Imperial Journal of Interdisciplinary Research (IJIR)
Vol-3, Issue-10, 2017
ISSN: 2454-1362, http://www.onlinejournal.in

Applications of Operations Research: Earth Observing Satellites

Sarthak Surya[1], Shivangi Gupta[2], Shivani Raipat[3]
Shivay Bansal[4] & Richa Saxena[5]
[1,2,3,4]Group No. 9
[5]Faculty, NMIMS University, India

Abstract : *By means of this paper, we have described the applications of Operations Research (OR) in planning and decision making in respect of satellites, precisely, Earth Observing Satellites (EOSs). The mission of an EOS is to acquire images of specified areas on the Earth surface, in response to observation requests from customers. We have also underlined the complexity of the planning problem for an agile (EOS). We have explained the Multi-objective mission planning problems of the new generation of agile EOS. Apart from this, the launch capacity analysis of satellites along with related decisions of selecting the launch centre, scheduling, and resource allocation has been included in the paper. These launch campaigns form a part of the launch process. Some OR tools that have been used are: simulations, greedy algorithm, Tabu search, and constraint programming among others. The expected outcomes from this paper are: the reader should understand the logical and systematic approach of making decisions related to profit maximization and also how to deal with multiple objective optimization problems. Though this paper does not provide a detailed analysis of all the operations in the launch process, but it gives a short overview of the essential ones for student's reference.*

Introduction to Operations Research

Operations Research (OR) is a discipline that enables one to make better and most optimal decisions in complex scenarios. In other words, it is an analytical method to solve a problem and make the best feasible decisions. This can be done using the OR tools and techniques along with advanced analytical methods. OR combines the theories, results and theorems of mathematics, statistics and probability with its own theories and algorithms for solving problems. Applications of OR techniques can be used in various fields in engineering, management and public systems. Here, problems are broken down into basic and simple components and then solved by defined steps in mathematical analysis.

The **analytical methods and tools used in OR** include mathematical logic, simulation, network analysis, linear programming, dynamic algorithm among others. The process can be broadly broken down into the following three steps:

- First, a set of all possible solutions to a problem is developed.
- Then, these solutions derived in the first step are analysed and reduced to a smaller set of solutions which is likely to be useful.
- The set of solutions or alternatives derived in the second step are tested for optimality, and if possible, tested out in real-world situations.

Need for OR

It is very important to make the best use of available resources. Owing to today's global markets and open communications, the customers are expecting high-quality products and services. Organisations need to provide these products and services to the right person at the right place and time as effectively and efficiently as possible. For this purpose, careful planning and analysis of available resources is required, which is the hallmark of OR. This is usually based on process modelling, analysis of options or business analytics.

Some applications of OR

- Airline Crew Scheduling
- Finance, Investment Analysis, Insurance and Revenue Management
- Inventory Management
- Maritime Transportation and Logistics
- Quality Control and Inspection
- Telecommunications and Information Technology
- Transportation of Materials

About Satellites

Living in a modern era, we don't find automation and technology driven lifestyle very unfamiliar. From telephones and electronic gadgets to aircrafts and motor-vehicles, all are machines that we use in our daily lives. But what about those we may not be aware of but essentially do use them. Ever thought of how we get TV signals, how are cloud patterns studies, how do we get images of the earth or galaxies or even how are we able to communicate with people across the globe so easily? Yes! The answer is "Satellites".

Satellites (artificial) are launched into the space for various reasons stated above and many other scientific purposes. The second half of the paper is all about planning activities in launch operations and how Operations Research (OR) techniques can be used to assist in the decision-making process. Some of the OR techniques used for the space launch planning and solving multi-objective problems are –

- Linear programming- Simplex
- Simulations
- Greedy algorithm
- Constraint programming
- Tabu search

Brief about Earth Observing Satellites

Earth observation satellites (EOSs) are satellites exclusively intended for observation of the Earth from a low orbit. They function in a manner similar to spy satellites but intended for non-military uses such as environmental monitoring, meteorology, map making etc.
Earth observing technologies from space have become a key role in various fields of energy and metrology. There is a rising need for global monitoring where satellites are used to deliver valuable data about our planet from which we get a better understanding and an improved management of the earth and its environment.

Some applications of EOSs:

- Earth Observation satellites are very useful for scrutinizing and protecting our surroundings, supervising our resources, responding to global humanitarian disasters and enabling sustainable development.
- They also provide vital information on a vast number of areas such as air quality, ocean salinity, ice thickness, crop health, etc.
- Typically EOSs are used for the remote sensing of natural resources, and agriculture, evaluation of natural disasters, and cartographic mapping.

The EOS can be classified into two categories:

- Agile Earth Observing Satellites (AEOSs) are those which can move on the three axes (roll, pitch and yaw). There is a potentially infinite number of ways of capturing a given area on the Earth surface, since the azimuth and the starting time of the image acquisition are now free (within given limits). Freedom of movement gives rise to better efficiency in the whole system. On the other hand, selection and scheduling of AEOSs becomes significantly more difficult because the search space is considerably large.
- Non-agile earth Observing satellites (NAEOSs) have only one degree of freedom which is a mobile mirror in front of each observation instrument. It can be moved only during transition between images. Also, there is only one possible azimuth for imaging- the one parallel to the track of the satellite. The starting time of any image is fixed. It is the exact time at which the satellite flights over the beginning of the area to be acquired. Therefore, the order of the candidate images cannot change.

Earth Observation Satellites (EOSs) are extremely expensive capital resources with relatively short operational lifetimes. To maximize the return on investment, these satellites must be utilized as efficiently as possible.

In this research paper, the main mission of an Earth Observing Satellite that we have considered is to acquire images of specified areas on the Earth's surface in response to observation requests from the customers. Since the requests for such images mostly overtake the capacity of satellites, daily planning becomes an optimization problem under constraints. Therefore, a feasible sequence of tasks needs to be determined.

Use of OR in Optimizing EOS-related decisions

Due to the large number of requests from customers concerning images from the some zones, all of these requests cannot be satisfied on one day. Accordingly, the overall problem consists of selecting, for each period of time, a feasible sequence of images that will be captured by the satellite over the period, with the objective of maximizing satisfaction to the customers.

Therefore, the mission planning problem of a low earth orbit satellite is the problem of choosing a set of photographs to be taken by the satellites during the planning horizon in order to satisfy a maximum part of the requested images. The daily planning of such satellite defines our basic problem. For solving it, we have presented several formulations using graph theory and mathematical programming. It's a very useful OR tool that helps in scheduling activities. It answers the questions- when, where, and how much. Through this method, the best solution can be generated automatically using optimization software. This technique uses probability and mathematical models to predict the future events and determine the most efficient way of allocating scarce resources.

For effective monitoring of environmental activities by a satellite, it is the main goal to achieve maximum coverage in the least possible time. Due to technical restrictions of the satellite hardware, it is only possible to use the camera for a limited time period per orbit, while rotating around the Earth. A software tool was developed which automatically optimized satellite trajectories and sensor operating time schedules for global observation. The technical restrictions were formulated into mathematical constraints and a non-linear optimizing method was used to find the solution.

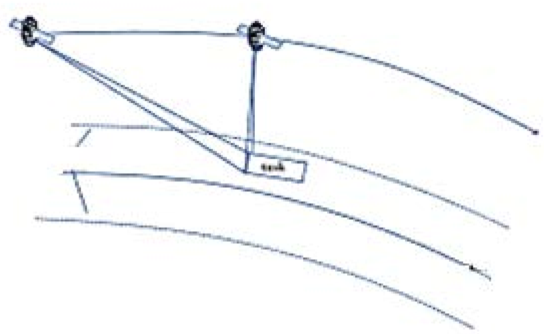
Objectives and constraints for EOSs summarized:

- Maximize the total weights i.e. profits from the requests fulfilled
- Maximize the customer satisfaction by improving the quality of images captured
- Minimize the duration of a transition manoeuvre
- Minimize the time taken by the satellite to reach the new observation location
- Minimize the unproductive areas of the rectangular strips which divide the image
- Maintaining a balance in temperature as there is a minimum temperature required to preheat the instrument in order to use it, while the temperature cannot be allowed to exceed a particular limit as the instrument may then burst

Usually, a control ground station ensures the management of such satellites.
The requests for specific images are sent by users to a centralized ground mission centre (control ground station) each day. This centre builds a precise activity plan for each satellite, taking into account the current requests, their priorities, and the weather forecast; these plans cover all the satellite activities: orbital manoeuvres when they are necessary to maintain the satellite on its reference orbit, observation of ground areas, downloading of observation data to ground stations, pointing of the solar panels towards the Sun in order to recharge batteries, and manoeuvring from one activity to another one, for example from the end of the observation of a ground area to the beginning of the observation of another one; these plans specify the sequence of activities to be performed by the satellite with their precise temporal positions.

The objective function of EOS mission planning is generally taken as: maximize the sum of weights or priority of tasks in schedule, but for agile satellites, based on its stronger ability of observation, a single objective function will not be a good measure of the planning results.
There are other criteria to measure the success of planning results. These are as follows:

- **Quality of images**: the image quality highly depends upon factors like- different observing angles, weather conditions, and the distance between camera and image.

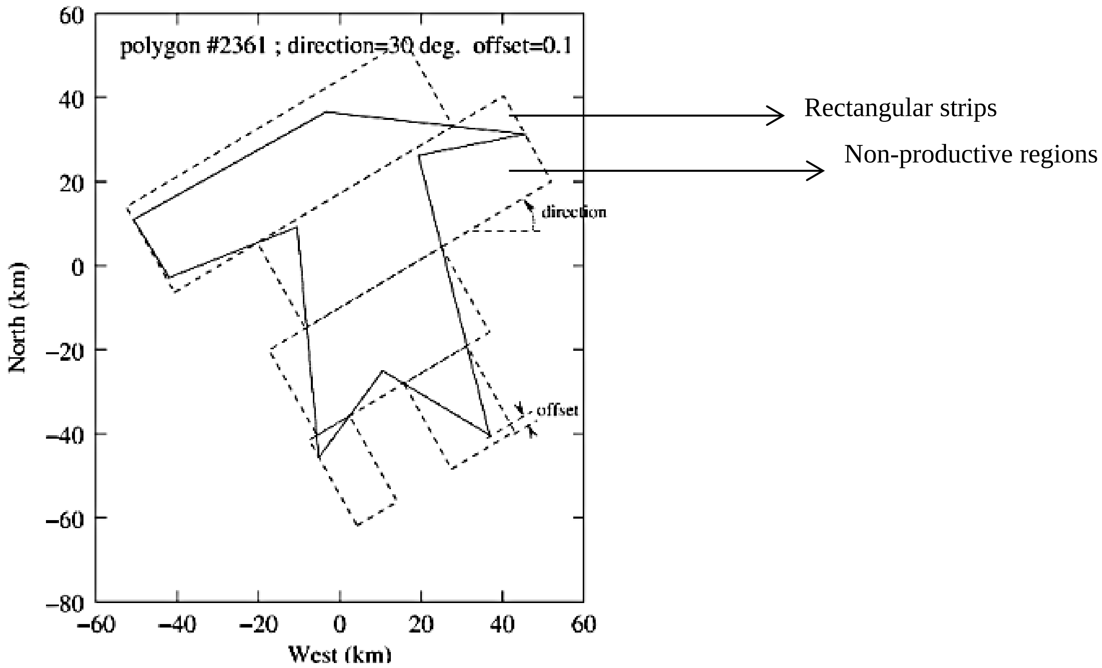


Different angles of observing a target image

- **Usage of satellites**: The use of satellites should be well balanced. E.g. If out of the four targets, all can be observed by only two satellites, then one may observe all four targets and the others will remain idle. This may lead to inefficient usage of satellites.

- **Total no. of tasks in the schedule**: Higher no. of customer requests is preferred even if they are not fully satisfied. This enables scheduling more customer requests and may satisfy more users, the result may be a good solution.

For the purpose of processing, images are constrained to be **strips** of rectangular shape. The width of a strip depends on the design of the instrument and length varies. The objective function here is to minimize the non-productive areas from all rectangular strips.



Time and duration constraints
With the help of orbital parameters of satellites, we can also calculate the **available time** for acquiring the required images. Each pair of images requires a minimum duration of a transition manoeuvre. Since a minimal duration is mandatory to preheat the instrument (a focal plane or the high-rate antenna) in order to use it, the temperature of the visible focal plane, as well as that of the antenna, cannot exceed a maximum value. Due to these temperature and energy constraints, switching off an instrument between two uses becomes necessary. This minimum duration not only depends on the location and the azimuth of the images, but also on the precise instant time of the beginning of the transition manoeuvre (which is also the end of the first image acquisition). The function here is to minimize the total time taken for the satellite to reach the new observation location so as to acquire maximum no. of images in least possible time to increase the aggregate weight. (Weight is the importance of each request. In other words, the price that consumers pay on fulfilment of the request) It can be done through a dichotomic search. This is done by selecting and comparing two alternatives at each step.

Observation area selection preferences
An acquired image may not always be a satisfactory one, due to possible bad climatic conditions. Therefore, a request may have to be selected several times, until it is acquired with satisfactory climatic conditions. The selection and scheduling process is explained by the following example:
Suppose two equally weighted observation areas A_1 and A_2 can be acquired during the same time window, but not both of them; if it is known that A_1 will probably benefit from better weather conditions than A_2 then, of course the acquisition of A_1 must be preferred.

Quality constraints
An important criterion is the quality which is to be maximized. This criterion is based on the sum of the weights of the satisfied requests. But the problem lies in the fact that some requests may only partially be covered by satisfactory images. As a result, a reward proportional to the acquired surface was developed. This criterion is named as the ‘Linear Quality Criterion.’

But, the Programming Centre favours the complete acquisition of one image, before beginning a new one. This preference constraint can be taken into account by a modified quality criterion wherein the sum of partial rewards obtained on each request is to be maximized. This is known as the 'Non-Linear Quality Criterion.'

Task Planning Algorithm

A '**chronological greedy**' algorithm is used in order to solve the problems mentioned above. This algorithm allows us to make choice which seem best at the moment and then solve the sub-problems later. It makes one greedy choice after another and reduces each given problem into a smaller one. In other words, a greedy algorithm never reconsiders its choices. That's what differentiates this algorithm from the dynamic programming algorithm, which is exhaustive and guarantees to find the best solution. Dynamic programming algorithm is explained in depth ahead in the paper.

The greedy algorithm is broadly based on these 4 levels of action:

- Orbital manoeuvres and associated observations
- Activities related to sun-pointing and geo-pointing
- Image downloading activity
- Switching an instrument on/off during transition

The four stages in detail

Here, a trade-off needs to be made between the topmost priority actions and the earliest feasible actions so as to leave space for other actions. So, among the most priority actions that are feasible within the decision-making time, the earliest ones are selected.
For example, a_1 is among the most priority actions that are feasible before a_1 and do not prevent the realization of a_1 select the earliest one. Same goes with a_2 and so on until no action satisfies the conditions.
A sun-pointing is chosen during daylight (on board), whereas a geo-pointing is chosen during night. A pointing of maximal duration is systematically planned (the earliest starting time and the latest ending time). At the next stage, the verified constraints are those of the available of mass memory and the downloading actions.
Finally, the resources taken into account are: energy, temperatures of both the visible focal plane and the high-rate antenna, the number of on/off commutations done for each instrument and the total time when each instrument is on.

Satellite Launch campaign and planning decisions

Increase in productivity and careful management of limited resources is the need of the hour not only in satellites but in any management activity. Prior to the process of launching satellites, the satellite manufacturer has to ensure the availability of all the resources in the prescribed time. The penalties for the non-availability of resources can cost a hundred million dollars to the manufacturers on account of poor capacity planning.

The **launch campaign** is a critical period for the spacecraft manufacturer to verify a spacecraft's functionality prior to launching it into orbit for a 5-15 year operational life. Such a campaign is a significant commitment of personnel, equipment and resources.

Manufacturer's major costs to support a launch campaign consist of cost of living for the team, launch base support infrastructure, transport, consumable materials (propellants) amongst others. If the no. of satellites to be launched is estimated in advance, then the manufacturer can select a combination that minimizes overall cost using LPP techniques.

An optimal solution is found for a given objective function with specified constraints on the variables of the function. In this case, the objective is to minimize the cost of launch campaigns. The solution is obtained using common optimization techniques such as MPL, CPLEX, LINGO/LINDO, and Excel.

Launch vehicles are used to launch satellites into space in such a manner that they cross the Earth's atmosphere and gravitational pull. OR tools are used by satellite manufacturers to deliver the satellites to launch bases. The manufacturer selects launch vehicles and corresponding launch sites from which to launch its satellites, and allocates accordingly resources to support the final satellite checkout and launch.

Linear programming is used to optimize selection of launch vehicles for cost minimization and assess the capacity of finite resources to support multiple campaigns. **Monte Carlo simulations** are generated to predict resource requirements given uncertainties in start and completion schedules. **Simulations** can also be used to determine probabilistic estimates of campaign durations.

Finally, a **decision-tree analysis** is applied to contingency decision-making for assigning critical resources. These tools provide basic approaches for improving productivity and reducing operating costs in space launch operations for the spacecraft manufacturer.
As a result, the manufacturer attempts to minimize the campaign duration without jeopardizing the mission or switch out its resources as they are needed elsewhere.

Launch Scheduling Problem and Camp duration

Satellite scheduling is a set of problems that arise in satellite mission planning of communications of spacecrafts with ground stations. Such problems can be classified under time window scheduling given that the communication between the ground stations and spacecrafts is limited to some specified time window. These problems are highly constrained and hard to solve to optimality. Therefore, these problems are solved in practice through heuristic and meta-heuristic approaches, discussed later in the paper, which are generally efficient for high constraint problems. We have considered some local search methods (Simulated Annealing and Tabu Search) and population based methods (Genetic Algorithms and their variants).

Jian and Cheng introduced an integer programming model of MSS based on the analysis of the resource constraints and task characteristic. To solve this combinatorial optimization problem, they provided a genetic particle swarm optimization (PSO) algorithm which searches only in the appointed integer space. **He et al**. presented a cooperative scheduling architecture of multiple satellites by converting this scheduling problem into a main problem and a sub-problem. In addition, an improved PSO algorithm was used to solve MSS problem by taking task benefits as an optimization objective.

However, those above researches have been primarily focused on static scheduling problem of EOSs. The problems are characterized as inherently **dynamic** as new image requests come from the user or changing weather conditions preclude already scheduled observations. Image requests are visible to the satellite within a time window de pending on the specified acceptable imaging angles.

A **dynamic programming algorithm** was proposed henceforth. It is a method for solving complex problems by breaking them down into a collection of simpler sub-problems, solving each of those separately just once, and storing their solutions.

Its main **advantages** over the traditional methods were:

- It becomes easier to generate a task planning within a short time. A dynamic planning process consists of repeated scheduling events, and can rapidly generate the planning scheme. Therefore, the high-efficiency heuristic algorithm should be used to address the dynamic scheduling problem of EOSs.
- The impacts of scheduling time on the available tasks are considered. Since tasks are considered dynamic arrivals, the planning system collects dissimilar task sets at different scheduling times. Thus, the tasks set are determined based on current scheduling time before the scheduling.
- The other constraints such as the storage capacity, maximum swing angle, and continuous observation time are also taken into consideration during dynamic scheduling.

Wolfe and Sorensen introduced three approaches to solve the EOS scheduling problem:

- **Priority dispatch method**: This is a quick and simplified priority dispatch method which was designed to produce acceptable schedules for the observation process.
- **Look-ahead algorithm**: It extends the priority dispatch method by redefining the best location rule to looking ahead in the queue of unscheduled requests.
- **Genetic algorithm**: It is applied effectively for multi-satellite scheduling by allocating resources optimally to meet the spacecraft requirements. This uses meta-heurists approach and provides feasible solutions in complex spaces.

Lemaitre and Verfaillie analysed the difficulties of the problem and provided a comprehensive description of AEOS scheduling problem. Then they simplified the problem to the AEOS Track Selection and Scheduling and proposed four different methods to solve the simpler problem:

- **Greedy Algorithm**: It's an algorithmic paradigm that follows the problem solving heuristic of making the locally optimal choice at each stage to find a global optimum. As a selection algorithm, it is very useful for prioritizing options within a search. It's suitable for many simple problems having an optimal substructure.

- **Constraint Programming Approach**: It is a generic technique used for modelling and solving problems that are combinatorial. With OPL (Optimization Programming Language), the components of the model of the problem are described: data, decision variables, constraints and optimization criterion. Generally, any kind of constraints can be expressed in this algorithm. Solving of the model by local modifications is possible as the technique is also robust and flexible.

- **Local Search Method**: It is a heuristic method for solving computationally hard optimization problems. Local search can be used on problems that can be formulated as finding a solution maximizing a criterion among a number of candidate solutions.

After analysing the techniques given by these researchers, we can conclude that permutation-based search combined with constraint-propagation works very well for agile EOS scheduling to solve oversubscribed resource scheduling problems.

A **tabu search algorithm** is another good technique to generate a near optimal and feasible schedule for EOS resource scheduling problem by exploring a search space which may be beyond local optimality. Tabu Search algorithm is to constrain an embedded heuristic from returning to recently visited areas of the search space, referred to as cycling. Its adaptive memory makes the search behaviour much simpler. The consistency of each new move in the search procedure is ensured by effective constraint propagation. Moreover, their algorithm is also is bridged with systematic search which uses partial enumerations. A dynamic programming algorithm was used to calculate upper bounds on a relaxed problem.

Simulations are highly used in tracking the movement of satellites. Once a trajectory (the path on which the satellite moves) is available, it can be simulated step by step. Thus, energy production can be estimated, the time windows, during which downloads are effectively made possible are computed, and the instrument non-dazzle is verified.

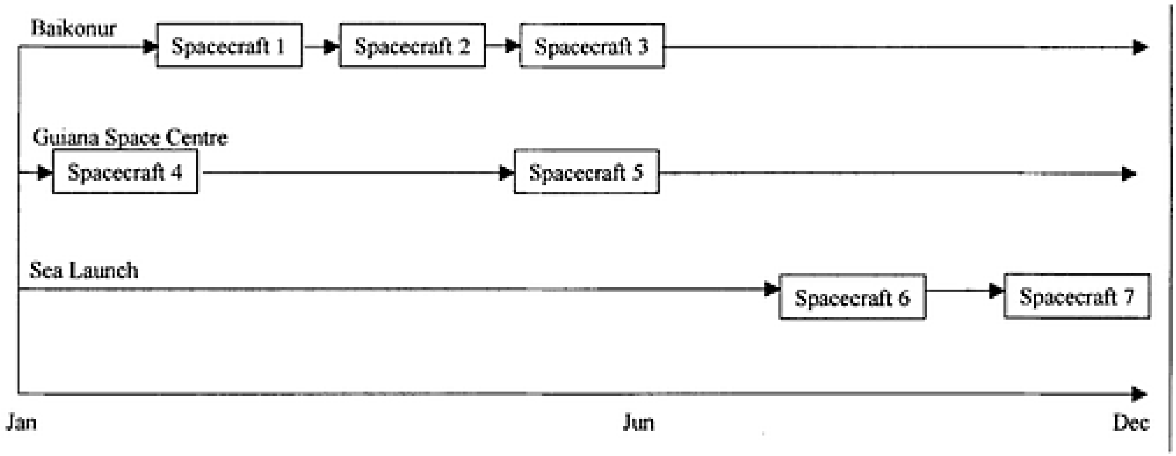
With the increase of satellite launch demand and the limited capability of launch centres, it becomes more difficult to schedule launch centres and launch time for multiple satellites. A mixed-integer programming model of optimizing multiple launch missions in multiple launch centres is set up, aiming at the least cost and the lowest failure probability.

MIP problems are those in which some of the decision variables are constrained to be integer at the optimal solution. The scope of important optimization problems can be expanded with the use of integer variables that can be later defined and solved. Space communication network problems also can be solved through mixed integer formulations. Dynamics between any two assets varying with respect to time and distance are linked. In accordance to the link capabilities and geometric dynamics network, the start time, end time, and link configuration of each view-period are optimized. This ensures the completion of the objective of schedule thus satisfying the operation constraints that the mission imposes.

Additionally, to solve the problem, a sample **approximation method** was suggested, which transforms the constraint programming model into an integer linear programming model. Subsequently, a branch and cut algorithm based on lazy constraint generation is developed to solve the ILP model.

Program Evaluation and Review Technique (PERT) and Gantt charts provide visual relationships of launch campaigns and tasks and are versatile tools for scheduling operations and defining critical paths. PERT charts evaluate and plan tasks in a particular project which makes it easier to coordinate with other team members to achieve the objective. Gantt breaks a project into smaller pieces of tasks with each of these spread out over time. This results in viewing of percentage of work completion along with scheduling of the constraints, dependencies of a task and the time taken for each task. These tools assist in minimizing the campaign duration and to schedule the necessary resources at the appropriate times. These tools also serve as a starting point for developing discrete simulation models that can assess schedule sensitivity and evaluate cost-benefit trades. Simulations are relatively simple means for incorporating complex inter-relationships and accounting for elements of uncertainty by inserting probability distributions in the model.

Sample schedule of launch campaigns using PERT and Gantt technique:



A simulation of the planned campaigns can be generated on an Excel spread-sheet. The manufacturer can use these simulations to identify the tasks which can reduce the campaign duration by applying more resources (e.g. personnel) based on associated costs.

Multi-objective optimization for selecting and scheduling observations by Earth Observing Satellites (EOSs)

Multi-objective optimization is applied to the scheduling of such satellites in context where multiple users request photographs from the satellites. Genetic algorithms are used to solve such problems. The ground station centre receives requests from several users and it has to consider all requirements and finalize an order consisting of a sequence of selected photographs to be transmitted to the satellites.
The two **objectives** of EOSs here are to (i) maximize the total profit and (ii) to ensure fairness among users by minimizing the maximum profit difference between users.

The management problem here is to select and schedule a subset of photographs from a set of applications.
Whereas, for AEOS the multi-objective mission planning problem is quite complicated in which four objectives contribute to the overall result. These objectives affect one another in complex and nonlinear ways. These are:

- Deciding the order of the tasks (task scheduling)
- Selecting the right opportunities for the tasks
- Estimating the task duration in a selected opportunity and fixing the exact start time
- Evolving and optimizing the scheduling results

This process can be complicated as there are many possible schedules for the same set of selected photographs. The time that can be used for each photograph is not fixed but it must be within a given time interval. The technique first builds an elite initial schedule using a prescheduling strategy and then improves the initial schedule using a rescheduling strategy in a subspace of feasible solutions.
Several algorithms including greedy algorithm, dynamic algorithm, and constraint programming have been applied for solving EOS scheduling problems.

Other methods like **simulated annealing** and **tabu search** were also suggested by researchers. Tabu search was generally used for multi-satellite, multi-orbit, and multi-user management to select and schedule requests.
Three ways to solve prioritize the distribution in multi-objective problems are: based on
(1) Fairness, (2) efficiency, (3) trade-off between fairness and efficiency. In such cases, instead of building non-dominated solutions, researchers suggest taking decisions closest to the line with a specified slope on the objective function. Another useful way discovered to solve such problems was 'biased random-key genetic algorithm' (BRKGA).

The upper limits of the profit were derived with the help of a **column generation technique** provided by the French centre for special studies. It's an efficient algorithm for solving linear programs which are too large to consider all the variables explicitly. A subset of variables is considered in while solving the problem. It generates only those variables which have the potential to improve the objective function

Conclusion

Through this research paper, we have highlighted the practical applications of OR in real-world planning problems in context of satellites. The management problems related to satellites include optimal resource allocation, launch planning and scheduling, maximizing profits on customer requests, etc. the paper has covered the criteria to be considered while designing decision rules for such problems. The main ones out of all those mentioned in the paper are: (1) Prioritizing activities, (2) their start time, end time, and duration, and (3) determining the amount of resource consumed by them. The highest priority activities are favoured in order to maximize the sum of weights. High priority activities include those which: (1) start as early as possible and do not let the system idle for too long, (2) Whose duration and resource consumption is as small as possible.

For EOSs, the main objectives were to improve image quality, maximize the no. of tasks i.e. no. of requests accepted, and minimize the transition time between two images. The use of several OR tools like simulations, constraint programming, dynamic programming, tabu search, among others has been explained with respect to launch planning and decision making. Multi-objective optimization problems include decisions like scheduling, selecting opportunities, estimating task duration and optimizing the results which are solved using genetic algorithms. Also, techniques of some other researchers for satellite scheduling problems have also been presented in the paper for a holistic view of the situation and solution. Thus, the paper overall covered the important aspects of Earth Observing Satellites and how OR can be used to the benefit of satellite manufacturers, ground control stations and customers.

References

Selecting and scheduling observations of agile satellites Michel Lemaître, Gérard Verfaillie, Frank Jouhaud, Jean-Michel, LachiverNicolas Bataille Published in 2002

Agile Satellite Scheduling via Permutation Search with Constraint Propagation Bistra Dilkina and Bill Havens; Actenum Corporation, 2005

Multi-objective mission planning problem of agile Earth observing satellites Kai SunJufang, LiYingwu, ChenRenjie He, 2004 National University of Defense Technology

Decision-Making on-board an Autonomous Agile Earth-Observing Satellite Grégory Beaumet and Gérard Verfaillie; Marie-Claire Charmeau

Interaction between action and motion planning for an agile Earth-observing satellite Romain Grasset-Bourd

Operations Research in Space and Air: 2014 Edited by Tito A. Ciriani, G. Fasano, S. Gliozzi, Roberto Tadei 2003 Kluwer Academic Publishers

Evans J.R., Olson D.L. **Introduction to Simulation and Risk Analysis**, 2nd Ed. New Jersey: Prentice Hall, 2002. Google Scholar

Lang D. E. **Launch Capacity Analysis for Commercial Communications Satellites**, in this book, 161–178. Google Scholar

Gabrel V., Murât C. **Mathematical Programming for Earth Observation Satellite Mission Planning**. Google Scholar

V. Gabrel, **Improved linear programming bounds via column generation for daily scheduling of earth observation satellite,** Technical Report, LIPN, Université 13 Paris Nord, January 1999.

N.G. Hall, M.J. Magazine, **Maximizing the value of a space mission**, European J. Oper. Res. 78 (1994) 224–241