DOCUMENT DE TRAVAIL 1999-021

MANAGING A DECISION-MAKING SITUATION IN THE CONTEXT OF THE CANADIAN AIRSPACE PROTECTION

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Original manuscript : ISBN -
Version original : ISBN -

Série électronique mise à jour : 12-1999
One-line publication updated : Seria electrónica, puesta al dia
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Abstract: An important activity of the Air Operation Center (AOC) is the elaboration, mitigation and evaluation of different Courses of Actions (CoAs) in order to respond to emergency situations. Defense Research Establishment Valcartier (DREV) initiated a research activity to provide the AOC Commander and his senior staff, with advisory tools. The Commander’s Advisory System for Airspace Protection (CASAP), a distributed and unsynchronized knowledge based decision support system, was then designed to help the AOC staff managing counter-drug events and their related CoAs. This C2 support system helps the Commander (or his representative) to screen and prioritize the proposed CoAs to overcome the emergency situation. CASAP uses multicriterion decision analysis (MCDA) concepts and models. A MCDA methodology was used for the knowledge engineering. This methodology was implemented in CASAP, with different add-ins to help the Decision-Maker analyzing the CoAs, and minimizing the risk component introduced by the subjectivity and the uncertainty of the evaluation process. In this paper, we review the modeling process of the decision-making situation, the formulation of the different criteria, and the aggregation procedure. We introduce also the analysis tools implemented in CASAP.

Keywords: Multicriterion analysis; multicriterion aggregation procedure; counter-drug operations; Canadian airspace protection; Courses of action analysis; decision-making situation

1.0 INTRODUCTION

Rapid developments in artificial intelligence and in other information technology areas, and especially in the modeling of decision-making processes, is to greatly influence the Command and Control (C2) strategy and structure of the 21st century armed forces. In fact these technologies might allow shorter chains of command, a flatter organizational structure, rapid sharing of the information, and faster task orders dissemination. Modern decision aids, that are able to deal effectively with complex operational situations involving masses of current information and prior knowledge, might help to enhance the C2 capabilities and structures.
Within 1 Canadian Air Division/Canadian NORAD region headquarters (1 CAD/CANR), Air Operation Centre (AOC) is responsible for the day-to-day air force operations monitoring and control. For routine operations, C2 decisions are effected through established doctrine, orders, and procedures. As contingency operations are introduced (crisis, contingency deployment or conflict) the AOC becomes the focal point for planning, directing, controlling and monitoring assigned forces. An important element for either type of operation is the elaboration, mitigation and evaluation of different Courses of Actions (CoAs) in order to respond to the emergency situations. During such situations, AOC staff members work under stress conditions, and have to process a large amount of information within a short time cycle. In fact, time constrains the process to extensively assess the situation, generate wide-range of CoAs, and intensively evaluate them according to significant point-of-views, before selecting and executing the “best” possible compromise. Moreover, it might be impossible to have access to the experience of resources that are not inside the command post at that specific time.

To help the people of the AOC, Defense Research Establishment Valcartier (DREV) started a research activity aimed at investigating approaches and concepts, and developing advanced technologies to provide the Commander and his senior staff, with advisory tools for planning, management and employment of air defense resources and capabilities. Commander’s Advisory System for Airspace Protection (CASAP), a distributed and asynchronous knowledge based Decision Support System (DSS), was foremost developed to assist the AOC staff managing counter-drug events and their related CoAs, as well as to analyze, evaluate and prioritize these CoAs according to different evaluation criteria. Since the Commanders need to balance several conflicting and incommensurable criteria to make “wise” decisions, Multicriterion Decision Aid (MCDA) methodology deemed to be appropriate to be implemented in CASAP.

In this paper, we report the methodology and procedures used to develop CASAP. In particular, in section 2, we review the context of operation of the Canadian Airspace Protection (CAP), and we introduce the MCDA methodology. In section 3, we discuss the structuring (modeling and formulation) process of the decision-making situation (DMS), and the knowledge engineering to formulate the different evaluation criteria. We introduce, in section 4, a multicriterion aggregation procedure based on the outranking synthesizing approach. This procedure is implemented in CASAP along with different add-ins to help the Decision-Maker (DM) analyzing the CoAs, and minimizing the risk component introduced by the subjectivity and the uncertainty of the evaluation process. In section 5, we present CASAP’s functional architecture as well as some physical interfaces. Finally, in section 6, we discuss the MCDA methodology, and we propose further developments.

### 2.0 REVIEW OF THE CONTEXT OF OPERATIONS AND THE MCDA METHODOLOGY

#### 2.1 Context of operations

Within 1 CAD/CANR, AOC is responsible for the day-to-day air force operations monitoring and control. For routine operations, C2 decisions are effected through established doctrine, orders, and procedures. As contingency operations are introduced (crisis, contingency deployment or conflict) the AOC becomes the focal point for planning, directing, controlling and monitoring
assigned forces. During stressful situations, AOC staff members have to process a large amount of information within a short time cycle. Moreover, it might be impossible to have access to the experience of resources that are not inside the command post at that specific time.

In case of airspace violation, the Force Employment staff within the 1 CAD/CANR AOC must elaborate, mitigate and evaluate different CoAs for the airspace protection. In the event of an airspace violation, whether it is intentional or not, falls into routine operations category [1 CAD], existing C2 relationships and aerospace doctrine will govern the response to this event. Through the application of this operation order, which clearly delineates what is expected from whom, a response to an airspace violation under normal circumstances can be handled in a timely fashion with minimal AOC staff effort. In this situation, the C2 process, modeled by the Object-Orient-Decide-Act (OODA) loop (Figure 1), particularly the D portion, gets compressed since there is are pre-defined operation orders, and more often default CoA is in place.

However, if the airspace violation event doesn’t fit into the routine operation, it will be considered as an immediate operational contingency. The AOC then moves to the Immediate Action Team (IAT). The IAT’s responsibilities include initial assessment, contingency planning, CoA development and analysis, as well as the issuance of warning and execution orders [1 CAD]. The IAT therefore completes all the activities in the Orient, Decide and Act processes once the team has been activated. The IAT is comprised of personnel who have the appropriate skill-sets to react to short-notice crisis situations and develop comprehensive contingency plans for CF air operations. In fact, time constrains the process to extensively assess the situation, generate wide-range of CoAs, and to intensively evaluate them according to significant point-of-views, before selecting and executing the “best” CoA; achieving the best compromise among all the evaluation criteria. It is here where a CoA advisory tool would greatly assist the IAT in ensuring that all the necessary functional activities are completed and verified, the CoA development and analysis process is correctly performed, and the selection of a suitable CoA is accomplished in a timely manner.

2.2 MCDA methodology

Commanders have always needed to balance objectives and factors to make “wise” decisions. Then MCDA models and procedures appear to be appropriate to deal with aerospace protection
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DMS. MCDA methodology aims to aid the DM to handle semi-structured decision and multidimensional problems with multicriterion, where the components are transitional and the required information insufficient [Siskos and Spyridakos, 1999]. Within the paradigm of the classical operational research, a decision problem is modeled by an objective function ($f$) to be optimized over a set of feasible solutions ($X$); it is the essence of classical mathematical programming. Within, the MCDA perspective, the idea of the optimal solution is replaced by the concept of satisfactory alternative, which realizes the best possible compromise for the DM considering all the conflictual evaluation criteria. This change was the beginning of the development of many MCDA methods.

A DM faced with a decision is often called upon to reconcile several aspects or points of view, which are often conflicting and incommensurable. MCDA models and procedures are merging from the OR field, and based on theories such as the social choice, decision-making, preferences modeling, measurement theory, etc. Within the MCDA perspective, the decision aid process can be seen as a recursive (iterative), and non-linear process composed of five steps [Guitouni, 1998]:

1. Structuring and formulation of the decision making situation: knowledge acquisition and engineering, and problem modeling (A- F - E),
2. Articulation and modeling of the DM’s preferences for each criterion (local preferences modeling) and inter-criteria information,
3. Aggregating these preferences and information to establish one/many global relationship system among the alternatives (CoAs),
4. Exploiting the relationship system, and
5. Result and recommendation.

In the context of MCDA, a set of alternatives (CoAs) has to be evaluated according to a set of criteria (see Table 1). Let $A$ be the set of the CoAs, $A = \{a_1, a_2, ..., a_i, ..., a_m\}$, and $F$, a coherent family of criteria, $F = \{C_1, C_2, ..., C_j, ..., C_n\}$. The value of the $i^{th}$ CoA evaluation according to the $j^{th}$ criterion is denoted $e_{ij}$. The evaluation of all the CoAs according to the set of criteria produces the multicriterion performance table $E$ (see table 1). Subsequent to the evaluation step, the decision-aid process involves an extensive effort of the DM’s preference articulation and modeling, which are discussed in the following sub-section.

<table>
<thead>
<tr>
<th>CoAs ($1...m$)</th>
<th>Criteria ($1...n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$e_{11}$</td>
</tr>
<tr>
<td>$a_i$</td>
<td>$e_{i1}$</td>
</tr>
<tr>
<td>$a_m$</td>
<td>$e_{m1}$</td>
</tr>
</tbody>
</table>

2.3 Preference modeling

Modeling the DM’s preferences is not an easy task because it is difficult to apprehend the subjectivity and the imprecision/ambiguity of the human behavior. The major challenge facing
the implementation of any decision-aid is the “accurate” assessment of these preferences. Siskos (1982) declared that “... the major problem for the analyst facing multicriterion phenomena raise, is the assessment of a model reflecting at best the preferences of the decision-maker.”

The literature reviewed reveals many ways and theories about preferences articulation and modeling. For example, utility functions, valued functions, pairwise comparisons, tradeoffs, and discrimination thresholds could be used (see [Fishburn, 1970; Keeney and Raiffa, 1976; Keeney, 1992; Roubens and Vincke, 1985; Roy and Bouyssou, 1993; Saaty, 1980; Vincke, 1989] for more details). In this section, we limit our review to the discrimination thresholds for preferences modeling.

Generally, when comparing two CoAs taking into account many aspects, a DM may be in one of the following situations: i) he is indifferent between \( a_i \) and \( a_k \) (denoted \( a_i \sim a_k \)), ii) he strictly prefers \( a_i \) to \( a_k \) (denoted \( a_i \succ a_k \)), iii) he weakly prefers \( a_i \) to \( a_k \) (hesitation between indifference and strict preference: denoted \( a_i \succ f a_k \), or iv) he considers that \( a_i \) is incomparable to \( a_k \) (hesitation between \( a_i \succ a_k \) and \( a_k \succ a_i \), or the two CoAs are a priori matchless: denoted \( a_i \sim a_k \)).

If when comparing two alternatives \( a_i \) and \( a_k \) according to a “true-criterion”, we get the following preference relations:

\[
\begin{align*}
\{ a_i \succ j a_k \} & \iff e_{ij} > e_{kj} \\
\{ a_i \sim j a_k \} & \iff e_{ij} = e_{kj}
\end{align*}
\]

(1.)

However, the evaluation of a CoA with regard to a criterion \( j \) is often uncertain and imprecise. Moreover, on top of these uncertainties and imprecision, the DM's preferences may involve some hesitations, doubts, indecision, etc. In order to take these behaviors into account, one can introduce an indifference threshold \( q_j \geq 0 \), such that if the performances of two alternatives on a criterion \( j \) differ by less than \( q_j \), then there is an indifference relation \( \sim_j \) such as:

\[
\begin{align*}
\{ a_i \succ j a_k \} & \iff e_{ij} - e_{kj} \geq q_j \\
\{ a_i \sim j a_k \} & \iff |e_{ij} - e_{kj}| < q_j
\end{align*}
\]

(2.)

A criterion having an indifference threshold is called a “quasi-criterion”. If \( q_j \) is set to 0, then the quasi-criterion collapses to a true-criterion. Moreover, one may define a strict preference threshold for a quasi-criterion \( j \), \( p_j \geq 0 \), such that if the performances of \( a_i \) and \( a_k \) according to this criterion differ by at least \( p_j \), then it is a situation where one alternative is strongly preferred \( \succ_j \) to the other one. However, if this difference is between \( q_j \) and \( p_j \), we can conclude to a weak preference \( \succ j \) between the two CoAs. A criterion with preference and indifference thresholds is called a “pseudo-criterion”, and is illustrated as follows:
\[
\begin{cases}
  a_i >_j a_k \iff e_j \geq e_{kj} + p_j \\
  a_i \succ_j a_k \iff q_j < e_{ij} - e_{kj} < p_j \\
  a_i \sim_j a_k \iff |e_{ij} - e_{kj}| \leq q_j
\end{cases}
\]

(3.)

where \( p_j > q_j \)

If \( q_j \) is set to 0, then the pseudo-criterion collapses to a pre-criterion, and if \( p_j = q_j \), then the pseudo-criterion collapses to a quasi-criterion. One should note that these thresholds are not necessarily constant; i.e. \( q_j = q_j(e_{ij}) \) and \( p_j = p_j(e_{ij}) \).

MCDA methodology also introduces the inter-criteria information. This information concerns the relative importance of the criteria, as well as the attribution of veto power to particular ones. The relative importance of the criteria can be an explicit set of scalars representing tradeoffs, scale harmonization, compromise, or intrinsic coefficients. Some procedures, like the lexicographic, introduce only a priority ranking of the criteria. We discuss the veto power in section 4.

2.4 Multicriterion aggregation approaches

The DM’s preferences and the data contained in \( E \) should be aggregated in order to recommend the “best decision”. During the last three decades, the MCDA discipline has undergone significant development, which gives rise to several methods and procedures. Each procedure is based on a particular hypothesis and operational approach. The review of the literature suggests that the different known discrete MCAPs are based on different operational approaches [Guitouni and Martel, 1998]. Here are the most two important:

- Single criterion synthesizing approach: The MCAPs of this approach seek to build an aggregation function \( V \) to represent the global score of a CoA \( a_i \) by a single synthesizing criterion \( C(a_i) \) obtained from the scores with regard to criteria \( c_1, \ldots, c_n \) by \( V(a_i) = f[C(a_i), \ldots, C(a_i)] \) (see [Fishburn, 1970; Keeney and Raiffa, 1976; Keeney, 1992]). This approach aims to the construction of a value system that aggregate the DM (DM)’s preferences on the criteria (attributes) based on strict assumptions; only the strict preference and the indifference are considered, and these preference relations are complete and transitive. For example, the MultiAttribute (Value) Utility Theory (MAUT/MAVT) drops within the framework of this approach. The DM’s preferences are modeled throughout partial utility functions, then aggregated in a single synthesizing utility function.

- Outranking synthesizing approach: The idea behind this approach is to be able to establish an outranking relation between two CoAs; \( a_i \succ a_k \) if \( a_i \) is at least as good as \( a_k \) (see [Roy, 1985; Roy and Bouyssou, 1993; Vincke, 1992]). Instead of computing a score for each CoA \( a_i \), it computes \( V(a_i, a_k) \) for each pair of alternatives \( (a_i, a_k) \in A \times A \). This approach is inspired from the social choice theory. Each criterion is considered as a voter, with a particular power, and each CoA as a candidate. The DM’s preferences are modeled throughout a set of parameters (thresholds), and the aggregation is partially compensatory. This aggregation approach is based on the pairwise comparison of the CoAs along with each
criterion. The preference relational system (p.r.s.) obtained could include the indifference, strict preference, weak preference, intransitivity or even the incomparability.

The review of the MCDA literature shows that the exploitation phase of a MCAP can be accomplished in different manners. For instance, if the MCAP is based on the single criterion synthesizing approach, the exploitation step is trivial in the sense that a unique value (according to the unique criteria) is associated to each CoA during the aggregation phase. The aggregation phase is often considered as a weighted sum of the CoA performances obtained according to each criterion. Sometimes, a multiplicative model may be used. Generally speaking, the aggregation of this type is totally compensatory. Then, no matter what the decisional problematic (sorting, ranking, choice, etc.) is, this unique value allows to address directly the proper problematic. However, if the MCAP belongs to the outranking approach, the exploitation phase is performed in light of the decisional problematic.

The aggregation phase of the MCAPs, based on the outranking approach, is achieved through a series of pairwise comparisons. For these procedures, the aggregation phase consists of computing concordance index for each pair of alternatives, which most of the time takes the form of a weighted sum of the pairwise comparison results. The DM’s local preferences modeling usually introduces discrimination thresholds: indifference threshold, strict preference threshold, and sometimes a veto threshold. Some outranking methods, like ELECTRE III [Roy, 1978], introduce a discordance analysis to consider the opposition of the discordant criteria. An outranking index for each pair of alternatives is then computed by fusion the global concordance index to the local discordance indexes. These thresholds and the discordance analysis enable to attenuate the compensation phenomena.

3.0 STRUCTURING THE DECISION MAKING SITUATION: FORMULATION PROCESS

In order to develop CASAP, researchers from DREV worked for a few years with the Executive Elements (Commander and his senior staff) at the former Fighter Group/CANR headquarters, in order to acquire knowledge about the DMS and to identify key factors considered to evaluate different CoAs. After a first prototype, multicriterion analysis methodology was chosen to engineer the knowledge acquired. The readings of Canadian military operation documents (ex. [1 CAD, 1999; FG, 1990; FG, 1992; FG/CANR, 1992]), and operational checklists confronted by knowledge acquisition sessions with the operational air force personnel led to the identification of five factors to be considered while evaluating CoAs for counter-drug scenarios in a peace time context. The key factors identified are Flexibility, Complexity, Sustainability, Cost-of-Resources, and Risk. Each of these factors was decomposed into one or many evaluation criteria. In fact, 14 criteria were formulated, and partially validated with the DM. This set of criteria was also presented to various plan staff in the new single air force operational headquarters (1 CAD/CANR HQ). In this section, we briefly present and discuss the various criteria obtained.

3.1 The Flexibility

The flexibility factor is concerned with the ability to adapt to various possible changes that may occur while implementing a CoA. This dimension is divided into three criteria: Covering
Operational Tasks \((C_1)\), Covering Mission’s Possible Locations \((C_2)\), and Covering Enemy’s CoAs \((C_3)\). The criterion \(C_1\) is concerned with the ability of CoA \(a_i\) to adapt to possible changes in operational task \(k\) \((OT_k)\), which may occur during its implementation. \(OT_k\) is the result of the hierarchical decomposition of the national security objectives, and can take values such as: Monitor transport routes / Coordinate with civilian and military units for joint operations / Participate in detection, tracking and interdiction of narcotics transport / Intercept communications, etc. Different \(OT_k\) may have different importance \((\pi_{OT_k})\).

For each selected operational task, staff member assesses a coverage degree \((x_{ik})\) for each CoA \((a_i)\) over each \(OT_k\). This criterion is to be maximized, and the evaluation of \(a_i\) is given by \(e_{i1} \in [0,1]\) as follows:

\[
e_{i1} = \sum_k \pi_{OT_k} \cdot x_{ik}, \quad \text{where } x_{ik} = \begin{cases} 1 & \text{if } a_i \text{ completely covers } OT_k \\ \text{between } 0 \text{ and } 1 & \text{if } OT_k \text{ is partially covered} \\ 0 & \text{Otherwise} \end{cases} \quad (4.)
\]

The criterion of covering mission’s possible locations \((C_2)\) is concerned with the ability of a CoA to adapt to possible changes in the predicted mission’s locations which may occur during the implementation of a COA. This criterion is to be maximized. Considering the weather conditions, the distance to Area of operations (AOO), as well as AOO characteristics, the staff member assesses the conditional probability \(p_{time_k}\) that \(a_i\) covers in time (no partial covering) the mission’s location \(ML_k\). Each possible mission location is predicted a probability \(p_{ML_k}\). A mission’s possible location can be specified by its coordinates or by its known name. The evaluation of \(a_i\) with respect to \(C_2\) is given by \(e_{i2} \in [0,1]\) in the following manner:

\[
e_{i2} = \sum_k p_{ML_k} \cdot p_{time_k} \quad (5.)
\]

The criterion of covering enemy’s CoAs \((C_3)\) is concerned with the ability of a COA \(a_i\) to adapt in time to possible changes in the enemy’s CoAs that may occur during the implementation. This criterion is also to be maximized. The operator assesses the conditional probability \(p_{cover_{ij}}\) that \(a_i\) covers in time the enemy’s course of action given that the enemy executes \(ECOA_j\). Each \(ECOA_j\) is predicted with a probability \(p_{ECOA_j}\). The evaluation of \(a_i\) with respect to \(C_3\) is given by \(e_{i3} \in [0,1]\):

\[
e_{i3} = \sum_{j=1}^{\Omega_j} p_{ECOA_j} \cdot p_{cover_{ij}} \quad (6.)
\]

### 3.2 Complexity

This factor is concerned with the CoA implementation complexity. It is divided into three criteria: operations complexity, logistic complexity, and C2 complexity. The Operations Complexity \((C_4)\) is concerned with the COA implementation difficulties caused by its operational requirements. For each important resource in operation to execute \(a_i\), and for each function to be performed by this resource, the operator assesses the complexity on an ordinal scale \((High, Medium, Low)\) by taking into account the AOO characteristics and deployment conditions. The resources might have different importance in the execution of the COA. An ordinal evaluation \(e_{i4}\)
of each \( a_i \) with respect to \( C_4 \) is obtained by redefining a global ordinal scale by aggregate the functions complexity evaluations (see [Abi-Zeid et al. 1998]) for more details). The redefined ordinal scale contains 5 levels: very low complexity, low complexity, moderate complexity, high complexity, and very high complexity. This criterion is to be minimized.

The criterion logistics complexity (\( C_5 \)) is concerned with the COA implementation difficulties caused by its logistics requirements. This criterion is to be minimized. For each \( a_i \), the operator assesses its Scheduling Logistics Requirements, Refueling Logistics Requirements, Landing and Take-Off Logistics Requirements, Communication Logistics Requirements, Personnel Logistics Requirements and Re-supply Requirements according to an ordinal scale of three levels (High, Medium, Low) scale. The different requirements may have different importance. Here again, an ordinal aggregation procedure amalgamates the requirement assessments to obtain an ordinal evaluation \( e_{i5} \) of \( a_i \) with respect to \( C_5 \); \( e_{i5} \) is expressed using the same scale as \( e_{i4} \) [Abi-Zeid et al., 1998].

The C2 Complexity criterion is concerned with the COA implementation difficulties caused by C2 relationships and Coordination requirements (CR) in operation. This criterion is to be minimized. For each \( a_i \), the operator assesses the C2 relationship complexity and the CR complexity on an ordinal scale of 5 levels (very high, high, medium, low, very low). Then, the evaluation \( e_{i6} \) of \( a_i \) with respect to \( C_6 \) is modeled by a distribution (see [Abi-Zeid et al. 1998]).

### 3.3 Sustainability

This factor is concerned with the ability to continue (stay in) the operation. It is represented by only one criterion: Sustainability. The sustainability criterion is used to evaluate an expected ratio of the COA estimated on-station time over the total required on-station time. This latest time includes the event required on-station time as well as an estimated additional operational time. It is obvious that this criterion is to be maximized.

### 3.4 Optimum use of resources

This factor is concerned with the optimality of the resources employment. It is represented by only one criterion: Cost of Resources. This criterion is to be minimized. The evaluation \( e_{i8} \) of each \( a_i \) according to \( C_8 \) is obtained by summing the incremental cost, in dollars, associated with the use of each resource (equipment) implied in this CoA \( i \).

### 3.5 Risk

This factor represents the risks of mission failure as well as the risks associated with the mission. This factor is developed into six criteria: Impact of the Sensors Coverage Gap, Risk of Military Personnel Loss, Risk of Collateral Damage, Confrontation Risk, CoA Equipment Reliability, and COA Personnel Effectiveness. The criterion Impact of the Sensors Coverage Gap (\( C_9 \)) is concerned with the possibility of mission failure caused by the possible radar and/or radio gaps. This criterion is to be minimized. For each \( a_i \), the operator assesses the mission failure risk due to a radar gap, and/or a radio gap on an ordinal scale (High, Medium, Low). These evaluations are
combined using the importance of each sensor to build a distribution, which represent the evaluation $e_{i9}$ of $a_i$ according to $C_9$.

The criterion risk of military personnel loss ($C_{10}$) represents the likelihood of military personnel loss during the mission. The operator assesses for each $a_i$ the likelihood of military personnel loss on an ordinal scale (highly likely, very likely, likely, unlikely, highly unlikely) given that the enemy is expected to execute the $ECOAx$ with a probability ($p_{ECOAx}$). Then, one will obtain as much conditional evaluations as there are predicted enemy’s CoAs. We use an ordinal aggregation procedure to transform this series of evaluation into an ordinal evaluation according a new ordinal scale with 7 levels. The evaluation $e_{i11}$ is an ordinal evaluation to be minimized [Abi-Zeid et al., 1998].

The criterion risk of collateral damage ($C_{11}$) measures the possibility of collateral damage (anything but the target) during the mission. The criterion confrontation risk ($C_{12}$) is concerned with the assessment of mission failure due to possible confrontations. The evaluations $e_{i11}$ and $e_{i12}$ of a CoA $a_i$ according to these two criteria are to be minimized, and obtained in the same way as $e_{i10}$.

The criterion $C_{13}$ is concerned with the equipment reliability and the robustness of the COA. The evaluation $e_{i13}$ for each CoA $a_i$ is a cardinal evaluation computed using the information about the failure risks of the different resources used to implement this CoA. This information can be expressed by the mean time between failures (MTBF). We use the system reliability theory to compute the evaluation $e_{i13}$. This criterion is to be maximized. The criterion $C_{14}$ is concerned with the effectiveness of the personnel, which may be jeopardized by fatigue, stress, etc. at any moment during the mission. This criterion is to be maximized. For each $a_i$, and taking into account its complexity, the operator assesses the effectiveness of the personnel on an ordinal scale with 5 levels (very highly effective, very effective, effective, lowly effective, very lowly effective). The evaluation $e_{i14}$ is considered as a direct linguistic evaluation, and modeled by a fuzzy number (fuzzy set theory).

The features of the 14 criteria are summarized in table 2. The first column identifies the criterion, the second identifies whether the criterion should be maximized or minimized, the third column identifies the type of individual scales used for the evaluation of the CoA with regard to the criterion. This evaluation can be deterministic or a probability value; it can be crisp (given by a single number) or a distribution (given by a vector of evaluation or a by a fuzzy number); the measurement scale can also be continuous or discrete.
Table 2: Summary of the 14 criteria [[Abi-Zeid et al. 1998]]

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criterion</th>
<th>Optimization</th>
<th>Scale</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>C1: Covering Operational Tasks</td>
<td>Maximize</td>
<td>Cardinal on [0,1]</td>
<td>Crisp, Deterministic, Continuous</td>
</tr>
<tr>
<td></td>
<td>C2: Covering Mission’s locations</td>
<td>Maximize</td>
<td>Cardinal on [0,1]</td>
<td>Crisp, Probabilistic, Continuous</td>
</tr>
<tr>
<td></td>
<td>C3: Covering Enemy’s CoA</td>
<td>Maximize</td>
<td>Cardinal on [0,1]</td>
<td>Crisp, Probabilistic, Continuous</td>
</tr>
<tr>
<td>Complexity</td>
<td>C4: Operations Complexity</td>
<td>Minimize</td>
<td>Ordinal, 5 echelons</td>
<td>Crisp, Deterministic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C5: Logistics Complexity</td>
<td>Minimize</td>
<td>Ordinal, 5 echelons</td>
<td>Crisp, Deterministic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C6: C2 Complexity</td>
<td>Minimize</td>
<td>Ordinal, 5 echelons</td>
<td>Distribution, Discrete</td>
</tr>
<tr>
<td>Sustainability</td>
<td>C7: Sustainability</td>
<td>Maximize</td>
<td>Cardinal, R⁺</td>
<td>Crisp, Deterministic, Continuous</td>
</tr>
<tr>
<td>Cost of resources</td>
<td>C8: Cost of Resources</td>
<td>Minimize</td>
<td>Cardinal, R⁺</td>
<td>Crisp, Deterministic, Continuous</td>
</tr>
<tr>
<td>Risk</td>
<td>C9: Impact of Sensors Coverage Gap</td>
<td>Minimize</td>
<td>Ordinal, 3 echelons</td>
<td>Distribution, Discrete</td>
</tr>
<tr>
<td></td>
<td>C10: Military personnel loss</td>
<td>Minimize</td>
<td>Ordinal, 7 echelons</td>
<td>Crisp, Probabilistic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C11: Collateral damage</td>
<td>Minimize</td>
<td>Ordinal, 7 echelons</td>
<td>Crisp, Deterministic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C12: Confrontation risk</td>
<td>Minimize</td>
<td>Ordinal, 7 echelons</td>
<td>Crisp, Probabilistic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C13: Equipment reliability</td>
<td>Maximize</td>
<td>Cardinal on [0,1]</td>
<td>Crisp, Probabilistic, Discrete</td>
</tr>
<tr>
<td></td>
<td>C14: Personnel effectiveness</td>
<td>Maximize</td>
<td>Ordinal, 5 echelons</td>
<td>Fuzzy, Distribution, Continuous</td>
</tr>
</tbody>
</table>

4.0 MCAP FOR CASAP: PAMSSEM I AND II

In order to select an appropriate MCAP to deal with the DMS in a context of CAP, one should match the MCAPs features to the decisional context requirements. In the context of violation of Canadian airspace, the requirements of CASAP could be summarized as follows:

- Evaluations are mixed: ordinal and cardinal, crisp and distribution;
- DM wants to get a ranking (prioritization) of the CoAs (also called Decision problematic P.γ);
- DM wants to assign a relative importance coefficient to balance the criteria;
- The DMS requires a “controlled” compensation between the criteria;
- Decision-making in a risky context: model the uncertainties, DM’s hesitations and preferences accordingly to the doctrine and the rules of operations;
- Limited time to evaluate and prioritize the CoAs (in case of emergency);
- The DM is well identified (single DM).

The majority of MCAP proposed in the literature considers implicitly the hypothesis that the nature and the type of data contained in Ε (representing the evaluations of the CoAs) are relatively homogenous. The MCAP to be implemented in CASAP should limit the compensation between the criteria, deal with their heterogeneity, and their measurement scales. Moreover, the thresholds should help the DM articulate and distinguish his preferences. Thus, a MCAP based on an outranking approach is suitable to deal with the DMS in the context of CAP. This approach
allows controlling the compensation phenomena among the criteria. Among the different MCAPs, PAMSSEM seemed to be the most appropriate for CASAP. In fact, PAMSSEM was designed to deal with mixed and missing evaluations. It produces either a partial or a total preorder of the alternatives. It offers enough flexibility to consider the DM’s preferences and to control the compensations.

A preliminary version of PAMSSEM I and II was developed by Martel et al. (1996). PAMSSEM belongs to the outranking approach and encompasses two phases: the aggregation and the exploitation. This MCAP is based on ELECRE III [Roy, 1978] for the construction of the outranking relation, on PROMETHEE I and II [Brans et al. 1984] for the exploitation of these relations, and on NAIADE [Munda, 1995] for the manipulation of fuzzy evaluations. The purpose of PAMSSEM is to construct an outranking relation, and provide further exploitation to recommend a “good” alternative. The construction of an outranking relation is based on a formal modeling of the DM’s preferences according to each criterion: the local preferences modeling phase.

Like ELECTRE III, PAMSSEM uses discrimination thresholds (indifference and strict preference) with different criteria. PAMSSEM’s inter-criteria information is of two types: explicit set of coefficients representing the relative importance of the criteria, and veto thresholds ($v_j$) for some criteria where it is appropriate. The veto threshold represents a limit of tolerance that the DM is willing to accept for any compensation. In other words, if the performance of $a_k$ is higher than the performance of $a_i$ according to the criterion $j$ by at least $v_j$, the DM may refuse to choose a CoA $a_i$ over $a_k$. For example, to intercept a drug smuggler, the Commander may have to consider two CoAs: $a_i$ and $a_k$. The CoA $a_i$ involves largely more losses of lives than $a_k$. A veto threshold on the criterion risk of losses of lives will prevent $a_i$ to globally outrank $a_k$, even if $a_i$ is at least as good as (even better than) $a_k$ on the other criteria. The veto threshold may vary with the position of the evaluation on the measurement scale associated to the criterion $j$ ($v_j(e_{ij})$).

PAMSSEM I and II allow to deal with different natures and different types of data. In fact, the evaluations can be crisp quantities, discrete/continuous random variables (with mass functions or density probability functions $f_j(x_{ij})$), linguistic or fuzzy numbers (which are associated with membership functions $\mu_j(x_{ij})$). PAMSSEM also deals with missing evaluations that could be the result of lack of knowledge, forgetfulness or inappropriateness.

4.1 Treatment of distributional evaluations

PAMSSEM is able to deal with an evaluation $e_{ij}$, which is a distribution representing a random variable (or statistical variable) $X_{ij}$ with a probability density or mass function $f_{ij}(x_{ij})$. A crisp evaluation can be seen as a degeneration of a distribution; the distribution is reduced to only one point ($P(X_{ij} = e_{ij})=1$). In case of fuzzy evaluations (e.g. linguistic evaluation) represented by a membership function, a “rescaling the ordinates of a membership function” is adapted from NAIADE [Munda, 1995]. One could defines a function $f_{ij}(x_{ij}) = K_{ij}\cdot\mu_{ij}(x_{ij})$, in such way to obtain a “probability density function” verifying the following condition:
\[ \int_{-\infty}^{\infty} f_{ij}(x_{ij}) \, dx_{ij} = 1 \]  

(7.)

4.2 PAMSSEM aggregation phase

The aggregation phase of PAMSSEM begins by computing a concordance index \( C(a_i,a_k) \) for each pair of CoAs \((a_i,a_k) \in A \times A\). This index is obtained as follows:

\[ C(a_i,a_k) = \sum_{j=1}^{n} \pi_j \cdot \delta_j(a_i,a_k) = \sum_{j=1}^{n} \pi_j \cdot \delta_j(e_{ij},e_{ik}) \]  

(8.)

Where \( \pi_j \) is a normalized scalar representing the relative importance of the \( j^{th} \) criterion; \( \sum_{j=1}^{n} \pi_j = 1 \). \( \delta_j(a_i,a_k) \) is a local outranking index computed for each pair of CoAs according to each criterion as follows:

\[ \delta_j(a_i,a_k) = \sum_{x_{ij}} \left( \sum_{x_{kj}} \delta_j(x_{ij},x_{kj}) \cdot f_{ij}(x_{ij}) \right) \cdot f_{kj}(x_{kj}) \]  

(9.)

\( f_{ij}(x_{ij}) \) and \( f_{kj}(x_{kj}) \) are respectively the probability distribution functions (discrete) of \( x_{ij} \) and \( x_{kj} \). In case of crisp evaluation, we obtain \( P(X_{ij} = x_{ij}) = f_{ij}(x_{ij}) = 1 \). \( \delta_j(x_{ij},x_{kj}) \) is an index computed according to the following formula:

\[ \delta_j(x_{ij},x_{kj}) = \begin{cases} 
1 & \text{if } -q_j \leq \Delta_j \\
\Delta_j - p_j & \text{if } -p_j < \Delta_j < -q_j \\
p_j - q_j & \text{if } \Delta_j \leq -p_j 
\end{cases} \]  

(10.)

Where \( \Delta_j = x_{ij} - x_{kj} = e_{ij} - e_{kj} \), and \( 0 \leq q_j \leq p_j \leq E_j \); \( E_j \) is the maximum range of the measurement scale of the \( j^{th} \) criterion; \( q_j = q_j(x_{ij}) \) and \( p_j = p_j(x_{kj}) \). The crisp evaluations can be handled by considering \( f_j(x_{ij}) = 1 \) if \( x_{ij} = e_{ij} \) and 0 otherwise. From the purist point-of-view, it is required to consider an ordinal criterion as a true-criterion. In this case, we will have \( q_j = p_j = 0 \). For sake of processing uniformity for the cardinal and ordinal evaluations, we suggest a slight modification in the computation of the concordance index for the ordinal criteria (when the number of levels of the ordinal scale >3) as follows:

\[ \delta_j(x_{ij},x_{kj}) = \begin{cases} 
1 & \text{if } 0 \leq \Delta_j \\
\frac{1}{2} & \text{if } -1 \leq \Delta_j < 0 \\
0 & \text{if } \Delta_j < -1 
\end{cases} \]  

(11.)
Where $\Delta_j$ is the inter-level gap.

The aggregation phase also involves the computation of another index: a **local discordance index**. This index is computed for each criterion and for each pair of CoAs $(a_i, a_k) \in \mathcal{A} \times \mathcal{A}$. The local discordance index $D_j(a_i, a_k)$ states the opposition of the criterion $j$ to the assertion that $a_i$ outranks $a_k$. This index is computed according to the following formula:

$$D_j(e_{ij}, e_{kj}) = \sum_{x_j} \left( \sum_{x_i} D_j(x_{ij}, x_{kj}) \cdot f_{kj}(x_{kj}) \right) \cdot f_{ij}(x_{ij})$$  \hspace{1cm} (12.)

Where $D_j(a_j, a_k) = D_j(e_{ij}, e_{kj})$; and

$$D_j(x_{ij}, x_{kj}) = \begin{cases} 0 & \text{if } -p_j \leq \Delta_j \\ \frac{(\Delta_j + p_j)}{v_j - p_j} & \text{if } -v_j \leq \Delta_j < -p_j \\ 1 & \text{if } \Delta_j \leq -v_j \end{cases}$$ \hspace{1cm} (13.)

$v_j = v_j(x_{ij})$ is the veto threshold; $v_j > p_j$. Note that the value of this threshold is influenced by the importance of the $j^{th}$ criterion. Here again, from the purist point-of-view, it is difficult to compute discordance indexes or define a veto threshold in the case of ordinal criteria (true-criteria). However, if we want to process uniformly the ordinal and cardinal evaluations, we suggest computing local discordance index for the ordinal criterion as follows:

$$D_j(x_{ij}, x_{kj}) = \begin{cases} 0 & \text{if } -\frac{j+1}{2} \leq \Delta_j \\ \min \left[ 1, -\xi(\pi_j) \cdot \left( \Delta_j + \frac{j+1}{2} \right) \right] & \text{if } \Delta_j < -\left( \frac{j+1}{2} \right) \end{cases}$$ \hspace{1cm} (14.)

where $j$ is the number of levels of the measurement scale associated with the $j^{th}$ ordinal criterion; $j > 3$. $\xi(\pi_j)$ is a non-decreasing function of the relative importance of the $j^{th}$ criterion. This function could be for instance linear, or exponential; $\xi(\pi_j) = 0.2 \left(1 + \pi_j/2\right)$, or $\xi(\pi_j) = 0.2 \left(2 + e^{\pi_j/2}\right)$, …

Then, PAMSSEM aggregates the concordance and the local discordance indexes to establish an **outranking degree** $\sigma(a_i, a_k)$ for each pair of CoAs $(a_i, a_k) \in \mathcal{A} \times \mathcal{A}$. As suggested by Rousseau and Martel [Rousseau and Martel 1994], these degrees can be obtained as follows:

$$\sigma(a_i, a_k) = C(a_i, a_k) \cdot \prod_{j=1}^{n} \left[ 1 - D_j^3(a_i, a_k) \right] \Rightarrow 0 \leq \sigma(a_i, a_k) \leq 1$$ \hspace{1cm} (15.)

$\sigma(a_i, a_k)$ represents the “consistency” level of the conclusion that “the CoA $a_i$ globally outranks $a_k$”, taking into account all the evaluation criteria. For example, if $\sigma(a_i, a_k) = 1$, then the conclusion “$a_i$ outranks $a_k$” is very well established. The valued outranking relations obtained can be represented in an **outranking matrix** (see table 3). The aggregation phase of PAMSSEM
authorizes the possibility to get incomparability; it is possible that at the same time $a_i$ outranks $a_k$, and $a_k$ outranks $a_i$. This result is mainly due to the introduction the discrimination and veto thresholds.

Table 3: Outranking matrix

<table>
<thead>
<tr>
<th></th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>...</th>
<th>$a_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>-</td>
<td>$\sigma(a_1, a_2)$</td>
<td>...</td>
<td>$\sigma(a_1, a_m)$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$\sigma(a_2, a_1)$</td>
<td>-</td>
<td>...</td>
<td>$\sigma(a_2, a_m)$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$a_m$</td>
<td>$\sigma(a_m, a_1)$</td>
<td>$\sigma(a_m, a_2)$</td>
<td>...</td>
<td>-</td>
</tr>
</tbody>
</table>

4.3 PAMSSEM exploitation phase

The exploitation of the outranking relations consists of making a synthesis of this outranking matrix to provide a recommendation. In CASAP, this recommendation will consist of ranking the CoAs. This exploitation may be obtained by introducing the concept of entering and leaving flows of PROMETHEE. For each CoA $a_i$, we compute its leaving flow $\sigma^+(a_i)$ and its entering flow $\sigma^-(a_i)$ as follows:

$$\sigma^+(a_i) = \sum_{a_k \neq a_i} \sigma(a_i, a_k) \quad (16.)$$  

$$\sigma^-(a_i) = \sum_{a_k \neq a_i} \sigma(a_k, a_i) \quad (17.)$$

The leaving flow represents the overall relative strengths of the CoA $a_i$, and the entering flow represents its overall relative weaknesses. Note that the values of these flows can change if a CoA is introduced or removed to/from the set $A$. On the basis of these two flows, PAMSSEM I computes a partial preorder by the following procedure:

- Rank the CoAs of $A$ according to a decreasing order of $\sigma^+(a_i)$: this ranking constitutes a first complete preorder $P^+$ of the CoAs;
- Rank the CoAs of $A$ according to an increasing order of $\sigma^-(a_i)$: this ranking constitutes a second complete preorder $P^-$ of the CoAs;
- A partial preorder $P$ is obtained by the intersection of these two complete preorders: $P = P^+ \cap P^-$. PAMSSEM I’s ranking includes incomparability. PAMSSEM II overcomes this incomparability by deriving (forcing) a total preorder. This preorder is the result of computing for each CoA $a_i$ a net flow $\Phi(a_i) = \sigma^+(a_i) - \sigma^-(a_i)$, and then ranking the CoAs according to a decreasing order of this flow.
4.4 Missing evaluations

In addition of mixed evaluations, PAMSSEM I and II allow to consider missing evaluations. We might have to deal with two types of missing evaluations: \( i \) non-relevant evaluation, or \( ii \) relevant evaluation but impossible to obtain. In the first case, we try to make sure that the “holes” in the performance table \( E \) do not favor or disfavor the concerned CoAs. If an evaluation \( e_{ij} \) is missing, then we consider that

\[
\Delta_j(a_i, a_k) = \Delta_j(a_k, a_i) = 0, \quad \forall a_k \in A
\]  

(18.)

This implies:

\[
\begin{aligned}
\delta_j(a_i, a_k) &= \delta_j(a_k, a_i) = 1 \\
D_j(a_i, a_k) &= D_j(a_k, a_i) = 0, \quad \forall a_k \in A
\end{aligned}
\]  

(19.)

In fact, expression (19) means that we replace, each time, missing evaluation \( e_{ij} \) by the one of the CoA \( a_k \) \((e_{kj})\) to which it is compared. In the second case (relevant missing evaluations), instead of replacing the missing evaluation by the mean-value of the other CoAs evaluations according to this criteria as it is regularly done in statistics, we replace it by a distribution of evaluations retrieved from the other (none missing) ones. If a relevant evaluation \( e_{ij} \) is missing, we replace it by the set \( \{e_{ij}, e_{2j}, ..., e_{kj}, ..., e_{mj}\} \) for all the CoAs \( a_k \in A \setminus \{a_i\} \); i.e. the evaluation of \( a_i \) will be modeled by a statistic variable \( X_{ij} \) with all the values of \( e_{kj}, a_k \in A \setminus \{a_i\} \) and a mass function \( f(x_{ij}) = 1/(m-1) \) \((m \text{ is the number of CoAs in } A)\).

5.0 RELATIVE IMPORTANCE COEFFICIENTS STABILITY ANALYSIS FOR PAMSSEM II

The relative importance coefficients of the criteria play a major role in the outcome of the evaluation and aggregation process. These coefficients are in reality an estimate of the relative importance \( \pi_j \) that the DM (Commander) gives to each criterion in order to balance his decision. CASAP includes a graphical and comprehensive procedure to set these relative importance coefficients, which is not discussed in this document (inspired from the method proposed by [Roy and Figueira, 1998]). However, we cannot eliminate completely the imprecision and vagueness of human judgements. In these circumstances, it is helpful to determine to what extent the solution (ranking) obtained is sensitive to the relative importance coefficient variations. Then, we introduce the stability analysis for PAMSSEM II. This analysis leads to determine stability intervals for the relative importance coefficient of each criterion \( \pi_j \). These intervals represents the limits of variations for each \( \pi_j \) without any reversal order. This analysis can help the Commander of the AOC identifying the sensitive factors that can affect the outcomes of the decision analysis process.

Recall that PAMSSEM II leads to a total preorder. The rank of each CoAs \( a_i \) is determined by computing a net flow \( \Phi(a_i) \) for each CoA. The expression of \( \sigma(a_i, a_k) \) is given by the equation...
(15). We can show that for quantitative criteria \( X_{ik} = \prod_{j=1}^{n} \left(1 - D_j(a_i, a_k)\right) \) is independent of \( \pi_j \). For qualitative criteria, we can suppose, without any loss of generality, that \( D_j(a_i, a_k) \) is a constant function of \( \pi_j \). Hence, we can rewrite the expression of \( \sigma(a_i, a_k) \) as follow:

\[
\sigma(a_i, a_k) = C(a_i, a_k) \cdot X_{ik} \Rightarrow \Phi(a_i) = \sum_{k=1}^{m} \sum_{j=1}^{n} \left[ \pi_j (\delta_j(a_i, a_k) \cdot X_{ik} - \delta_j(a_k, a_k) \cdot X_{kj}) \right]
\]

(20.)

Let \( Q_{ik}^j = \delta_j(a_i, a_k) \cdot X_{ik} \), and \( Q_{ii}^j = 0 \) \( \forall i, j \). Then

\[
\Phi(a_i) = \sum_{j=1}^{n} \left[ \pi_j \cdot \sum_{k=1}^{m} \left(Q_{ik}^j - Q_{ki}^j\right) \right], \quad \forall i \in \{1, 2, ..., m\}
\]

(21.)

If \( \Phi(a_i) \geq \Phi(a_k) \), then \( r_i \leq r_k \); where \( r_i \) and \( r_k \) are respectively the ranks of \( a_i \) and \( a_k \). The objective of the sensitivity analysis is to determine \( \pi'_j \) for each selected criterion in a way to respect the following condition:

If \( \Phi(a_i) \geq \Phi(a_k) \) \( \Leftrightarrow \Phi'(a_i) \geq \Phi'(a_k) \) \( \tag{22.} \)

Where \( \Phi'(a_i) \) is the net flow computed using \( \pi'_j \). Let \( \pi'_j = \pi_j + d'_j - d'_j \), where \( d'_j \) and \( d'_j \) are respectively positive and negative deviations of \( \pi_j \) (this decomposition is originally suggested in [Wolters and Mareschal, 1995]). The new net flow can be computed as follow:

\[
\Phi'(a_i) = \Phi(a_i) + \sum_{j=1}^{n} \left( d'_j - d'_j \right) \cdot \sum_{k=1}^{m} \left(Q_{ik}^j - Q_{ki}^j\right), \quad \forall i \in \{1, 2, ..., m\}
\]

(23.)

This transformation reduces the problem of finding the intervals of variations of the relative importance coefficients to the problem of maximum deviations. This problem is in reality an optimization problem where the objective function can be written as follows:

\[
Max \sum_{j=1}^{n} \left(d'_j + d'_j\right)
\]

(24.)

The first constraints should represent the condition (22). In order to reduce the number of constraints and reduce the computation burden, we suggest ordering the set of CoAs according to their rank obtained by PAMSSEM II. Let \( (A) \) be an ordered set of CoAs, then we have

\[
a_{(i)} \in (A) \Rightarrow \Phi(a_{(i)}) \geq \Phi(a_{(i+1)}), \quad \forall i \in \{1, 2, ..., m - 1\}
\]

(25.)

By ordering the set of CoAs, the condition (22) will be expressed by only \( m-1 \) constraints. These first constraints can be formulated as follows:
\[
\sum_{j=1}^{n} \left( d_j^+ - d_j^- \right) + \sum_{(k)=1}^{m} \left( H^j_{(i)(k)} - H^j_{(i+1)(k)} \right) \geq \Phi \left( a_{(i+1)} \right) - \Phi \left( a_{(i)} \right), \quad \text{for } i = 1, 2, ..., m - 1
\] (26.)

Where \( H^j_{(i)(k)} = Q^j_{(i)(k)} - Q^j_{(k)(i)} \). Each \( \pi_j \) should be between 0 and 1, then we have these constraints:

\[
\begin{align*}
&d_j^+ - d_j^- \leq 1 - \pi_j, \quad \text{for } j = 1, 2, ..., n \\
&d_j^- - d_j^+ \leq \pi_j
\end{align*}
\] (27.)

To impose maximum deviations, we add the following constraints to the mathematical program:

\[
\begin{align*}
&\pi_j + d_j^+ \leq 1 \\
&\pi_j - d_j^- \geq 0
\end{align*}
\] (28.)

The sum of the \( \pi_j \) should be 1. This constraint is given by the following expression:

\[
\sum_{j=1}^{n} \left( d_j^+ - d_j^- \right) = 0
\] (29.)

Finally, we add the following constraints to impose that any increase or decrease of \( \pi_j \) should respect the limits authorized on the other criteria:

\[
\begin{align*}
&d_j^+ - \sum_{k=1; k \neq j}^{n} d_k^- \leq 0 \\
&d_j^- - \sum_{k=1; k \neq j}^{n} d_k^+ \leq 0
\end{align*}
\] (30.)

The mathematical program obtained is a linear program easy to solve using any solver based on the simplex method. The number of constraints of this program is limited at most to \((m+6n)\) with only \(2n\) variables. It is also possible to make local sensitivity analysis by considering only sub-set of the criteria. For example, it is possible to perform local analysis only by considering the risk factor’s criteria. In order to implement such functionality, we add the following constraints to the mathematical program for each unselected criterion \( j \):

\[
\begin{align*}
&d_j^+ = 0 \\
&d_j^- = 0
\end{align*}
\] (31.)

6.0 CASAP PROTOTYPE

The prototype CASAP was developed to deal with events of counter-drug operations. CASAP helps the AOC team to describe and share information about such an incident, to develop pertinent CoAs, to evaluate these CoAs and to determine which is most appropriate. This
knowledge based DSS is based on a distributed architecture implemented with JAVA applets and servlets and can be accessed through an Intranet browser (see figure 2).

The functional architecture of CASAP comprises six modules (figure 3). One allows a user to describe a counter-drug event and to share this information with other users. It includes a retrieval facility to search out similar past events and manage the event’s database. A second module assists in the generation and description of CoAs that might be executed to respond to the described event. This module includes the ability to retrieve and duplicate CoAs from past or archived events. Once a satisfactory set of candidate CoAs is generated, CASAP notifies the Commander. Then the selection process begins. To help in this process, a third module evaluates each CoA according to each selected criterion. These criteria are selected and weighted using the fourth module. A screening procedure (using a conjunctive method) is implemented to insure the quality of the CoAs presented to the Commander.
The fifth module makes use of the multicriterion decision aid method and analysis tools that were previously described to help the DM selecting the “best” CoA. Moreover, the Commander can communicate with anyone logged on the CASAP system, either to announce the selection of a specific CoA or to request additional candidate CoAs. After the execution of a particular CoA, a post-analysis module (6) can be used to summarize and manage lessons learned. Although the present system was developed to deal specifically with counter-drug scenarios, this module allows it to be extended easily to other situations, by suitable adjustments to criteria and other parameters. To help the DM in the selection process, CASAP uses many friendly-user interfaces. For example, the ranking of CoAs is presented using a graphic and different result charts (figure 4).
Since, the evaluations of the CoAs according to the different criteria might include uncertainty, ambiguity, fuzziness, and subjectivity, we developed several analysis tools to help the DM minimizing the risk component introduced in the evaluation process. It was then possible to implement the relative importance coefficient stability intervals (see section 5 and figure 5), and two types of “what if analysis”: i) “what if analysis” on the CoAs, which evaluations consists of answers to the following question: “What could happen to the actual result if one or more evaluations of one or many CoAs change?”, and “what if analysis” on the DM’s preferences thresholds. In figure 5, the blue chart represents stability variation limits of the criteria weights for which the ranking will be almost unaffected (no rank reversal).
7.0 CONCLUSION

This paper describes the work done related to the development and the implementation of a distributed and asynchronous DSS for the C2 in a context of airspace violation (counter-drug operations). CASAP was developed based on MCDA methodology for knowledge engineering and criteria formulation. In order to evaluate and prioritize the different CoAs, a MCAP, called PAMSSEM, was implemented. This MCAP is based on the outranking approach, and is able to deal with mixed and missing evaluations. PAMSSEM uses discriminating thresholds with different criteria to model the DM’s preferences. The inter-criteria information is of two types: relative importance coefficient to balance the criteria, as well as veto thresholds for some criteria.

To better assist the DM analyzing the alternatives, analysis facilities have been developed and included to CASAP. These facilities are related to: i) relative importance coefficient stability analysis method that has been proposed for PAMSSEM, ii) “what if analysis” method to analyse the possible effects of the evaluations modifications, iii) “what if analysis” method to deal with the effects of the thresholds. This analysis allows the DM to see the possible effects of different thresholds over the ranking.
This work allowed to better defining the types of decision-aid that could be provided to AOC staff. There is still a lot of validation to be accomplished before being able to qualify or quantify the advantages of such tool. The criteria and their settings have to be validated to be sure that they represent a coherent family of criteria for the DM. The analysis approaches developed have to be fully validated with users to get of precise idea of the understanding that the DM will give to the analysis results. These validations will allow completing the prototype, which will be used to demonstrate the potentials and the effectiveness of such tools in an operational environment. In further publications, we will present in depth the functional architecture of CASAP as well as the implementation developments.

ACKNOWLEDGEMENTS

The authors would like to thank Mr K. Jabeur for the implementation of PAMSSEM’s calculation module, Mr K. El-hage and Mr C. Gauthier (Neosapiens inc.) for the implementation of CASAP modules, as well as Ms S. Leclerc for the implementation of some basic user interface.

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