Journal of Soft Computing Exploration

Multi-objective optimization for multi-satellite scheduling task

Mohamed Atef Mosa[1], Heba Abdulrahman Khojah[2]
[1]Digital Transformation and Information Center, Institute of Public Administration, Riyadh, KSA
[2]Collage of computer and information Sciences, King Saud University, Riyadh, KSA
[2]School of Computer Science, University of Manchester, United Kingdom

Article Info

Article history:

Received Mar 25, 2022
Revised Mar 25, 2022
Accepted Mar 28, 2022

Keywords:

Satellite Scheduling,
GSA,
Earth Observation,
PageRank Algorithm,
MOO Task

ABSTRACT

The satellites scheduling mission play an effective role in enhancing the role of ground station control and monitoring systems. In this search, SGSEO is re-formulated into a multi-objective optimization task. Therefore, the Gravitational Search Algorithm GSA is exploited to attain several essential objectives for generating tight scheduling. Moreover, particle swarm optimization model PSO is consolidated with GSA in a novel form for strengthening its ability of local search and slow the speed of convergence. On the other side, to make the most of the satellite resources in the right direction, we have observed targets that have fewer observational opportunities to keep them from being lost. The PageRank algorithm is used to fulfil this issue by ranking the candidate's strips. Finally, the effect of different parameters of the proposed approach was studied by experimental outcomes and compared with previous methods. It has shown that the performance of the proposed approach is superior to its peers from other methods.

Corresponding Author:

Mohamed Atef Mosa,
Digital Transformation and Information Center,
Institute of Public Administration.
Email: mosamo@ipa.edu.sa

1. INTRODUCTION

The satellite scheduling constellation for the Earth observation (SGSEO) mission is a kind of huge harmonic optimization problem concerning the aerospace field. Great effort has been achieved to tackle the task of scheduling multiple satellites. Moreover, many types of research used heuristic methods for this task. [1] modelled the problem based on the mesh planning and heuristic search. Unfortunately, the authors did not consider targets conflicts. Moreover, others used the TAPU search (TS) to address the scheduling problem [2]–[4]. The TS was used under many complex conditions [3]. TS was developed for this problem by adapting the memory capacity, which came to contain all possible tables. Numerical experiments have shown that the robust algorithm outperforms other mechanisms that rely on space-shifting solutions [4]. The authors [2] have introduced TS strategy based on time constraints.

On the other hand, [5] suggested directing Lagrangian instructions for the scheduling task. It consists of a series of independent maximum weighted values shown in interval graphs. The genetic algorithm (GA) has been in use to solve this problem. It is also known that GA is one of the best intelligent and specialized methods for searches [6], [7]. On the other hand, the scheduling task is formulated as a multi-objective optimization task MOO. The authors [8], [9] proposed a GA-PSO model by integrating PSO with the GA genetic algorithm to build a modified model based on analyzes of scheduling properties.

Ant colony optimization (ACO) is one of the most powerful ways to address complex optimization problems [10]–[12]. A new optimization algorithm is proposed by [13] based on routing solution (GsB-ACO) to avoid early convergence and quickly cover a promising area. The authors in [13] adapted the ACO algorithm by integrating directly with Local Iterative Search (ACO-ILS), to further improve the initial ant solutions. The authors in [13] proposed an innovative scheduling system by grouping common tasks with the same features. After that, a graph is built based on these groups, and then the search process begins.

It is noteworthy that the GSA method has been used in many real-time applications and MOO missions [14], [15]. Accordingly, in that study, a new approach was developed to address mission scheduling of Earth observation satellites. Initially, many may Customers have requested a set of targets which are the area of the polygon for observation at a specific time. In addition to the fact that customers require observing with a certain accuracy, which depends on the degree of the angle of rotation of the satellite left or right. Customers may not ask to observe the entire target, they may be satisfied with 80% or 90% of them or whatever percentage they specify. In this case, it is not necessary to observe the whole target. The main objective of this approach is to schedule missions of Earth's satellite constellations. Besides, the satellites connect to GDRS to transmit and receive remote control data. We have formulated the Earth Observation Mission of a multi-objective improvement problem in a new form to achieve many goals. 1) Gross profit maximization is prioritized in response to fewer resource control opportunities and emergency missions. 2) Low viewing angle to capture high-resolution images. 3) Maximization and optimization of satellite operating times by reducing the time window to move from one location to another with the same bandwidth. 4) Finally, reduce the overlap between points of the same target so that it is not scheduled more than once. To accomplish this problem, the GSA gravity search algorithm [16] is employed to optimize by creating coherent scheduling. Furthermore, particle swarm optimization (PSO) is mixed with GSA in a new form to enhance the local searchability and the slow convergence speed of standard GSA. Furthermore, to ensure that Pareto trades almost uniformly, the NBI model of normal boundary intersection was used for this issue [17]. The decisive factor in this task is that clients and ministries accept only the goal for which the required percentage is observed. Therefore, the PageRank model has been reformulated on a priority basis in response to fewer opportunities for monitoring as one of our most important goals.

The remainder of the research is structured as follows. The second section provides a detailed definition of the problem, from a general description and a mathematical model. In the third section, the proposed approach is presented in some detail. The fourth section also provides testing and analysis of results with other methods for the purpose of comparison and evaluation. Finally, the fifth section appears as a conclusion to the scientific paper.

2. METHOD

In this part, the components of SGSEO are shown in Figure 1. After identifying the targets of the customers and their specifications they are all plotted on the map using the STK simulator. Ballistic information for future orbits is calculated according to Section 2.1.1. A simple algorithm has been developed to divide the polygon into a grid of latitude and longitude points as shown in Section 2.1.2. After the targets are divided into a matrix of points, they have been divided again into a set of strips. These strips are the result of an intersection between the swath width of a satellite and those targets as presented in Section 2.1.3.

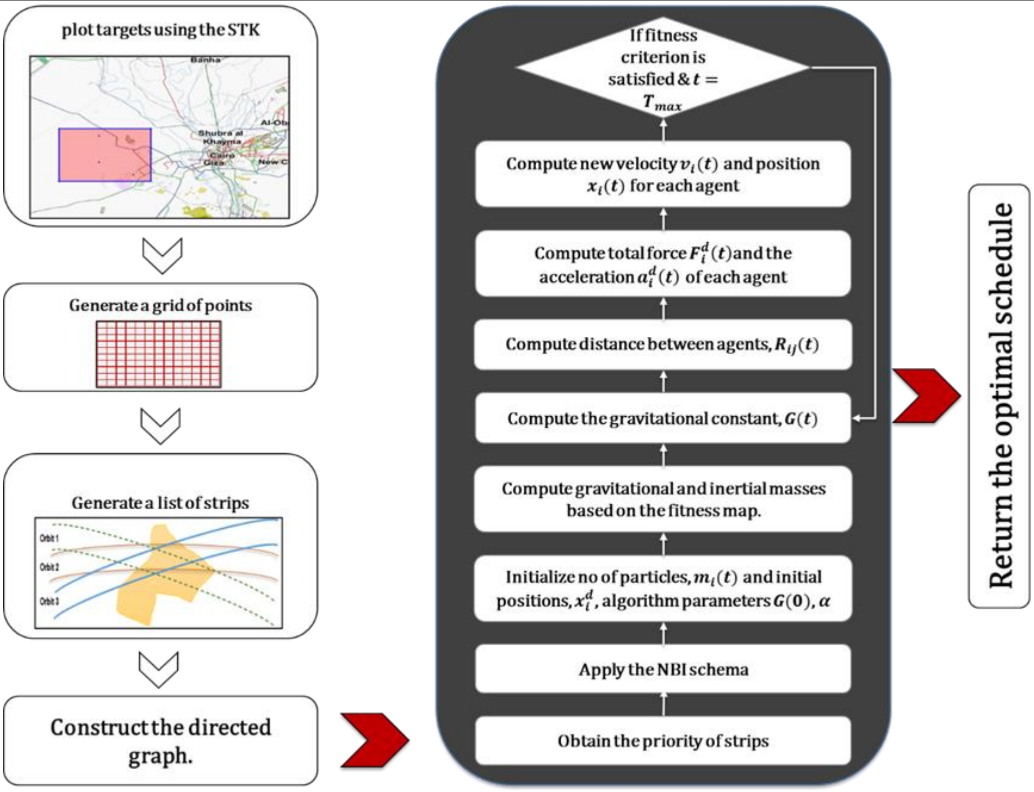

Figure 1. System model of the scheduling approach

The length of the strip has relied on the observation duration under condition NO/. 7. Additionally, as illustrated in Fig. 2. the width of a strip depends on the outer and the inner of halfangle. But we assumed that the width of the strip is a constant for simplicity. Moreover, a very large number of possible overlaps and possible strips are generated in order to select the most suitable algorithm from them. To accomplish our objectives and satisfy the pre-defined constraints, PSO and GSA are mixed to tackle a MOO to obtain the best schedule. And to enclose the near-regular spread of Pareto-best solutions in the frontier, this task is tackled by the NBI model. During iterations of the algorithms, when there is no improvement in the results, the program stops. Here the details of the proposed in Figure 1 approach will be illustrated

The remainder of the research is structured as follows. The second section provides a detailed definition of the problem, from a general description and a mathematical model. In the third section, the proposed approach is presented in some detail. The fourth section also provides testing and analysis of results with other methods for the purpose of comparison and evaluation. Finally, the fifth section appears as a conclusion to the scientific paper.

3.1. Pre-Processing

Firstly, the ground station operation centre receives different targets that need to be monitored by many customers simultaneously. Images data must be specified by clients containing: coverage required area percentage, the ratio of image resolution, the time of delivery, the type of cameras and channels, and finally, the type of target (through which the importance is determined). Subsequently, all targets are plotted using the STK of future orbits to determine the locations of future satellites to enable accurate scheduling.

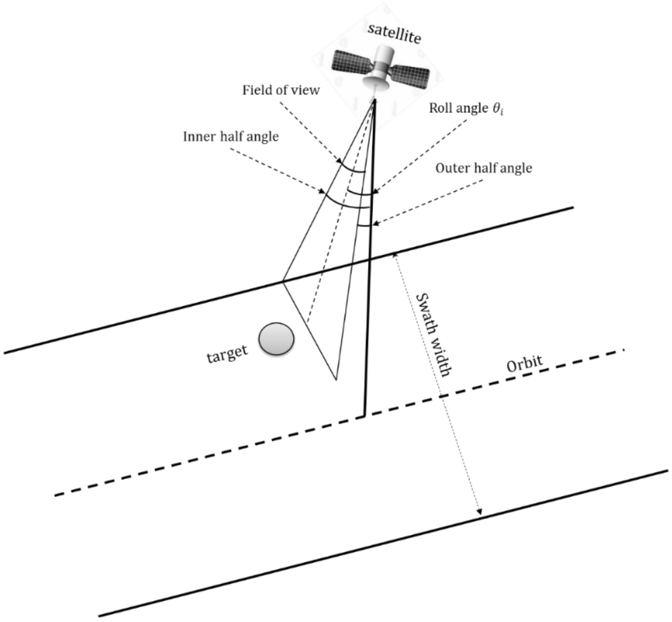

Figure 2. Observation process of the satellite

2.1.1. Generate a grid of points

The polygon targets were divided into a matrix of small squares, which are expressed by latitude and longitude. The main objective behind the partitioning process is to be able to measure the observed ratio with high accuracy.

2.1.2. Generate Strips

The polygon target cannot be observed in a single shot. So it must be divided into several strips from a number of satellites and in different orbits. The satellite's swath width is considered to be the boundary of the area projected to the ground during manoeuvring and reaching the maximum angle of rotation. Therefore, the strips are generated from the intersection of the satellites' swath width with the targets during a specified time window. The time window is denoted by $TW_{ki} = [ts_{ki}, te_{ki}]$.

Therefore, a rational procedure for segmenting large targets was also developed considering maximum rotation angle, time window, and overlap between multiple strips. Bearing in mind that these strips may overlap each other due to the selection of strips with lower observation angles to improve image resolution. Therefore, one of our goals is to reduce the overlapping points between the tabular strips as much as possible.

2.1.3. Graph Representation

A graph model for each orbit is generated by connecting all the strips together when all constraints are met. It can be seen from Figure 3, that the strips are arranged sequentially for each orbit in order of precedence. The strip can belong to a number of orbits and a number of satellites. What is required is to assign the strip to a particular satellite and a particular orbit. For example, in Figure 3, strips S8 and S10 have time windows in orbits 1, 2, and 3. What is required is to assign the three strips to the most appropriate satellites.

DOI: 10.52465/joscex.v3i1.67

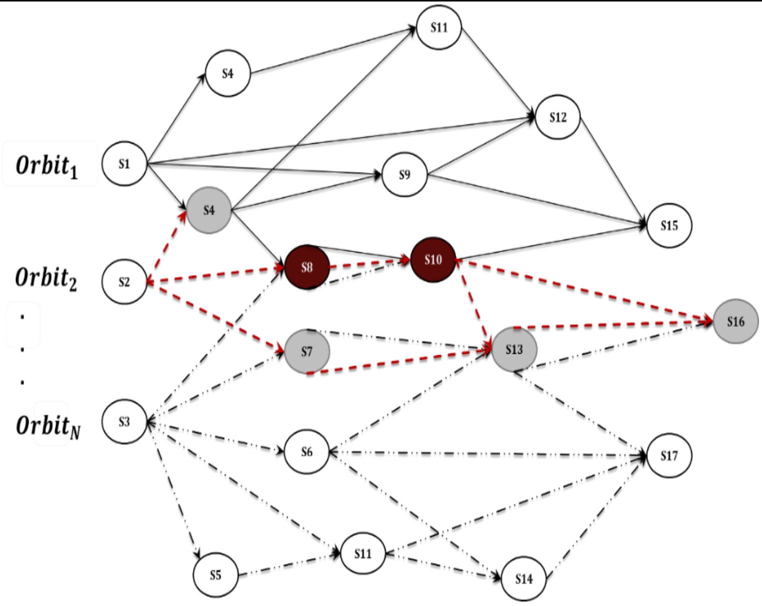

Figure 3. A directed graph model of strips

Finally, the input of SGSEO contains a set of targets, and for each target, a set of possible strips. Besides, there is some information that has to be appended to each strip, i.e., the satellite ID, orbit number, the start/end time of observation ts_{ki}, te_{ki}, a slewing angle θ_{ki} of stripS_k, the time-window for a transition to another position in the same swath width $(\theta_{ki} - \theta_{hl}$ and the $priority\ (s_{ki})$ of stripS_k.

3.2. Calculate Priority

In our study, we characterize the priority based on two components. The primary one is how important the target is, where important is indicated by the customers to be typical or critical. The second factor is the priority in responding to the lack of opportunities to observe strips. In this case, we are going not to consider the priority in observing the strips to be given randomly but rather it will be calculated in an imaginative way to be reasonable. After you have all the possible strips, now it's time to stamp them with the real priority for observation. Our hypothesis is based that when a strip has numerous opportunities for observation by a few satellites at diverse times, then the priority of observing for that strip diminishes. On the contrary, when the strip has exceptionally few possible observations, it's a priority to observe increments. And it reaches the peak if the number of potential opportunities is only one. In this issue, we must observe the specified percentage of the target so that the ministries or different clients can acknowledge it. We may not be able to observe many of these strips that do not have many opportunities for observation, so we may lose them forever. After losing these strips, we may not be able to complete the required percentage of the target, and therefore it will be rejected. Therefore, our hypothesis is based on observing the strips that have the lowest chances of being observed to be scheduled first and prohibited from being missed.

We have developed the Strip-Rank algorithm based on the Page Rank algorithm in a new form to calculate the expressive priority of strips. A strip is not considered to require urgent observation based on four issues. The first one is when other previous strips (voter strips) have higher potential opportunities of being observed. We could better understand the meaning of higher opportunities of observation. If we look at Figure 3, we notice that the greater the number of internal arrows to a strip, the means that this strip has higher the opportunities for observation. Therefore, the opportunity of this strip being noticed is diminished if its voter strips do not have a huge probability of being observed. The second issue is the number of prefixes strips: when the number of voter/neighbour strips is abundant, it acts on its probability. Increasing tapes from neighbours may increase the likelihood of scheduling after any of them, and thus increase the number of scheduling opportunities. The third factor is that the value of the Strip-Rank decreases when the number of shares exiting the strip of voters is low. This is because the value of these bars will be divided by the number of bars they refer to. The fourth and final factor is the type of strip if it is of urgent importance. If the tape is of typical importance, this weakens the chances of scheduling it early. On the other hand, the priority of the tape is highest if there is one chance of being noticed. And to calculate the rank for each bar by Eq. 1.

$$ps_{ki} = \left(\frac{1}{\alpha \sum_{ps_{hl} \in N_{ps_{ki}}} ps_{jl} * \frac{ty_{ki}}{\sum_{ps_{ng} \in N_{ps_{hl}}} ps_{ng}} + (1-\alpha)} \right) \quad (1)$$

Where ps_{ki} is a rank score of strips s_k in target t_t. ps_{lh} is the set of neighbours of a strip s_{ik}. ps_{ng} is the set of out link neighbours of a strip s_{hl}. ty_{ki} is a type (importance) of a strip s_k for target t_i. α is a damping factor. The strip rank value is set to one. The Strip-Rank algorithm keeps updating the values until they reach the stage of stability and do not change.

3. RESULTS AND DISCUSSIONS

In this section, data generating method, selection of optimal parameter values for SGSEO algorithm, presentation and analysis of results are discussed.

3.1. Simulated instances

Since there are no standard datasets prepared for testing so far in the field of satellite schedules, a random data generation method has been developed to test the proposed algorithms. The database for testing was synthesized according to the following rules: 1) The targets were created within a zone of latitude 20°~50°N and longitude 70°~130°E. Eight simulated cases are set in this paper. The satellite has 14 turns around the Earth, day and night. The maximum angles that the satellite can achieve in the range [-33, 33]. Each proposed group includes a number of targets, each target is divided into a set of points and a number of strips. The targets were randomly distributed on the surface of the Earth between latitude between [-33, 60] and longitude between [0, 153]. Using the popular STK simulation software, the time windows for each bar and its observation angle were calculated. The information is presented as follows divided into eight cases in Table 1.

Table 1. Practical case data for simulation

Instance	# satellite	#antennas	#targets	# Strips	# edges	Scheduling period
S01	7	5	30	420	2993	2018/05/4–24
S02	10	7	40	560	3637	2018/05/4–25
S03	12	9	50	711	3950	2018/06/8–28
S04	15	10	60	788	4588	2018/06/10–24
S05	17	11	70	833	4800	2018/07/10–27
S06	18	12	80	889	5238	2018/07/12–28
S07	19	13	90	940	6309	2018/07/19–29
S08	20	15	100	990	7755	2018/08/18–28

3.2. Effect of parameters

On the other hand, through extensive experimental study, we want to reach the optimal values of the parameters that give the best results for GSA solutions. The effect of changing GSA parameters was analysed experimentally with the restriction that none of the restrictions was violated. The effect of changing the parameter values shown in Table No. 1 was studied experimentally by running the algorithms thirty independent times for each experiment, based on scenario S08. And the maximum number of turns was 150. Initial parameter $\boldsymbol{G_0}$, Number of mass agents $\boldsymbol{n}$, Constant parameter α, and ε vary between the candidate values except for one parameter that remains unchanged. The default value of each parameter is $\boldsymbol{G_0}$ = 80, $\boldsymbol{n}$ = 10, α = 20, ε = 0.01. The parameter ranges are restrictive in table 2.

Table 2. Ranges of proposed approach' parameters

Parameter	Range
Initial param, G_0	{30, 50, 80, 100, 120, 150}
NO of mass agents, n	{5, 7, 8, 10, 12, 15}
Constant param, α	{5, 8, 12, 15, 20, 25}
Constant param, ε	{0.005, 0.01, 0.02, 0.03, 0.04, 0.05}

Figure 4 shows the algorithm performance varying in $\boldsymbol{G_0}$ parameter that represents the weight of the initial parameter. It is observed the best value is obtained when the value is 100.

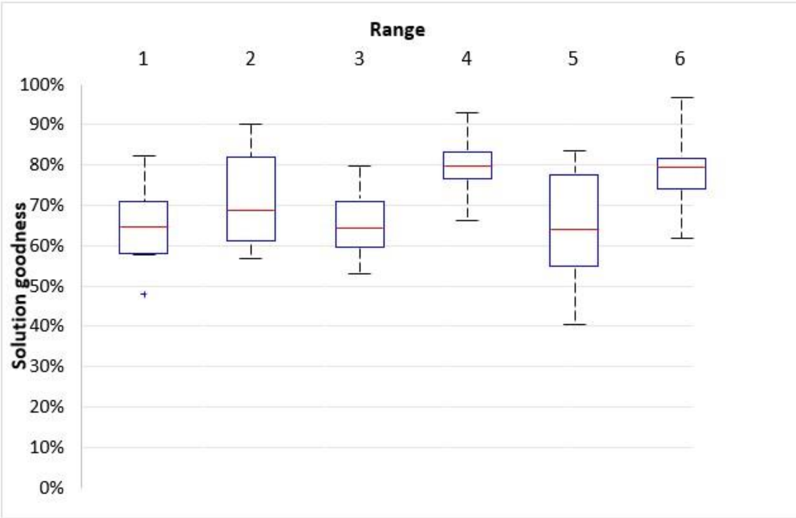

Figure 4. Performance over a range of parameters values, $\boldsymbol{G_0}$

Figure 5. The performance of the algorithm shows a variable with parameter n which denotes the weights of the number of mass agents. It is noticeable that the optimal value of the parameter appeared when it was 8.

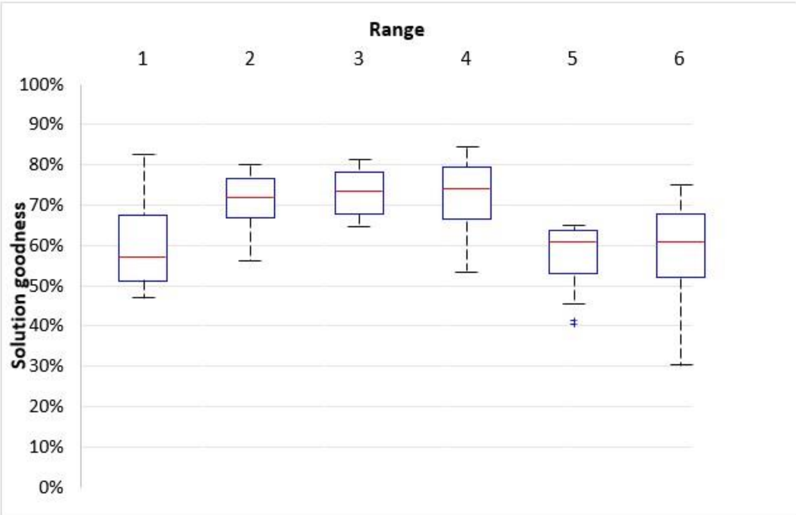

Figure 5. Performance over a range of number of mass agents, n

Figures 6 and 7 show the variance of the results when the algorithms are executed with parameter α and $\boldsymbol{\varepsilon}$. The quality of the results and the gap between them fluctuates between increasing and decreasing. In the end, the best values are captured for α and $\boldsymbol{\varepsilon}$ at 20 and 0.01, respectively.

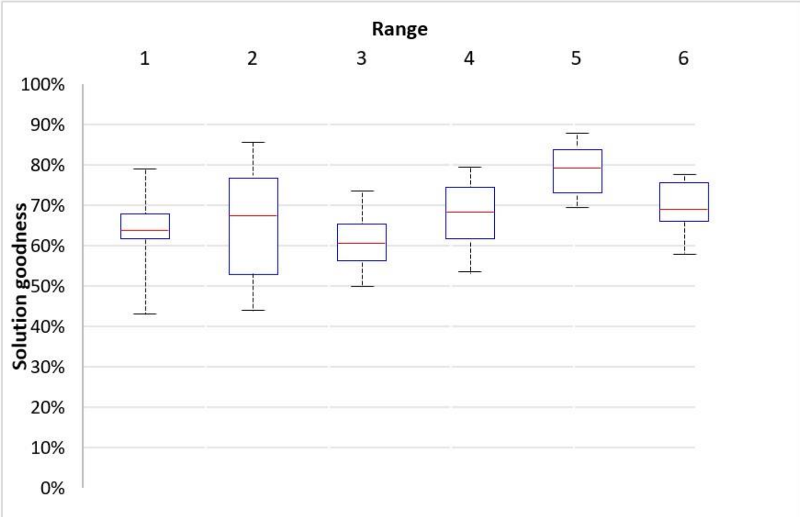

Figure 6. Performance over a range of parameter value, α

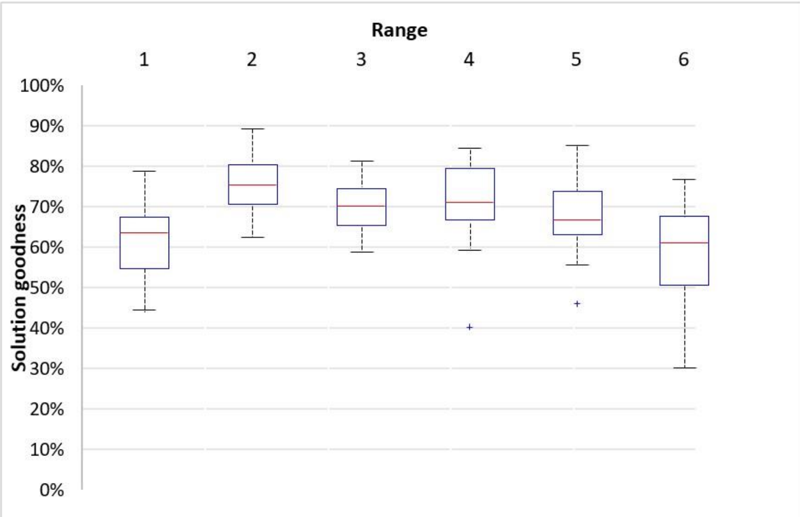

Figure 7. Performance over a range of parameter value, ε

The optimal parameter values for the GSA algorithm were selected and recorded in Table 3. In the end, since the algorithms run randomly, thirty independent executions were made for each scenario and averaged, the maximum values of the parameters were recorded as shown in Table 3.

Table 3. Values of proposed approach' parameters

Parameter	Value
Initial param, G_0	100
NO of mass agents, n	8
Constant param, α	20
Constant param, ε	0.01

DOI: 10.52465/joscex.v3i1.67

3.3. Computational result and discussion

The proposed approach was evaluated with some previous work such as a mixed-integer linear program MILP [18], NSGA-II [19], and simulated annealing [20]. Some of these clustering methods have been used for a set of targets with common features. In our case, the target is a set of points, so the concept of aggregation is not needed here. The parameters of these algorithms were set by [18]–[20].

All mentioned algorithms were re-implemented and tested for comparison on the same data set. Thirty independent implementations of the algorithms were carried out for each scenario separately, and in the end, the average score for all scenarios was calculated. The efficiency of the proposed approach and other algorithms was examined. We also note in Figure 8 the overall performance of the comparison algorithms in all scenarios in terms of the total number of strips observed in the same period.

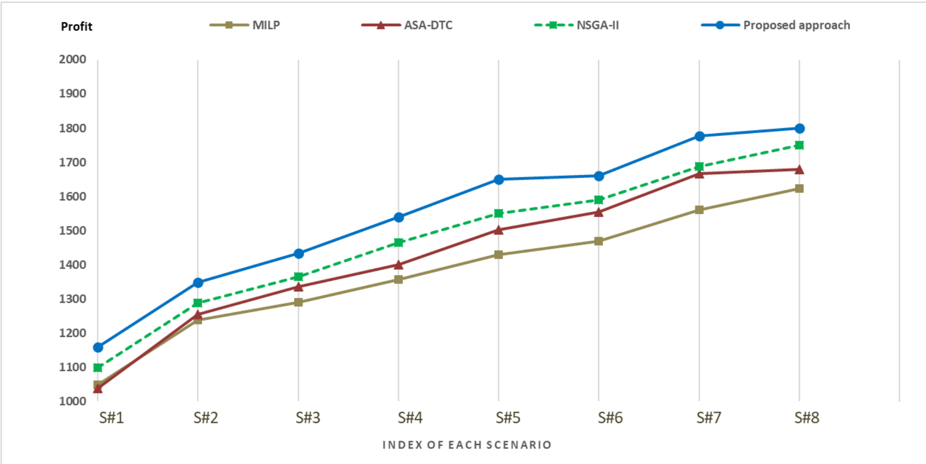

Figure 8. Comparison among different scheduling algorithms

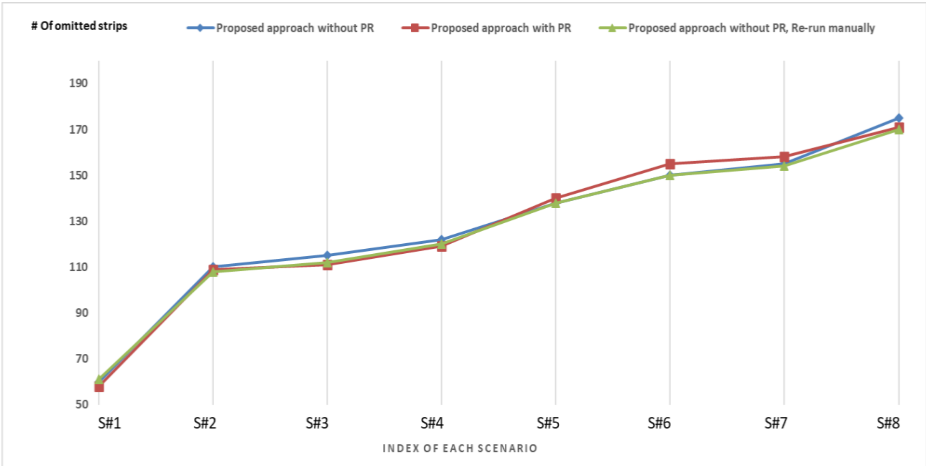

Figure 9. Performance influences of number strips omitted with, without PageRank priority, and manual targets removal

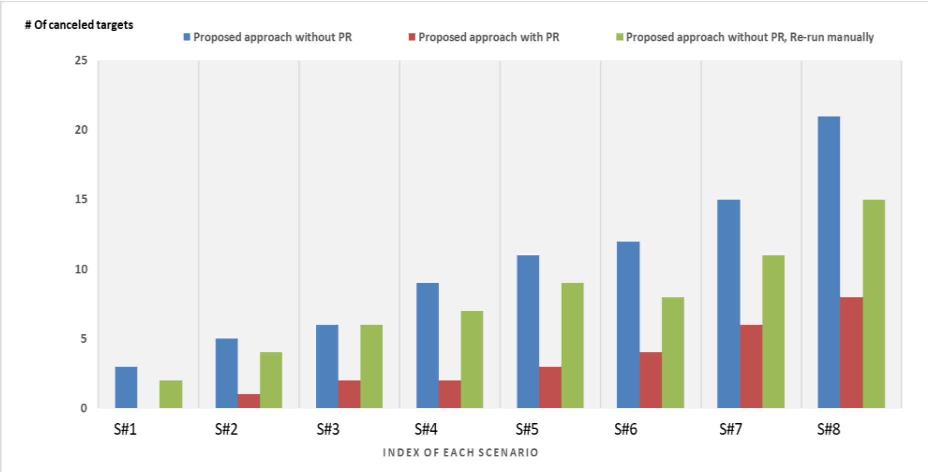

Figure 10. Performance influences of number of targets omitted with, without PageRank, and manually targets removal

Regarding the problem at hand, it was noted that the proposed approach is superior to other algorithms in all scenarios. Therefore, through this we can reach two vital conclusions: The first is that the proposed approach is a competitive approach to solving multi-satellite resource scheduling tasks. Another conclusion is to consider the priority algorithm for stripe observation based on the number of fewer observations as described in Section 3.2 using the PageRank technique which is a necessary issue. In this way, one of the most real things proposed was to enhance scheduling efficiency. On the other hand, Figure 9 shows the performance of the proposed approach, since the observation priority of potential strips based on fewer observations is maximized, either with or without the PageRank technique. We notice from Figure 9 that the number of discarded strips in all cases is approximately equal. But up to this point, we don't know which strip belongs to which target! So, we want to know the effect of those strips omitted on the targets. We can observe in Figure 10 the number of omitted targets when the priority algorithm is not considered. A target is not considered "observed" unless it achieves the required percentage of acceptance.

On the other hand, the targets that were omitted due to the incompleteness of the required percentage of them affected other targets by depriving them of further observation opportunities. So, we wanted to experiment if we neglected the priority algorithm, run the model and then neglected some targets (that didn't hit 50% shoot) that didn't succeed in completing it the first time and repeat the experiment to see if it would improve performance. As we can see from Figures 9 and 10, the amount of improvement is somehow little compared to the complexity of the algorithm.

In general, the pivotal points obtained from adopting the priority of a strip observation based on the number of opportunities of observations are: First, the gross profit increases for the goals. Second, it reduces conflict between observing targets. Third: Preventing the target from being omitted due to not completing the required percentage by observing the strips that may be lost firstly. Finally, satellite resources are used optimally and are not wasted.

On the other hand, we wanted to experiment if we consider the priority observation algorithm based on the lowest number of observations with all comparison algorithms. From Figure 11, note that the performance rate of all algorithms used in the comparison has been improved.

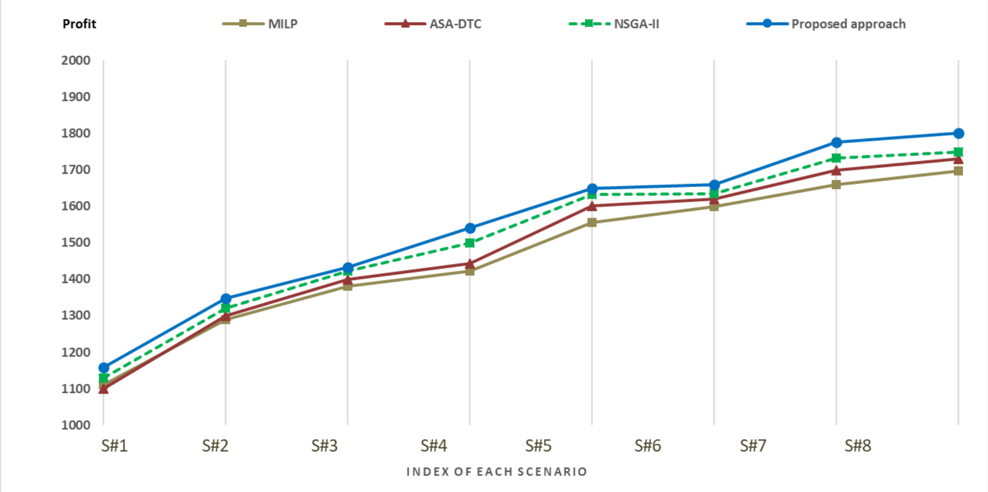

Figure 11. Comparison among different scheduling algorithms with PageRank priority

4. CONCLUSION

In this work, considering task priorities during the scheduling task relying on fewer observation occasions can enhance Earth observation scheduling effectiveness. The GSA algorithm was combined with PSO in a new form to solve the scheduling problem, after converting it into a multi-objective task with the execution of the NBI strategy. We have seen the positive impact of considering a reasonable priority rather than a random priority on the overall scheduling task. Even after combining their priority algorithm with comparison algorithms, their performance progressed significantly.

REFERENCES

[1] J. Frank, A. Jonsson, R. Morris, D. E. Smith, and P. Norvig, "Planning and scheduling for fleets of earth observing satellites," in *Int. Symp. Artif. Intell. Robot. Autom. Space*, 2001.

[2] A. Sarkheyli, B. G. Vaghei, and A. Bagheri, "New tabu search heuristic in scheduling earth observation satellites," in *2010 2nd Int. Conf. Softw. Technol. Eng.*, 2010, vol. 2, pp. V2-199.

[3] N. Bianchessi, J.-F. Cordeau, J. Desrosiers, G. Laporte, and V. Raymond, "A heuristic for the multi-satellite, multi-orbit and multi-user management of Earth observation satellites," *Eur. J. Oper. Res.*, vol. 177, no. 2, pp. 750–762, 2007.

[4] N. Zufferey, P. Amstutz, and P. Giaccari, "Graph colouring approaches for a satellite range scheduling problem," *J. Sched.*, vol. 11, no. 4, pp. 263–277, 2008.

[5] F. Marinelli, S. Nocella, F. Rossi, and S. Smriglio, "A Lagrangian heuristic for satellite range scheduling with resource constraints," *Comput. Oper. Res.*, vol. 38, no. 11, pp. 1572–1583, 2011.

[6] L. Barbulescu, A. E. Howe, J.-P. Watson, and L. D. Whitley, "Satellite range scheduling: A comparison of genetic, heuristic and local search," in *Int. Conf. Parallel Probl. Solving Nat.*, 2002, pp. 611–620.

[7] S. Baek *et al.*, "Development of a scheduling algorithm and GUI for autonomous satellite missions," *Acta Astronaut.*, vol. 68, no. 7–8, pp. 1396–1402, 2011.

[8] Y. Chen, D. Zhang, M. Zhou, and H. Zou, "Multi-satellite observation scheduling algorithm based on hybrid genetic particle swarm optimization," in *Adv. inf. technol. ind. appl.*, Springer, 2012, pp. 441–448.

[9] R. H. Saputra and B. Prasetyo, "Improve the accuracy of c4. 5 algorithm using particle swarm optimization (pso) feature selection and bagging technique in breast cancer diagnosis," *J. Soft Comput. Explor.*, vol. 1, no. 1, pp. 47–55, 2020.

[10] M. A. Mosa, A. S. Anwar, and A. Hamouda, "A survey of multiple types of text summarization with their satellite contents based on swarm intelligence optimization algorithms," *Knowl.-Based Syst.*, vol. 163, pp. 518–532, 2019.

[11] D. Thiruvady, C. Blum, and A. T. Ernst, "Maximising the net present value of project schedules using CMSA and parallel ACO," in *Int. Workshop Hybrid Metaheuristics*, 2019, pp. 16–30.

[12] I. A. Ashari, M. A. Muslim, and A. Alamsyah, “Comparison Performance of Genetic Algorithm and Ant Colony Optimization in Course Scheduling Optimizing,” *Sci. J. Inform.*, vol. 3, no. 2, pp. 149–158, 2016.
[13] K. bin Gao, G. H. Wu, and J. H. Zhu, “Multi-satellite observation scheduling based on a hybrid ant colony optimization,” in *Adv. Mater. Res.*, 2013, vol. 765, pp. 532–536.
[14] M. A. Mosa, “Real-time data text mining based on Gravitational Search Algorithm,” *Expert Syst. Appl.*, vol. 137, pp. 117–129, 2019.
[15] M. A. Mosa, “A novel hybrid particle swarm optimization and gravitational search algorithm for multi-objective optimization of text mining,” *Appl. Soft Comput.*, vol. 90, p. 106189, 2020.
[16] E. Rashedi, H. Nezamabadi-Pour, and S. Saryazdi, “GSA: a gravitational search algorithm,” *Inf. sci.*, vol. 179, no. 13, pp. 2232–2248, 2009.
[17] I. Das and J. E. Dennis, “Normal-boundary intersection: A new method for generating the Pareto surface in nonlinear multicriteria optimization problems,” *SIAM j. optim.*, vol. 8, no. 3, pp. 631–657, 1998.
[18] S. Augenstein, A. Estanislao, E. Guere, and S. Blaes, “Optimal scheduling of a constellation of earth-imaging satellites, for maximal data throughput and efficient human management,” in *Proc. Int. Conf. Autom. Plan. Sched.*, 2016, vol. 26, pp. 345–352.
[19] X. Shao, Z. Zhang, J. Wang, and D. Zhang, “NSGA-II-based multi-objective mission planning method for satellite formation system,” *J. Aerosp. Technol. Manag.*, vol. 8, pp. 451–458, 2016.
[20] G. Wu, H. Wang, W. Pedrycz, H. Li, and L. Wang, “Satellite observation scheduling with a novel adaptive simulated annealing algorithm and a dynamic task clustering strategy,” *Comput. Ind. Eng.*, vol. 113, pp. 576–588, 2017.