Where is this USED? | |
| NAME | ACTIVITY NAME(S) | GROUP(S) |
| Detailed Comd's Guidance | Mission Analysis Brief | All |
| Mission Analysis Brief | Mission Analysis Brief | All |

COMMENTS:

Figure 5 An Excel Spreadsheet for Collecting Process Model Data

## 5. CPN Process Model of the JMAP

This section presents the CPN model of the JMAP with an overview and selected representative steps and sub-steps. It is intended that the complete set of the JMAP model will be made an annex to the ADF operational planning doctrine.

JMAP is represented as a hierarchy of steps and activities. The use of hierarchies in the representation of complex processes such as JMAP is essential for understanding the processes. Design/CPN enables the use of hierarchies in modelling.

Figure 6 shows the hierarchy of an operational planning process where JMAP itself is part of the hierarchy. The operational planning process (*OperationalPlanningProcess*) comprises JMAP (*JMAP*) and the supporting processes (*SupportingProcesses*). The supporting processes include JIPB, Logistics, Targeting and Information Operations (IO) processes. The supporting processes are separately modelled as they follow procedures different from JMAP. The supporting processes must however interact with JMAP in order to inform the process.

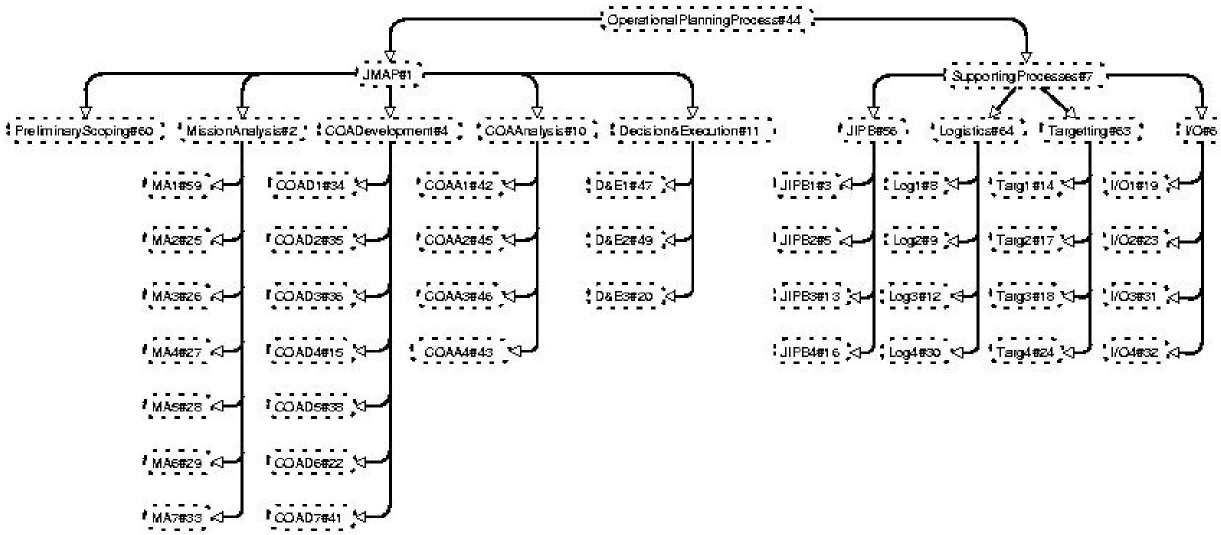



Figure 6 The CPN Hierarchy of JMAP

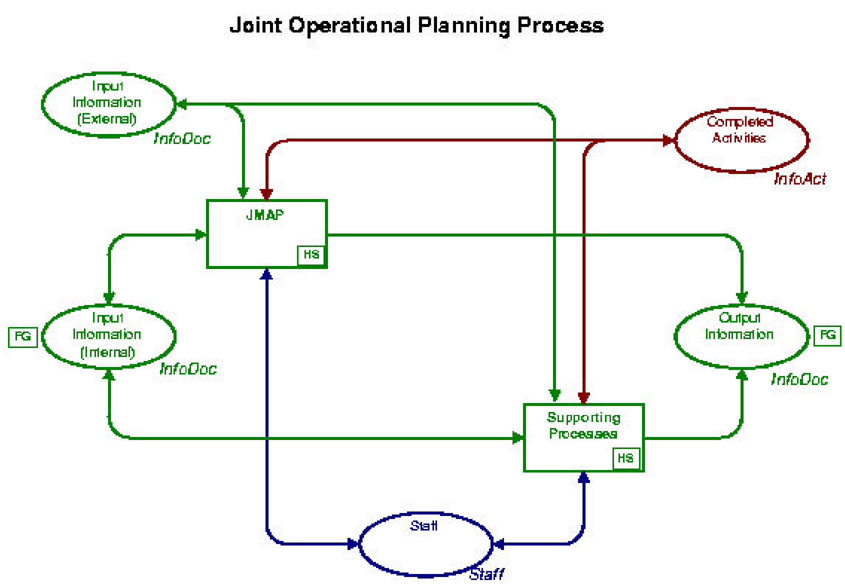



Figure 7 Operational Planning Process incorporating JMAP and Supporting Processes

Figure 7 shows the top-level representation of the hierarchy. It contains two substitution transitions: *JMAP* and *Supporting Processes*, corresponding to the two second-level nodes shown in Figure 6. Substitution transitions and fusion places are the two mechanisms in CPN [Jensen 1994] that enable the modelling of a hierarchy. A substitution transition is a transition that has a lower level representation called a subpage. Graphically, a substitution transition is marked by a label “HS”. Fusion places are copies of a single place across a hierarchy (labelled by “FG”), different areas or instances of the same page (labelled “FP” and “FI”, respectively). JMAP and the supporting processes are triggered by external information residing in the *Input Information (External)* place. Triggers include warning orders and planning directives. In the CPN model, JMAP and the supporting processes are related by the places of *Staff*, *Input Information (Internal)*, *Input Information (External)*, *Output Information*, and *Completed Activities*. It is important to note that the place of *Input Information (Internal)* only holds information produced by other activities within the modelled process. Information from external sources resides in the *Input Information (External)* place. This distinction is implicitly described for Figures 4 and 5 but explicitly modelled in the CPN structure. The places of the *Input Information (Internal)* and *Output Information* are the fusion places to ensure that information produced by one activity can be used by other activities. The detailed interactions between JMAP and the supporting processes are represented at the lower level models where individual activities of these two processes interact.

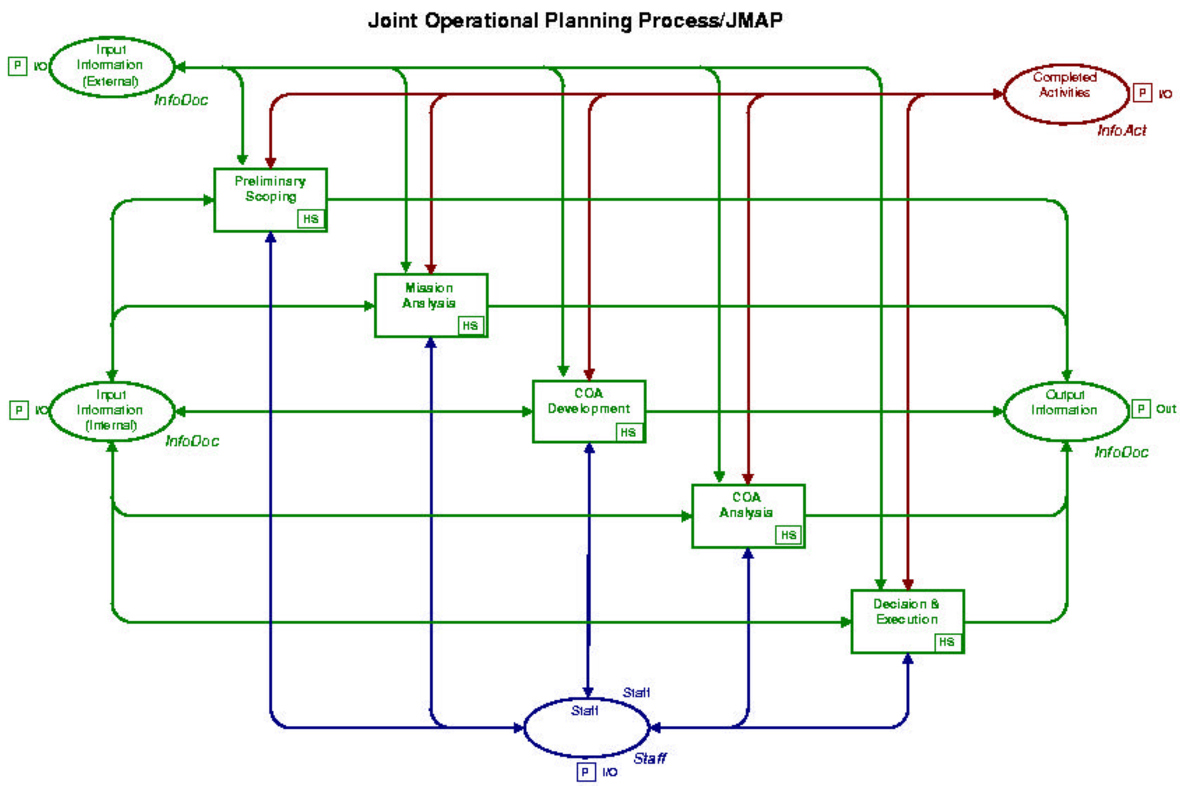



Figure 8 CPN Model of JMAP

Figure 8 shows the *JMAP* process comprising *Preliminary Scoping* and the four JMAP steps: *Mission Analysis*, *COA Development*, *COA Analysis*, and *Decision & Execution* modelled as five substitution transitions. These substitution transitions correspond to the third level of the hierarchy shown in Figure 6. Again, the JMAP steps relate through the places of *Staff*, *Input Information (Internal)*, *Input Information (External)*, *Output Information*, and *Completed Activities*. This pattern of representation corresponds to the model pattern of individual activities (Figures 4 and 5). The advantage of using this pattern is that the resulting model is highly parameterised thereby allowing a rapid population and analysis of the model. The disadvantage is that the interactions between activities are hidden from the net structure. The only information about the flow of activities is the implicit flow from the top left corner of the page to the bottom right corner.

The CPN model of the Mission Analysis step is shown in Figure 9. It contains seven sub-steps: *MA1 Review Situation*, *MA2 Analyse Superior Comd's Intent & Mission*, *MA3 Analyse Tasks*, *MA4 Analyse Freedom of Action*, *MA5 Analyse Critical Facts & Assumptions*, *MA 6 Draft Comd's Guidance*, and *MA7 Mission Analysis Brief*. The models of these sub-steps correspond to the Mission Analysis sub-steps shown in Figure 3 and the Mission Analysis fourth level nodes in the hierarchy (Figure 6). Again, the JMAP steps relate through the places of *Staff*, *Input Information (Internal)*, *Input Information (External)*, *Output Information*, and *Completed Activities*.

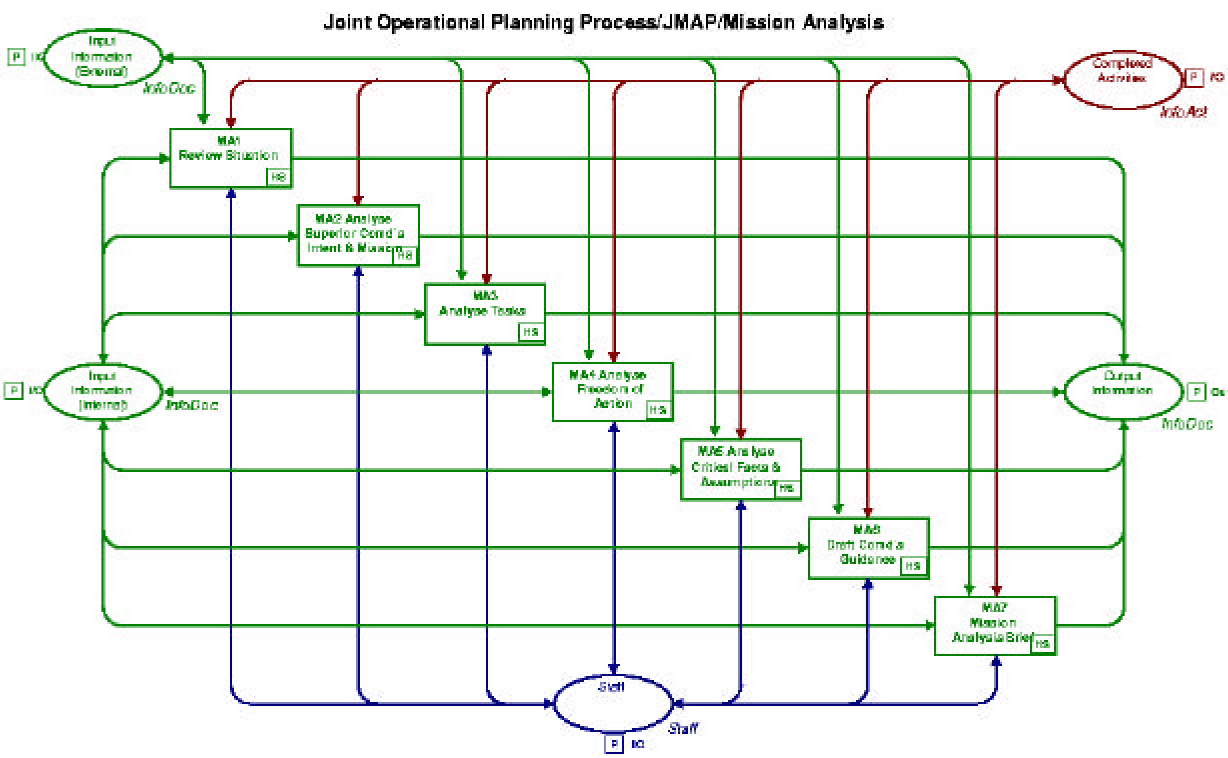



Figure 9 CPN Model of Mission Analysis

The activity of drafting the commander's guidance (*MA6 Draft Comd's Guidance*) is modelled in Figure 10. This is an example of the lowest level representation of the JMAP model. The activity takes external input information "Superior Commander's Intent" (arc inscription *1`Superior_Comds_Intent*) and internal input information "Commander's Initial Guidance" (arc inscription 1`*Comds_Initial_Guidance*). As mentioned earlier, the difference between external input information and internal input information is that external input information is given to the process by external sources whilst internal input information was produced by activities prior to the modelled activity. In this example, the internal input information "Commander's Initial Guidance" was produced during *Preliminary Scoping*. The *Input Information (Internal)* and *Output Information* places are one of the mechanisms that implicitly relate activities in JMAP.

According to Figure 10, the *MA6* activity must be preceded by five Mission Analysis activities (*MA1* to *MA5*, corresponding names can be found in Figure 9). When the activity is completed, it returns an *MA6* into the place of *Completed Activities* for possible use by future activities. The activity is performed by the Theatre Planning Group, lasts (typically) 240 minutes, and produces a Detailed Commander's Guidance and a Mission Analysis Brief upon completion.

As we discussed earlier, CPN models are dynamic. Once a CPN model is developed and populated, it can be executed over time. Design/CPN [CPN Group, 1996] supports the visualisation of the execution of the JMAP model. This completes our representative description of the model given the page limit.

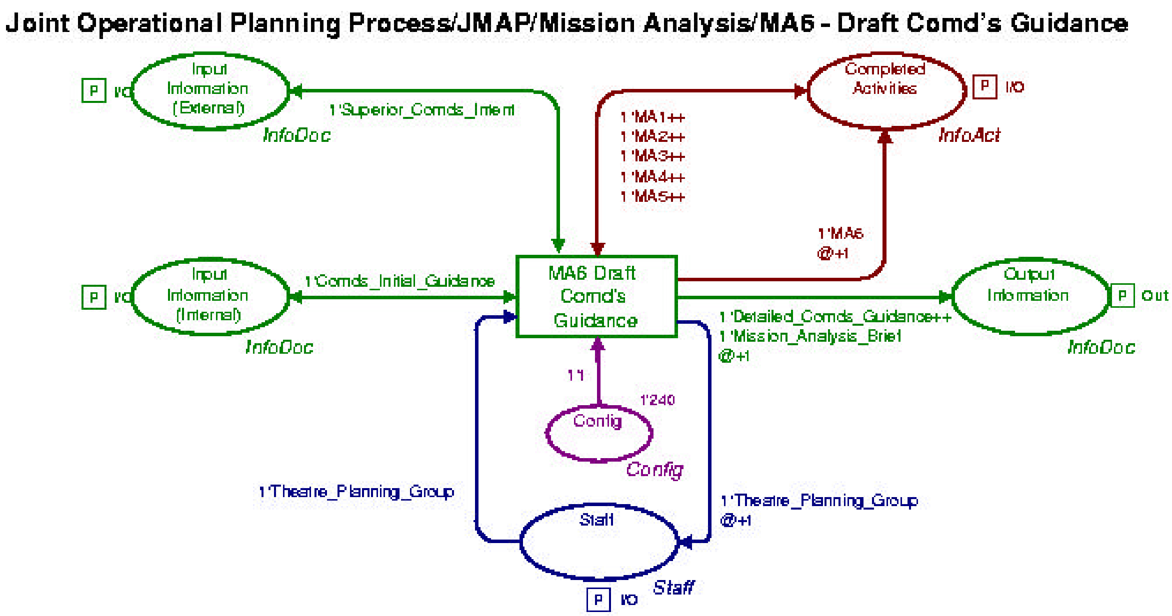



Figure 10 CPN Model of the Activity of Drafting the Commander's Guidance

## 6. **Analysis Results**

In March 2001, one of the authors observed a planning exercise conducted at the ADF Deployable Joint Force Headquarters. Detailed information on individual staff activities, duration of the activities and information flow was collected during the observation to populate the model described in the previous section. State space techniques were then employed to analyse the populated model to answer domain-specific questions. Details of the analysis can be found in [Kristensen et al, 2002].

This section presents the analysis results that are of interest to the Headquarters that conducted the planning exercise. As the model presented in the previous section is generic and doctrine based, it can be used as a basis to observe and conduct analysis of any planning exercises that employs JMAP. It is noted that there are some small variations on the naming of some activities peculiar to the Headquarters that developed the JMAP doctrine into the HQ SOP.

We would like to stress that the results presented in this section are aimed at conveying the merit of applying modelling formalisms to the representation and analysis of Military Headquarters planning activities. As there was only one observer and the planning process took place in the form of concurrent activities, the model and analysis results presented in this report are necessarily undefining and requires validation.

The analysis shows that the total amount of time taken for developing the operational plan is 2522 minutes. The result is in agreement with the actual amount of time spent on planning, which is over 5 working days.

Figure 11 depicts the activities that the planning staff were involved in over the period of the exercise. The legend for the activities is given in Figure 12.

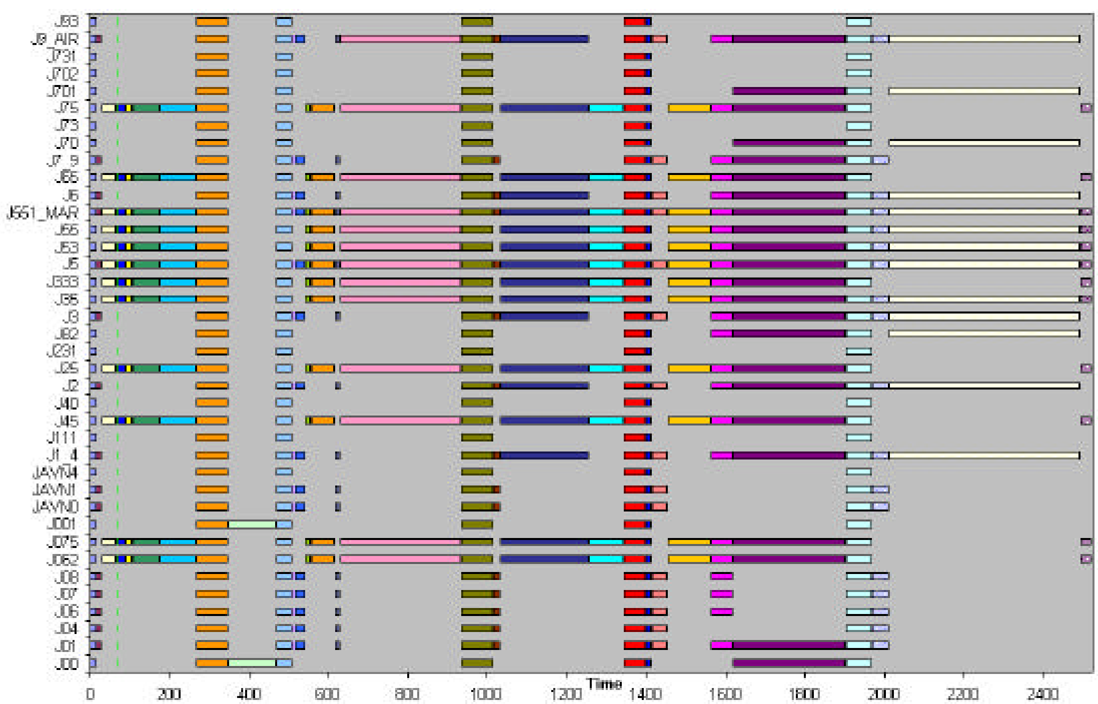



Figure 11 Staff Activity Chart

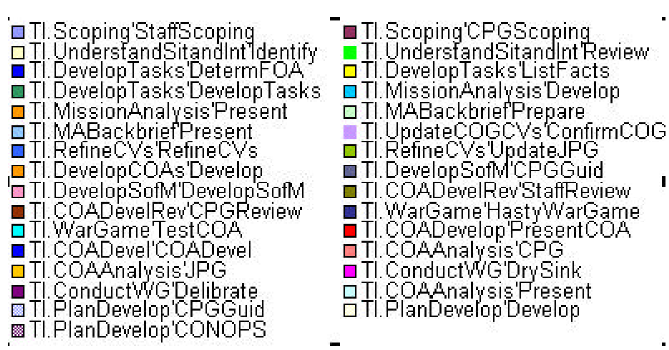



Figure 12 Correspondence between Planning Activities and Colours

Figure 13 shows the planning activities over time. The activities are shown sequential due to the limitation of one person observing the exercise. During the exercise observed, there were concurrent activities carried out by a number of planning groups. The red portions of three bars in Figure 13 indicate the delays occurred during the process due to the unavailability of certain staff members. These staff members were simultaneously required by more than one activity, and hence certain activities would have to wait though the required information for these activities was already available.

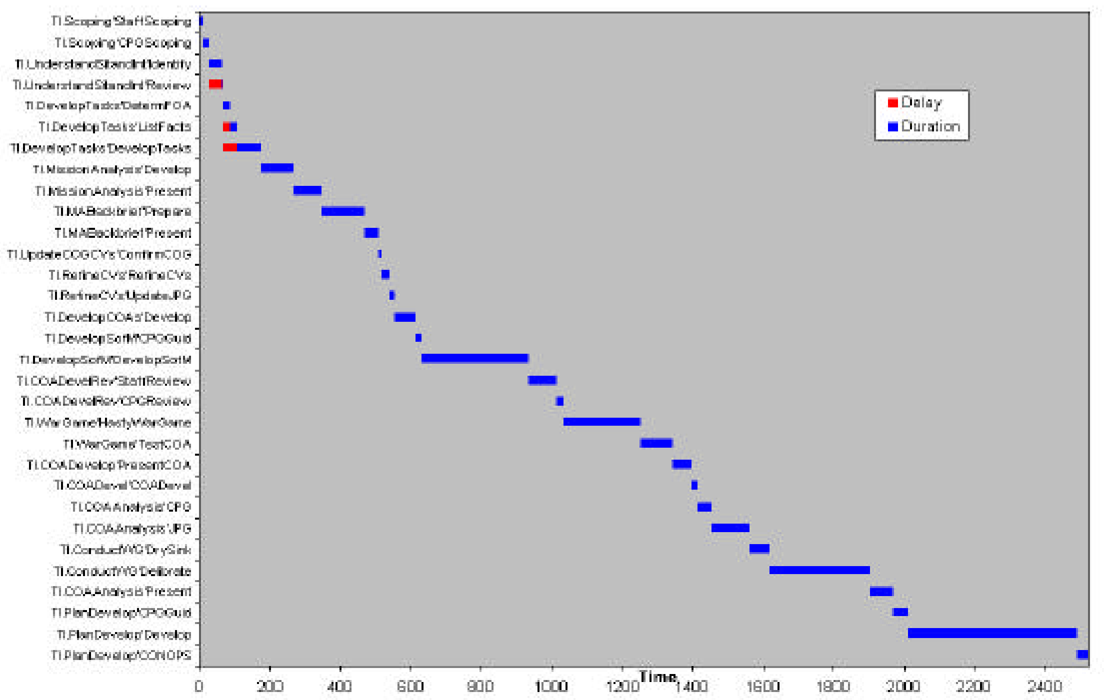



Figure 13 DJFHQ Planning Activities over Time

Instances of staff simultaneously required by multiple planning activities are illustrated in Figure 14. There were three occasions when these staff were simultaneously required, corresponding to the three red bars in Figure 13.

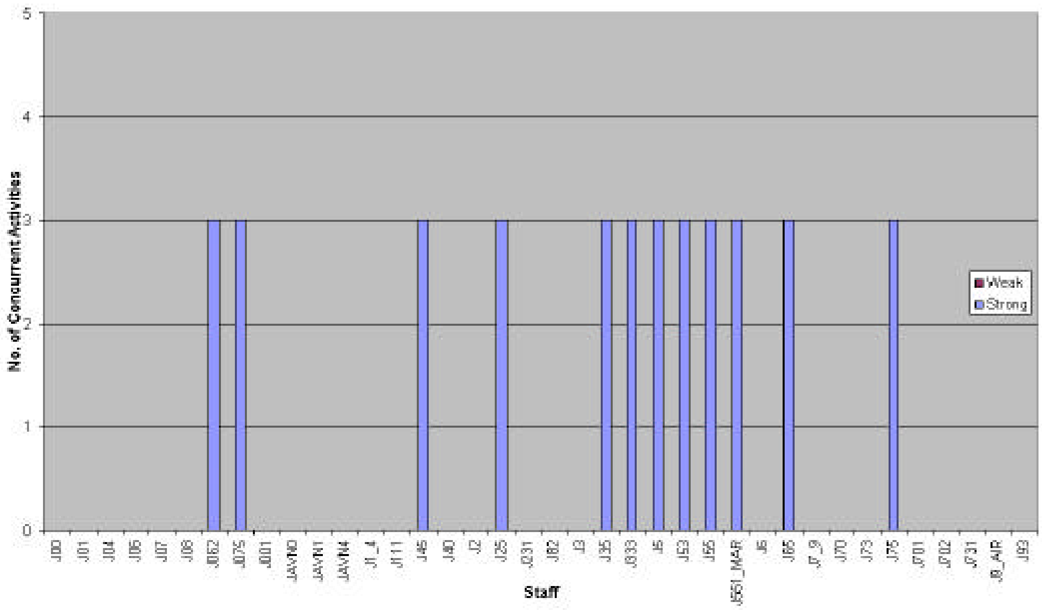



Figure 14 Instances of Staff Required Simultaneously by Multiple Activities

Finally, Figure 15 shows the amount of time (as percentages of the total planning time) that staff members spent on the planning activities as computed by the state space technique from the observed information for each individual activity.

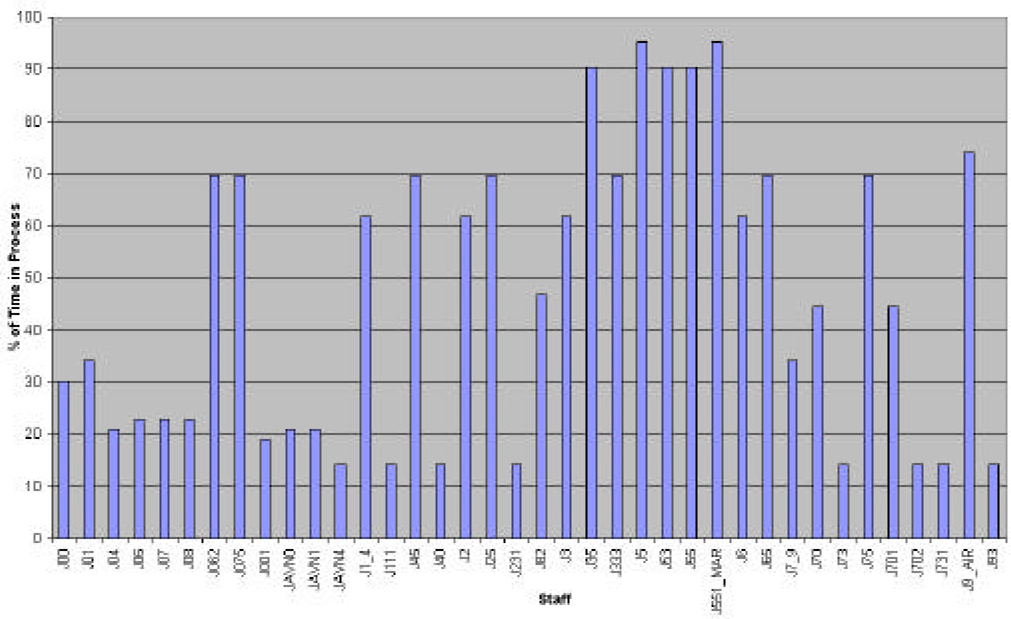



Figure 15 Time (% of the Total Time) Spent on Planning Activities by Staff Members

## 7. **Conclusions**

The key contribution of this paper is the provision of alternative views of the JMAP doctrine expressed in the form of a formal model that is both graphical and analytical. The insight that can be gained by officers through examining the process, by both graphical and dynamical means, e.g.

by step-through of a token game simulation, enhances understanding of the doctrine and helps its application in real world operational level planning. Moreover, the formal model can be applied to specific military HQ for the quantitative analysis of its operational planning SOP. Examples of quantitative analysis results were reported in this paper.

A topic of future work is the integration of the CPN model of JMAP with real-time workflow monitoring tools, and the use of state space analysis of the CPN model to forecast, e.g. bottlenecks and termination of a planning process given the current state. With a formal representation of JMAP in place, it will be possible to use CPN models for formal checking of whether the planning processes in the Headquarters of the ADF conform to the doctrine.

## 8. Acknowledgements

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