DEVELOPMENT OF AN OPTIMIZATION MODEL FOR IMAGE COLLECTION PLANNING

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Abstract: Customer service requests for satellite-based image collection rapidly grow in Korea as the number of available satellites increases. The customer requests must meet their due dates under several complicating conditions, such as memory capacity limits, weather conditions, role tilts and segment conflict resolutions. In this paper, we address this problem by presenting a mixed-integer program model and propose an investigative solution approach that handles millions of segment conflict resolution constraints. The proposed approach would reduce the model size to improve its solvability by utilizing a new redundancy checking pre-processing technique.

1 INTRODUCTION

Since the first satellite was launched, satellite imagery service has been applied to various practical areas, including meteorology, agriculture, forestry, geology, regional planning and warfare.

In recent years, customer service requests for satellite-based image collection rapidly grow as the number of available satellites increases. Such ever-growing requests, which cause major complications in planning, bring several challenges to service providers who try to satisfy customer demands as much as possible. One of the challenges in a satellite image collection process is to build an image collection schedule so as to minimize the delays in the service requests while multiple parameters and constraints, such as memory capacity limits, weather conditions, role tilts, segment conflict resolutions and due dates, must be satisfied. Because of the complexity of the problem, it is essential to build a fully automated scheduling system, which utilizes optimization models and algorithms.

This paper is organized as follows. In section 2, related works are presented. In section 3, a brief description of the problem and parameters in the satellite image collection planning is provided. In sections 4 and 5, a mathematical formulation and a solution approach for it are presented, respectively. Concluding remarks along with future studies are provided in the last section.

2 RELATED WORKS

Over the years, the satellite image collection planning has been well-studied. Some of the studies in literatures, which are pertinent to this study, are as follows. Vasquez and Hao (2001) generalized satellite image collection planning as a variation of the knapsack model and proposed a tabu search algorithm. Bianchessi *et al* (2007) developed tabu search algorithm for a multiple satellite and multiple orbit problem. Gabrel and Vanderpooten (2002) formulated a model as a selection of multi criteria longest path in a directed acyclic graph. Wolfe and Sorensen (2000) presented a description on the earth observation system for NASA.

3 SATELLITE IMAGE COLLECTION PLANNING

The satellite image collection planning builds an optimal schedule to handle the customers' requests in an efficient manner. The schedule has to be designed by taking various scheduling parameters and assumptions into account. Because of a large number of parameters and constraints to consider, the construction of an optimal schedule for the satellite image collection planning becomes a complicated task. In addition, a general reference

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model is not available in literature for accommodating different situations.

3.1 Problem Description

The satellite image collection planning problem aims at maximizing daily collections. The collected images must meet each customer's requirements on picture quality. Figure 1 shows how the image collection planning system under consideration works.

All customers' requests are put in the order database, and the process handles them as an input data. After image collection planning process is done by checking all steps, the activated orders are passed to the collection assessment. The inactive orders will remain in the order database for a future use.

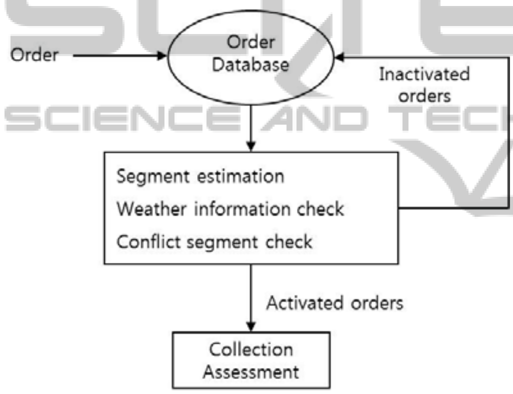

Figure 1: Image collection planning process.

All satellite image collection orders have specifications on order priorities, maximum cloud/ snow cover limits, due dates and roll tilts. All these order parameters are employed as an input to the automated scheduling system. The orders are assigned to the schedule while maintaining the memory consumption limit and the segment conflict resolutions. Currently, the process is carried out manually by human experts.

The detail information of the parameters and the memory consumption limit are provided in the next subsection.

3.2 Parameters

Six parameters are considered as major factors in the satellite image collection planning.

3.2.1 Memory Consumption Limit

The memory consumption limit is a constraint which enforces the overall memory usage between two consecutive download stations not to exceed satellite's memory size.

3.2.2 Segment

The segment is defined as a possible geographical section to collect images. The set of segments is determined prior to build a scheduled plan. A geometrically large order which is called Area of Interest (AOI) consists of many segments (Figure 2). In order to collect all images of an AOI, the image collection task may span several months to complete (Martin, 2002).

Figure 2: The Area Of Interest (AOI) (bold black box) consists of the segments (yellow box).

3.2.3 Priority

A higher priority request must be carried out prior to a lower one. The priority condition can be satisfied by sequentially optimizing problems from the highest priority to the lowest priority.

3.2.4 Weather Condition

Two kinds of weather conditions, cloud and snow cover, are considered. It is essential to consider maximum cloud and snow cover limit at the same time. Collected images with unacceptable cloud/ snow cover must be recollected (Martin, 2002).

3.2.5 Roll Tilt

High quality images are in general obtained when the camera is positioned at a low angle. Client's orders have acceptable intervals of angles so that only segments which satisfy the angle condition must be scheduled.

3.2.6 Due Date

Each request has to be finished before its deadline.

4 MATHEMATICAL FORMULATION

In a recent paper, Baek *et al* (2011) regarded the satellite mission scheduling problem as a knapsack problem. In this paper, we present a formulation in which the assignment and the knapsack constraints both are considered. Two assumptions are made to derive our formulation and a solution approach.

- All orders can be carried out in a given planning horizon. That is, the problem has at least one feasible solution

- Every inter-image-collection epoch has the same length

The epoch is defined as a time interval between two consecutive stations on earth for memory download.

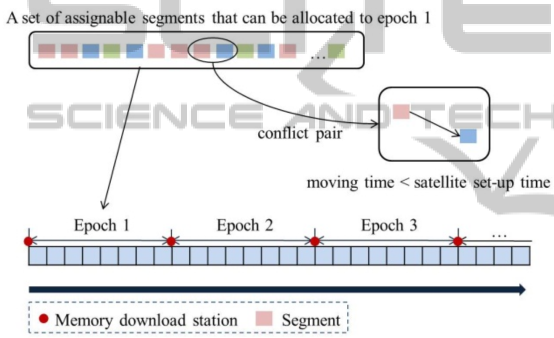

Figure 3: Graphical representation of model.

The following is the formulation for the satellite image collection planning problem.

$$\text{Mimimize} \quad \xi \tag{1}$$

subject to

$$\xi \geq t_j - d_j, \quad \forall j \in J \tag{2}$$

$$t_j \geq f_i x_{ik}, \quad \forall i \in I, \forall k \in K_j, \forall j \in J \tag{3}$$

$$\sum_{i \in I} x_{ik} = 1, \quad \forall k \in K \tag{4}$$

$$\sum_{k \in P_i} a_k x_{ik} \leq MR, \quad \forall i \in I \tag{5}$$

$$x_{ik} + x_{ik'} \leq 1, \quad \forall (k,k') \in C, \quad \forall i \in I \tag{6}$$

$$x_{ik} \in \{0,1\}, \quad \forall i \in I, \ \forall k \in K \tag{7}$$

$$t_j \geq 0, \quad \forall j \in J \tag{8}$$

Notations:

i : epoch index, $i \in I$

j: AOI index, $j \in J$

k: segment index, $k \in K$

MR: memory capacity

K_j: a set of segments for AOI $j \in J$, $K_j \subset K$

P_i: a set of segments that can be allocated to epoch $i \in I$

f_i : completion time of epoch $i \in I$

d_j: due date of AOI $j \in J$

a_k: amount of memory required for segment $k \in K$

t_j: completion time of image collection for AOI $j \in J$

C: a set of a pair of conflict segments, (k,k'), $k \in K, k' \in K$, $k < k'$

The objective of the model is to deliver collected images before the due dates. Constraints (1)-(3) assure the minimization of the maximum lateness of the orders. Constraint (4) ensures that the segments are assigned to one of the epochs. The memory consumption limit for each epoch is considered in (5). As the image collection requires a set-up time, conflicts can occur if the moving time between two consecutive segments is less than the set-up time. The conflicts are prevented by constraint (6).

The formulation above can be used to obtain optimal schedule. However, for practical scheduling problems, millions of segment conflict resolution constraints reduce the solvability of the problem. In section 5, we present an investigative solution approach to handle enormous number of constraints.

5 SOLUTION APPROACH

The mathematical model (1)-(8) has two types of constraint structures. First, constraints (4)-(5) can be transformed to an assignment structure by introducing slack variables. Second, constraints (5)-(6) have the knapsack structure. The auction algorithm and dynamic program are well-known solution approaches for the assignment problem and the knapsack problem, respectively. It is possible to develop a Lagrange-relaxation based algorithm by utilizing the two kinds of constraint structures and the corresponding algorithms.

Prior to an algorithm development phase, we explore applicability of a pre-processing procedure which reduces the number of constraint to improve the solvability of the problem. The mathematical model (1)-(8) contains a large number of knapsack constraints (5)-(6). Especially, the number of constraints (6) may exponentially explode depending on AOI structure.

Because the knapsack structure is dominant the model, the pre-processing procedure given by Choi and Choi (2011) can be employed. Their procedure identifies redundancy in multi-dimensional knapsack constraints. This approach utilizes the concept of constraint intercepts in Paulraj *et al* (2006) and extends it by using surrogate constraints. They construct feasibility problems in which constraint redundancy can be detected. Then, they suggest a $O(n^3)$ heuristic algorithm for solving the feasibility problems. To identify redundancy in constraints (6), we consider the following feasibility problem:

The (i, k, k') constraint of (6) is redundant if and only if feasibility problem (9) has any feasible solution

$$F^{(i,k,k')}\lambda \le 0,\ \lambda \ge 0,\ e^T\lambda > 0 \tag{9}$$

where

$$F_{pq}^{(i,k,k')} = \{0, 1, -M\}$$

$$\lambda^T := \begin{bmatrix}\lambda_1 & \cdots & \lambda_m\end{bmatrix}$$

$$e^T := \begin{bmatrix}1 & \cdots & 1\end{bmatrix}$$

$$M := BigM\ value$$

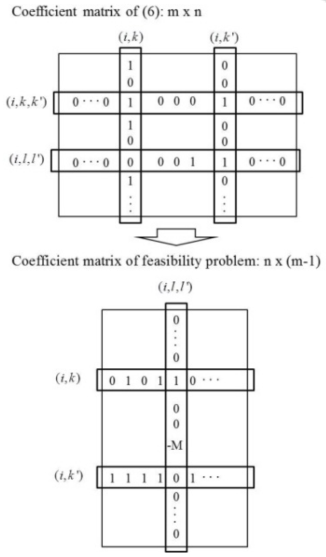

Figure 4: Matrix pattern of coefficient matrix of (6) and F.

The coefficient matrix F consists of components with 0, 1 and $-M$ values and the matrix pattern follows the 0-1 component pattern of A^T (A:= coefficient matrix of (6)). These structures can be utilized in developing an algorithm for solving the feasibility problem. Moreover, the above described redundancy checking procedure can be applied to constraint (5) in a similar fashion.

6 CONCLUSIONS

In this paper, we presented a mathematical model for the satellite image collection planning. The presented model deals with long term planning and reflects real-world constraints in practice. We also proposed an investigative solution approach that utilizes a new redundancy checking pre-processing technique. It remains to be seen through a further study on computational experiments whether the proposed approach results in a high-quality schedule for the satellite image collection.

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