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GENERATION AND SELECTION OF EFFICIENT PATHS IN A MULTIPLE CRITERIA GRAPH: THE CASE OF DAILY PLANNING THE SHOTS TAKEN BY A SATELLITE WITH AN INTERACTIVE PROCEDURE

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Génération et sélection de chemins efficaces dans un graphe multicritère : le cas de la planification quotidienne des prises de vue effectuées par un satellite avec une procédure interactive

Résumé

Nous considérons un satellite défilant autour de la Terre afin de réaliser des prises de vue permettant de satisfaire des demandes d'images de divers clients. Gérer quotidiennement l'activité d'un tel satellite consiste à définir des séquences de prises de vue réalisables et satisfaisantes. Ce problème présente des difficultés combinatoire et multicritère. En effet, le nombre de séquences de prises de vue réalisables croît de façon exponentielle avec le nombre d'images demandées, et l'évaluation d'une séquence de prises de vue se base sur plusieurs critères conflictuels. Nous proposons de formuler ce problème comme celui de la sélection d'un chemin multicritère dans un graphe sans circuit. Notre approche pour résoudre ce problème présente deux phases : génération des chemins efficaces et sélection d'un chemin satisfaisant en utilisant une procédure multicritère interactive.

Mots-clés : planification de missions spatiales, chemin multicritère, procédure multicritère interactive.

Generation and selection of efficient paths in a multiple criteria graph: the case of daily planning the shots taken by a satellite with an interactive procedure

Abstract

We consider a satellite following orbits around the Earth in order to take shots corresponding to images requested by various customers. Daily operating such a satellite consists of defining a feasible and satisfactory sequence of shots. This problem involves both combinatorial and multiple criteria difficulties. Indeed, the number of feasible sequences of shots grows exponentially with the number of images asked for, and the evaluation of a sequence of shots is based on several conflicting criteria. We propose to formulate this problem as the selection of a multiple criteria path in a graph without circuit. Our approach for solving this problem involves two stages: generation of efficient paths and selection of a satisfactory path using a multiple criteria interactive procedure.

Keywords : satellite mission planning, multiple criteria path, multiple criteria interactive procedure.

Introduction

The mission planning of an Earth observing satellite in order to satisfy a set of image requests involves several decision problems. One of these, called the daily planning problem, consists of selecting a feasible and satisfying daily mission plan (that is a shot sequence taken by the satellite). Since all the images requested cannot usually be satisfied, the daily planning problem does not reduce to a classical scheduling problem where all the tasks must be scheduled. Indeed, the daily planning problem involves both the selection of tasks (shots) to be performed and the sequencing of these tasks. The quality of the resulting shot sequences must be appreciated taking into account several viewpoints related to the satisfaction of image requests and the resources use.

In this context, we propose to resort to a multiple criteria approach for supporting the planner in the selection of a satisfying feasible shot sequence. This approach involves two stages:

- Generation of candidate shot sequences: in order not to exclude any sequence of possible interest, we propose a technique for generating all efficient (or Pareto optimal) sequences.
- Selection of a satisfying shot sequence: considering the large number of candidate sequences and the variability of the decision context, we propose to resort to a multiple criteria interactive procedure.

In the proposed model involving the definition of a multiple criteria graph without circuit, the determination of the efficient shot sequences amounts to the enumeration of all the efficient paths. We use an extension of a classical label-setting algorithm in order to solve this problem. Some numerical experiments are presented for real size instances. It appears that the execution time and the cardinality of the efficient set are both satisfying and allow the subsequent use of an interactive procedure. Moreover, some additional results lead us to underline some characteristics of the interactive procedure to be used.

This paper is organized as follows. In section 1, we present the decision context, that is to say the mission of an Earth observing satellite and the main features of the daily planning problem. The proposed approach for solving this problem is sketched in section 2 and compared with other approaches presented in the literature. The model describing the daily planning problem as a multiple criteria graph problem is introduced in section 3. The algorithm for enumerating the efficient paths is presented in section 4 with numerical experiments. The specific features of the interactive multiple criteria procedure to be used are developed in section 5. Some conclusions are finally provided.

1. The decision context: mission planning of an Earth observing satellite

1.1 The mission of an Earth observing satellite

We consider an Earth observing satellite which turns around the Earth from pole to pole at constant speed. Each orbit of this satellite allows to photograph different Earth landbelts. Moreover, it is equipped with one camera with visible optical that photographs Earth landbelts in the daylight when there is no cloud cover. Consequently, a sequence of orbits is an alternation of day half-orbits during which the camera can be used and night half-orbits during which the camera is unused. The camera can move its shot axis laterally. Consequently a same landbelt can be photographed from different orbits. However, owing to the distance between

two consecutive day half-orbits, any landbelt (except those located around the poles) can be photographed from at most one orbit during a same day (see fig. 1).

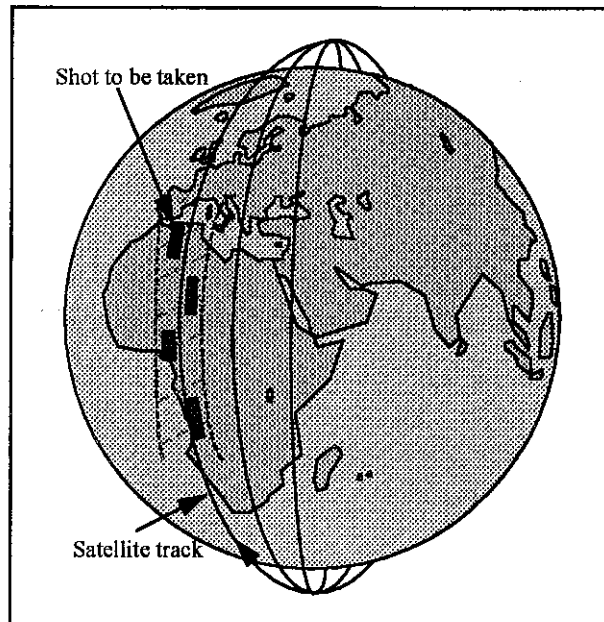


fig. 1: The satellite operation.

These satellite characteristics correspond e.g. to those of the SPOT satellites: such satellites describe around 15 orbits during one day, they photograph Earth landbelts, which are about 60 km wide and between 70 and 700 km long, in a "corridor" around 900 km wide (centered on the satellite track).

Such a satellite is designed to satisfy image requests from various customers. These requests induce a set of shots to be taken. A same shot may concern more than one request. Generally all the shots cannot be taken. Therefore planning the mission of a satellite amounts to selecting the shots to be taken (what), how and when.

In the mission planning of Earth observing satellites, we focus on the daily planning problem, i.e., the selection of a daily shot sequence. Even if this is the main operational stage, it is interesting to include this short term planning in a broader perspective and to prepare this stage by a long-term planning (see Gabrel, 1994).

1.2 The daily planning stage: a combinatorial and multicriteria problem

The selection of a feasible sequence of shots involves combinatorial difficulties since the number of sequences grows exponentially with the number of shots. However this combinatorial explosion is limited by constraints due to the viewing capacities of the satellite. We can distinguish the following constraints:

1. at most one shot can be taken at a time (there is only one camera),
2. any shot can be taken at most once (within a day, a same landbelt can be seen only once),
3. any shot can be taken at a unique moment (a landbelt can be seen only when the satellite is exactly above it; this is not the case for satellites endowed with camera whose shot axis can move along the satellite track),
4. set-up times must be respected between two consecutive shots (these times depend on the motion of the shot axis).

Owing to the existence of night half-orbits during which the camera is switched off, shots from different day half-orbits do not interfere. In other words, the day half-orbits of a same day can be considered as independent.

Moreover, the evaluation of a sequence of shots must take into account several conflicting criteria. Indeed, the viewpoints to be considered are:

- the demand satisfaction,
- the priority (related to the strategic importance),
- the satellite use (the number of instruments on/off),
- the sharing of production capacities among the satellite users,
- the constitution of archives (for future demands).

Relative importance attached to these different viewpoints can vary according to production contexts. However it is widely acknowledged by experts that the first three viewpoints are much more important than the two other ones. Indeed a planner would not accept to reduce the quantity and quality of the production in order to obtain a "fair" sharing or to make up "good" archives.

2. The proposed approach

In the field of satellite mission planning, we can distinguish two categories of study: *sequencing-oriented* studies and *selection-oriented* studies. The purpose of sequencing-oriented studies (see, e.g., Gaspin, 1989 ; Hall and Magazine, 1994) is to determine a feasible sequence maximizing a single criterion. For example, Hall and Magazine (1994) propose and compare several heuristics to determine a feasible sequence that maximizes the sum of the tasks values in the sequence. In the context considered by these authors, each task to be performed is associated with a single value that measures its scientific, military, political or commercial importance; it permits to dismiss the multiple criteria aspects for the tasks selection. On the other hand, the purpose of selection-oriented studies is to select the tasks to be performed in order to obtain a feasible sequence. Several researchers are investigating knowledge-based approaches (see Biefield, 1986 ; Fuch and al., 1988 ; Tessier-Badie, 1988) for helping the planner to choose the tasks to be completed. Only Fabiani (1992) explicitly defines several criteria to evaluate the tasks and the sequences, but these criteria are finally aggregated through a weighted sum into a single measure. In this paper, we propose an approach which deals explicitly with sequencing and selection problems. Indeed it involves the determination of a large number of "interesting" shot sequences in order to permit the planner to choose one of them considering several criteria with a flexible procedure.

For selecting a feasible and satisfying sequence of shots to be completed during a day, the proposed approach involves the two following stages:

1. *generation of a set A of candidate sequences*: the candidate sequences we are considering must be **feasible, maximal and efficient**¹. Feasibility is related to the constraints expressed in section 1.3. Maximality is imposed since any sequence whose shots are strictly included in another sequence is considered as irrelevant. As to efficiency, it is obvious that any sequence which achieves better scores on all criteria than another one should be preferred.

¹ Given a set of criteria $(g_1, \dots, g_m)$ to be maximized, an alternative a is efficient in a set A of alternatives iff there is no alternative b in A such that $g_j(b) \geq g_j(a)$ for all $j = 1, \dots, m$ (with at least one strict inequality).

2. *selection of a satisfying sequence among A with a multiple criteria interactive procedure*: since the set A of candidate sequences is relatively large, it is quite appropriate to explore this set using a multiple criteria interactive procedure.

For validating our approach, a particular interest must be given to computational times since in real decision contexts the daily planning must be achieved quite quickly (around one hour).

In the next section, we propose a model allowing to generate the set A . Within this framework, the problem amounts to determining all the efficient paths in a multiple criteria graph.

3. The modelling: a multiple criteria path problem

3.1 The feasibility graph

Given a set of n shots to be taken from the p day half-orbits described by the satellite during a day, we define a directed graph $G = (X, U)$, called the *feasibility graph*. Since, the p half-orbits are independent, G is constructed from p subgraphs $G_i = (X_i, U_i)$. The set X_i represents all the shots that can be taken from the i^{th} day half-orbit and two fictitious vertices b_i and e_i that represent the beginning and the end of the i^{th} day half-orbit respectively. The set U_i is defined as follows:

- $\forall j \in X_i, (b_i, j) \in U_i, (j, e_i) \in U_i$
- $\forall (j, k) \in X_i \times X_i, (j, k) \in U_i$ iff the shot k can be taken after the shot j .

G_i is asymmetric and transitive (and therefore without circuit).

It is obvious that any path from b_i to e_i in G_i represents a feasible sequence of shots that can be completed from the i^{th} day half-orbit. As we are interested in maximal sequences of shots, all the transitivity arcs in G_i can be deleted.

From these graphs $G_i, i = 1, \dots, p$, we define the graph G as follows (see fig. 2):

$$X = \bigcup_{i=1}^p X_i \text{ and } U = \left(\bigcup_{i=1}^p U_i \right) \cup \{(e_i, b_{i+1}), i = 1, \dots, p-1\}$$

Notice that arcs (e_i, b_{i+1}) represent night half-orbits.

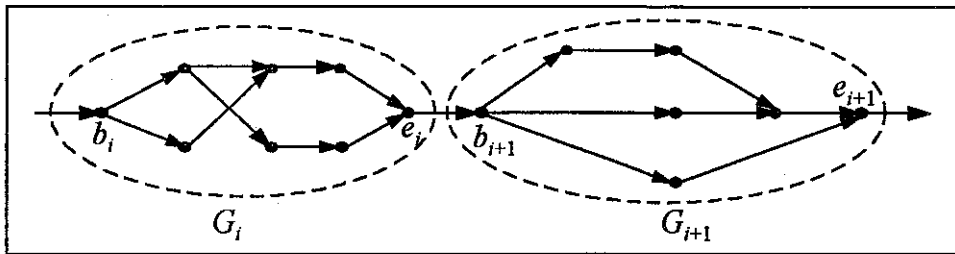


fig.2: The feasibility graph G .

Feasible and maximal sequences of shots are represented by paths from b_1 to e_p in G . Therefore, in order to determine the candidate sequences, we must consider among such paths those which are efficient with respect to relevant criteria.

3.2 Multiple criteria evaluation of paths in G

We have previously stated the viewpoints to be taken into account when evaluating a given candidate sequence (see section 1.2). As indicated in section 1.2, three main viewpoints must be considered giving rise to the three following criteria:

- g_1 , the *demand satisfaction*. A shot sequence, denoted by S , is evaluated on g_1 in the following way:

$$g_1(S) = \sum_{j \in S} v_1(j)$$

where $v_1(j)$ is the number of images that the shot j permits to satisfy, $v_1(j)$ may be equal to 1, 2 or 3. Obviously, this criterion must be maximized.

- g_2 , the *respect of priorities*. The evaluation of S on g_2 is related to the number of shots having priority in S , that is to say:

$$g_2(S) = \sum_{j \in S} v_2(j)$$

where $v_2(j)$ is the priority of the shot j , $v_2(j)$ may be equal to 0 or 1. As the first criterion, this one must also be maximized.

- g_3 , the *satellite use*. The evaluation of S on g_3 is related to the number of shots in S :

$$g_3(S) = |S|.$$

where $|S|$ denotes the cardinality of S . This criterion must be minimized in order to limit the satellite use.

The candidate sequences are the efficient sequences according to these three criteria. These criteria are partially conflicting. In the case of g_1 and g_3 , they may even appear contradictory. However, this opposition is significantly reduced in so far as we restricted the investigation to maximal sequences (see section 2).

On the feasibility graph G , we associate with each vertex j (representing the shot j) a vector of scores denoted by $v(j)$: $v(j) = (v_1(j), v_2(j), 1)$. Thus, the vector of scores of a path in G , which is computed in summing the vectors of the vertices that belong to this path, is the score of the sequence represented by this path on g_1, g_2, g_3 . So, **determining the feasible, maximal and efficient sequences of shots that can be completed during a day is determining the efficient paths from b_1 to e_p in the associated feasibility graph.**

In the following section, after presenting some main results about the determination of all the efficient paths in a multiple criteria graph without circuit, we present an exact algorithm to solve this problem and some numerical experiments. Our results show that all the efficient paths from b_1 to e_p in the feasibility graph can be determined in satisfying time for real size instances.

4. The determination of all the efficient paths in a multiple criteria graph without circuit: algorithm and numerical experiments

4.1 Complexity and algorithm

In terms of complexity, it is well-known that, even in a bicriteria graph, the number of efficient paths can grow exponentially with the number of vertices as shown in Hansen (1980). Consequently, the enumeration of all the efficient paths in a multiple criteria graph may not be tractable in polynomial time. However, the example considered in Hansen (1980) (in which all paths are efficient) makes use of exponential arc values. In practice, arc values are far from being exponential and the number of efficient paths may be relatively low.

Several algorithms have been proposed for determining all the efficient paths between two vertices in a multiple criteria graph. They often appear as direct modifications of classical shortest path algorithms (see Climaco and Martins, 1982 ; Corley and Moon, 1985 ; Hansen, 1980 ; Henig, 1985 ; Martins, 1984 ; Tung and Chew, 1992 ; Vincke, 1994) where the central test based on a 'min' operator is replaced by a dominance test (with more complex data structures to store all the efficient paths). This simple modification is valid since the basic principle of shortest path algorithms, which is Bellman's principle of optimality, is transposable for the multiple criteria path case. Indeed, in a directed multiple criteria graph, any subpath of an efficient path is an efficient subpath.

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 $P(j) \leftarrow \emptyset \quad (j = s, 1, \dots, t)$ 
 $P_i(j) \leftarrow \emptyset \quad (j = s, 1, \dots, t ; i = i_1, \dots, i_j) \quad \{i_1, \dots, i_j\} \text{ denotes the subset of all precedents of } j$ 
for  $j \leftarrow 1, \dots, t$ 
  for  $i \leftarrow i_1, \dots, i_j$ 
    for all  $p \in P(i)$ 
       $P_i(j) \leftarrow P_i(j) \cup \{g(p) + v(j)\} \quad v(j) \text{ is the criterion vector of vertex } j$ 
    end for
  end for
   $P(j) \leftarrow P_{i_1}(j)$ 
  for  $i \leftarrow i_2, \dots, i_j$ 
    for all  $p \in P_i(j)$ 
      for all  $p' \in P(j)$ 
        if  $p$  dominates  $p'$ 
           $P(j) \leftarrow P(j) \setminus \{p'\}$ 
        if  $p'$  dominates  $p$ 
           $P_i(j) \leftarrow P_i(j) \setminus \{p\}$ 
        end for
      end for
    end for
     $P(j) \leftarrow P(j) \cup P_i(j)$ 
  end for
end for
end for

```

fig. 3 : An algorithm for determining all efficient paths.

The algorithm we use is an adaptation of the label-setting shortest path algorithm used for graphs without circuit. Recall that in a graph without circuit, it is possible to number the vertices so that $i < j$ for every arc (i, j) (topological order). The basic idea of a label-setting

algorithm for such graphs is to set at each iteration a definitive label to vertices in the increasing number order (see, e.g., Ahuda and al., 1993]). In the feasibility graph G , this numbering is reached in a very natural way by labelling the vertices (shots) according to their starting times.

When we determine all the efficient paths between two vertices s and t in G (see fig. 3), the labelling of each vertex j , or equivalently the determination of all the efficient paths from s to j , is achieved in two stages. In the first stage, we define for all the precedent i of j in G the set $P_i(j)$ of paths constituted of efficient subpath from s to i plus the arc (i,j) . A path p in $P_i(j)$ is described by its criterion vector $g(p)$. We denote by $P(j)$ the union of all the sets $P_i(j)$. In the second stage, we delete from $P(j)$ all the dominated paths.

The label of the vertex t describes all the efficient paths from s to t in G .

4.2 Numerical experiments

Among the fifteen orbits (see section 1.1) described by the satellite during one day, the problem of selecting and sequencing the shots to be taken really only concerns a small number of half-orbits, around 4. This is due to the fact that the satellite is unused over the sea and that the image requests (around 2000) are often clustered round a small number of distinct areas. Consequently, the graph G is typically constituted of 4 sub-graphs G_i of large size.

In a first stage, we tested our algorithm for solving the problem of determining all the efficient paths from b_i to e_i on one subgraph G_i , or in other words for enumerating all the feasible, maximal and efficient sequences of shots that can be completed from the i^{th} orbit of a day. We randomly generated G_i in the following way:

- the vertices correspond to shots randomly located on a 10000 km long Earth area in which all points can be photographed from the i^{th} orbit, and the arcs are defined according to the computation for each pair of shots of the possibility to take one after another,
- the scores of the shots are randomly chosen.

The number of vertices varies between 50, 100, 200, ..., until 1000; for each case, we randomly generated 50 graphs. On these graphs, we determined both the set of efficient criterion vectors and the set of efficient paths. The average number of efficient vectors and the average CPU time are reported for graphs of same order (see fig. 4 and 5).

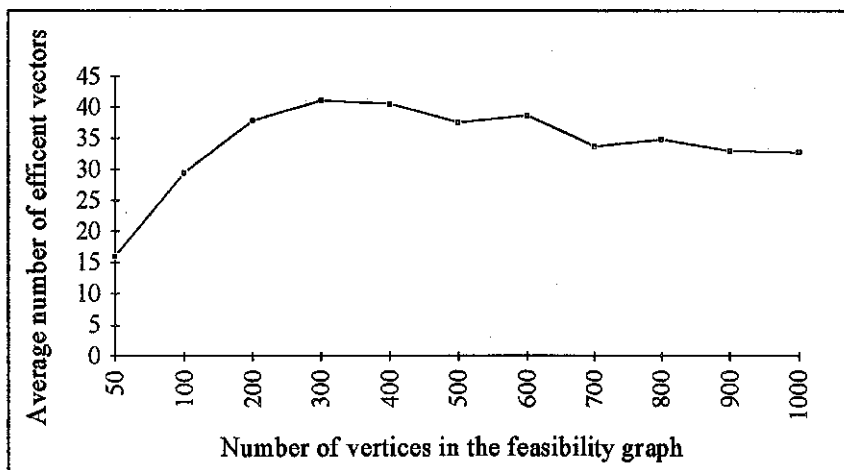


fig. 4: Average number of efficient vectors

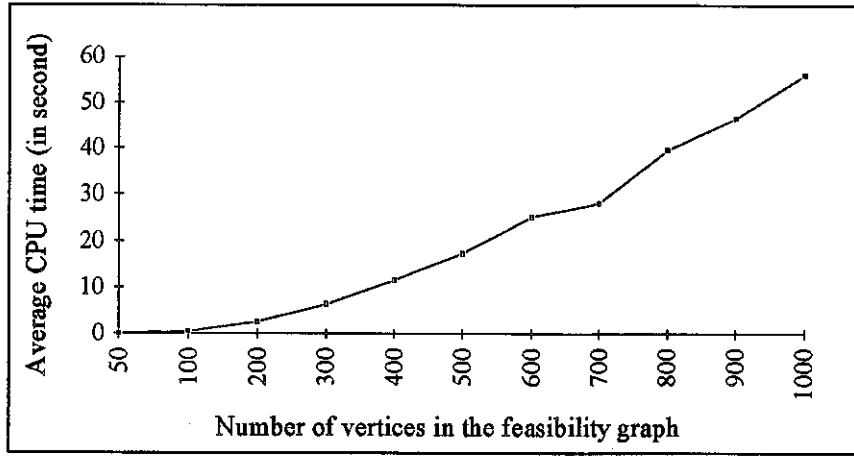


fig. 5: Average CPU time

The average number of efficient vectors varies from 15 to 40: this small number is due to the criterion scales which are quite limited. Consequently, computation times are satisfying since they never exceed 1 minute. However, these small numbers of efficient vectors correspond to larger numbers of efficient paths as we can see in the above table:

number of vertices	average number of efficient vectors	average number of efficient paths
50	16	74
100	29	441
200	38	1301
300	42	2049

We apply the algorithm for determining all the efficient vectors from b_1 to e_p in $G = (X, U)$. In order to construct one graph G , we randomly generated 4 different graphs $G_i = (X_i, U_i)$, each with 500 vertices, in order to get:

$$X = \bigcup_{i=1}^4 X_i \text{ and } U = \left(\bigcup_{i=1}^4 X_i \right) \cup \{(e_i, b_{i+1}) \mid (i = 1, 2, 3)\}.$$

We generated that way 20 different graphs G , and we obtained:

- an average number of efficient vectors of 258,
- an average CPU time of 13 minutes.

These results are very important because the capacity of completing in a satisfying time the efficient paths (or equivalently the feasible, maximal and efficient sequences of shots) and the weak number of them allow us to use a multiple criteria interactive procedure for choosing daily mission plans.

5. An interactive multiple criteria procedure for the daily mission planning of an Earth observing satellite

We have already mentioned that it is not possible in the decision context we are interested in to use the same decision rules for selecting each day a sequence of shots to be performed. This is why we propose to resort to a multiple criteria interactive procedure in order to support the construction of daily sequences. Thanks to this procedure, the decision maker (DM) may adapt her/his strategy to the production context.

The interactive procedure we used is an adaptation of the one presented by Vanderpooten (1990). In the following description (fig. 6), we use the following notations:

- A : set of alternatives (paths),
- J : set of criteria,
- Z_A : image of A in the criteria space.

In our context, the set to be explored consists of a list of efficient alternatives. The computation stage is quite easy since it only amounts to determining the minimal element of a list. Considering that typical lists contain about a few hundreds of solutions (see section 4), computation times are extremely fast (about one second). Notice also that since the set to be explored consists of efficient alternatives only, we used as a scalarizing function in the computation stage a simple Tchebychev-like function (and not an augmented Tchebychev-like function - see, e.g., Bowman Jr, 1976 ; Steuer, 1986 ; Wierzbicki, 1986). For this same reason, the determination of the ideal and nadir points in the initialization stage is quite easy; they are simply determined by computing the maximal and minimal values on each criterion.

(0) INITIALIZATION

Determine the ideal point z^* and the nadir point n

$$\bar{z} \leftarrow z^* ; \lambda \leftarrow \frac{1}{z^* - n} ; Z_A^h \leftarrow Z_A$$

(1) COMPUTATION STAGE

Determine the current proposal z^h

$$z^h \leftarrow \text{Arg}(\min_{z \in Z_A^h} s(\bar{z}, \lambda)) \text{ where } s(\bar{z}, \lambda) = \max_{j \in J} \{\lambda_j (\bar{z}_j - z_j)\}$$

(2) DIALOG STAGE

Present the criterion vector z^h and the corresponding efficient paths to the DM.

If z^h is satisfactory then STOP

else Propose the following dialog modes

(a) *Reaction on the criterion values:*

(a.1) Qualitative mode

Considering z^h , which criteria should be improved?

- let K denote the subset of corresponding criteria,

$$Z_A^h \leftarrow \{z \in Z_A : z_j \geq z_j^h \text{ } j \in K\}$$

- determine z^* the ideal point on Z_A^h

$$\bar{z} \leftarrow z^*$$

(a.2) Numerical mode

Define the desirable values on some or all criteria $v_j, j \in L$.

$$\bar{z}_j \leftarrow v_j \text{ } j \in L \quad \bar{z}_j \leftarrow z_j^* \text{ } j \in J \setminus L$$

(b) *Reaction on the corresponding paths*

Indicate some shots to be introduced or deleted in the sequence.

Redefine Z_A so as to satisfy these modifications.

Goto (1)

fig. 6: An interactive multiple criteria procedure.

The most important part of the procedure is the dialogue stage. As for any classical interactive multiple criteria procedure (see e.g. descriptions in Steuer, 1986 ; Vanderpooten and Vincke, 1989), the procedure includes a first level of interaction on the criterion values. We suggest here two basic dialogue modes. The first one is quite easy to use since it requires only to specify the criteria to be improved (no numerical information is required). However, if the DM

wishes to express more precise information, she/he is given the possibility to specify aspiration levels on some or all criteria. This second mode is particularly interesting when the DM wishes to control the exploration and, e.g., investigate quite different solutions.

A second level of interaction on the structure of the solutions is integrated. The existence of this level is due to the fact that additional aspects related to the structure of the solutions cannot be captured by the criteria. Moreover, a criterion vector usually corresponds to several sequences. It is then important to allow the user to express local requirements regarding specific shots from the sequence. Notice that such requirements can be integrated in the construction of the graph G (section 3) by imposing or suppressing some specific shots. Except when these requirements are really strong, we suggest not to impose a priori these constraints. Indeed, offering the user the possibility of including and removing constraints interactively allows the user to weigh up the impact of a given constraint (showing, e.g., that imposing a given shot prevents from undertaking other valuable shots or reduces the value of some criteria).

Conclusion

Daily planning an Earth observing satellite mission, i.e. determining a satisfying daily shot sequence, is a difficult problem which includes both combinatorial and multiple criteria aspects. We propose an original modelling of this problem as the selection of a satisfying efficient path in a multiple criteria graph. A two-stage approach for solving this problem is presented. The first stage involves the determination of all efficient paths in a multiple criteria graph without circuit. We developed and tested an algorithm based on a classical label-setting algorithm for shortest paths problems. The second stage is based on an original interactive multiple criteria procedure allowing to explore the set of candidate sequences in a quite flexible way.

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