SPACE MISSION DEFINITION BASED ON ANALYTICAL HIERARCHY PROCESS (AHP) METHOD

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ABSTRACT

Generally, missions of remote sensing satellites are divided into three types: monitoring missions, recognition missions and surveillance missions. These missions need the Sun Synchronous Orbits (SSOs) or Multi-Sun Synchronous Orbits (MSSOs) in order to perform the operations. These SSOs and MSSOs have many requirements that make deciding the best type a multi-criteria decision problem. To this end, the Analytical Hierarchy Process (AHP) methodology is utilized to decide the orbit type in the remote sensing satellites missions. Therefore, the objective in the above methodology is to reach the orbit in the minimum amount of time and with the minimum cost (SSOs or MSSOs). The criterions are remote sensing missions, and the alternatives in the AHP methodology are the SSOs and MSSOs. In the conclusion, the results of methodology are presented and evaluated.

Keywords: AHP; space mission; remote sensing; SSO; MSSO

1. Introduction

The requirements of a planetary observation system are strictly related to the orbit design and, in particular, to its shape and inclination. The Periodic Sun Synchronous Orbits (PSSOs) are often considered the most suitable option with regards to the observation of the Earth, the ground resolution, the coverage (both in latitude and in longitude), the repetition of observation, and the same condition of solar illumination, (Ortore et al., 2012). In fact, these orbits allow observation of a given region of the planet at regular time intervals (periodic orbits) with approximately the same solar illumination conditions (Sun-Synchronism). Unlike the strict Sun Synchronous Orbits (SSOs), which are characterized by a typical relationship between orbit altitude and inclination and that can be modified using solar sail systems, the introduction of the periodicity (repetition of observation) limits the possible altitudes to a finite number (represented by the points belonging to the previously mentioned altitude–inclination curve) (Bolle & Circi, 2011). The choice of the solution results was developed from a compromise among the several requirements since it is not possible to have the best solution for all of them (e.g. the coverage and the repetition of observation are in contrast) (Ortore et al., 2012).

The Multi-Sun Synchronous Orbits (MSSOs), which the classical PSSOs are a particular solution of, represent an important alternative to the use of the PSSOs. The MSSOs form a general category of orbits that are characterized by two periodicity conditions. The first

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condition is related to the observation of a given area (periodic orbit), and the second one refers to the solar illumination which repeats itself at regular time intervals (Multi-Sun Synchronism).

The two periodicities are properly linked so as to obtain cycles of observation of the same area in which the solar illumination gradually varies along with the choice of the orbit elements. It returns to the initial condition after a number of nodal days which is a multiple of the revisit time. A significant advantage of the MSSOs lies in the great flexibility of choice of the orbit inclination concerning the SSOs that are retrograde and usually quasi-polar. For that matter a limitation of the exploitable launching sites is determined. (Ulivieri & Anselmo, 1991).

The critical factors for decision making (criteria/sub-criteria) are as follows:

1. Remote sensing satellites (Capderou M. 2005; Larson Wily J. et. al. 1999; Fortescue P. et. al. 2011; Griffin M. D. et. al. 1991): one of the most important key parameters in the space mission definition is orbital parameters (e.g. orbital inclination, eccentricity, argument of perigee, ascending node, etc.). The orbital parameters are strongly affected by performance of sub-systems in remote sensing satellites (Larson Wily J. et. al. 1999). Hence, sub-criteria of remote sensing satellites are technology complexity, power supply subsystem, thermal control subsystem, remote sensing payload (camera), number and location of ground segment, satellite operation and satellite security.

2. Mission application: there are many applications from the remote sensing satellites, but the most important applications are environment and resources management, target surveillance, change detection, cartography, and meteorological missions (Larson Wily J. et. al. 1999; Fortescue P. et. al. 2011). Furthermore, these sub-criterions are influenced from the orbital specifications (Capderou M. 2005). Hence, sub-criterion of level two related to the orbit type are revisit time, local time of imaging in the each day, sensor calibration, overlap criteria, and regional coverage.

Recently, some research has focused on the application of the Analytic Hierarchy Process (AHP) methodology. For example, the selection of scholarship recipients has been studied. This research involves the analysis of multi-criteria decision making by prioritizing which criterion was the most important for the student selection process (Kim et. al., 2017). The scholarship distribution process for the students was conducted by the selection team as the expert and with the scholarship budget which has been determined by Universal University. Furthermore, the AHP process is executed and implemented in detail in a way that can show the AHP procedure and the methodology expressions (Taherdoost, 2017). The AHP has gained increasing attention in the construction management (CM) domain as a technique to analyze complex situations and make sound decisions (Darko A. et. al., 2018). Also, it is performed as the combination of insights from a scientometric mapping technique and social network analysis (SNA) to study collaboration networks. Scientometric mapping technique overlay mapping was applied to obtain a cognitive map of the AHP field, and SNA was used to study co-authorship networks (Emrouznejad et. al., 2016). Classical AHP was extended by use of the D-AHP to model various types of uncertainty, and represents an extension of the Dempster–Shafer theory (Deng et al., 2014; Fan et al., 2016). The D-AHP allows determination of the weights of the alternatives and has proved effective in addressing supplier selection

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problems, to represent the decision matrix of pairwise comparisons given by experts and to deal with problems of grouting efficiency evaluation (Deng et al., 2014; Fan et al., 2016).This branch of the literature includes a group of works combining insights from DEA with AHP (DEAHP) and in some cases with FAHP (Ramanathan, 2006; Che, Wang, & Chuang, 2010). Following Ramanathan (2006), Sevkli et al. (2007) apply this hybrid approach to a real industry case and show that DEAHP outperforms the AHP method for supplier selection. On another hand, this paper has been criticized by Wang, Chin, and Leung (2009) and shows the weaknesses of the DEAHP.

There has been some known effort functions mentioned in the literature. In the study, in order to look for a suitable effort function for the allocating purpose, we first made a comparison among them. As a result of the lack of data for creating the parameters, an effort function cannot always be depended on. The AHP was considered as a possible method to compensate for this deficiency. A common example used in the literature was also illustrated for an elementary test and verification. To accomplish the mission definition procedure, a revised effort minimization method was used for an integral calculation (Naseh, 2011).

2. The AHP – step by step

The AHP is based on the experience gained by its developer, T. L. Saaty (1980), while directing research projects in the U.S. Arms Control and Disarmament Agency. It was developed as a reaction to the finding that there is a miserable lack of common, easily understood and easy-to-implement methodologies to enable complex decisions to be made. Since then, the simplicity and power of the AHP has led to its widespread use across multiple domains in every part of the world. The AHP has been used in business, government, social studies, R & D, defense and other domains involving decisions in which choice, prioritization or forecasting is needed.

The AHP provides a means of decomposing the problem into a hierarchy of sub problems which can more easily be comprehended and subjectively evaluated. The subjective evaluations are converted into numerical values and processed to rank each alternative on a numerical scale. The methodology of the AHP can be explained in the following steps:

Step 1: The problem is decomposed into a hierarchy of goal, criteria, sub-criteria and alternatives. This is the most creative and important part of decision-making. Structuring the decision problem as a hierarchy is fundamental to the process of AHP. A hierarchy indicates a relationship between elements of one level with those of the level immediately below. Figure 1 shows a generic hierarchic structure. At the root of the hierarchy is the goal or objective of the problem being studied and analyzed.

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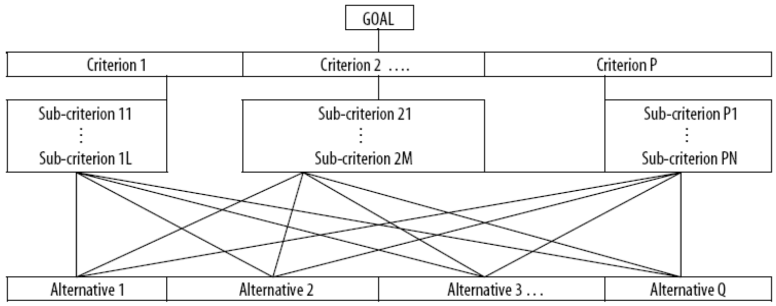

Figure 1 Generic hierarchic structure

Step 2: Data are collected from experts or decision-makers corresponding to the hierarchic structure in the pairwise comparison of alternatives on a qualitative scale as described below. Experts can rate the comparison as equal, marginally strong, strong, very strong, and extremely strong. The opinion can be collected in a specially designed format as shown in Figure 2.

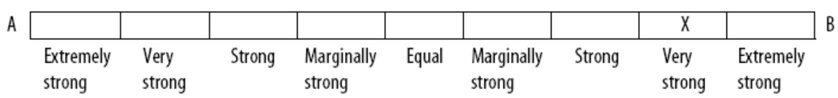

Figure 2 Format for pair wise comparisons

Step 3: The pairwise comparisons of various criteria generated in step 2 are organized into a square matrix. The diagonal elements of the matrix equal 1. The criterion in the i^{th} row is better than the criterion in the j^{th} column if the value of the element (i, j) is more than 1; otherwise, the criterion in the j^{th} column is better than that in the i^{th} row. The (j, i) element of the matrix is the reciprocal of the (i, j) element.

Step 4: The principal eigenvalue and the corresponding normalized right eigenvector of the comparison matrix give the relative importance of the various criteria being compared. The elements of the normalized eigenvector are termed weights with respect to the criteria or sub-criteria and ratings with respect to the alternatives.

Step 5: The consistency of the matrix of order n is evaluated. Comparisons made by this method are subjective and the AHP tolerates inconsistency through the amount of redundancy in the approach. If this consistency index fails to reach a required level, then answers to comparisons may be re-examined. The consistency index, CI, is calculated as shown in Equation 1.

$$C.I. = \frac{\lambda_{MAX} - n}{n - 1} \tag{1}$$

Where $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix. This CI can be compared with that of a random matrix, RI. The ratio derived, CI/RI, is termed the consistency ratio (CR). Saaty suggests the value of CR should be less than 0.1.

Step 6: The rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings with respect to each criterion. The local ratings are then multiplied by the weights of the criteria and aggregated to get global ratings. The AHP produces weight values for each alternative based on the judged importance of one alternative over another with respect to a common criterion.

3. AHP applied to the decision making problem

In this section, we applied AHP as a systematic approach to develop a decision making method for determining the favorite alternative (sun synchronous prioritization) and requirements to meet in space mission design. The schematic of AHP applied to the decision making problem is shown in the Figure 3. Figure 3 shows the objective function in level 1, the decision making criterion in level 2, and the alternative of the problem in level 3. In this case, the alternatives are repeated with each application sub-criteria. Next, the criteria and sub-criteria for our decision making model will be introduced. See the Appendix for the decision model definitions.

The remote sensing satellite is influenced from the technology complexity (Figure 4), thermal control subsystem (Figure 5), power supply subsystem (Figure 6), payload as an active or passive sensor (Figure 7), number and location of the ground segment (Figure 8), and satellite operation (Figure 9).

The second level of sub-criterion in remote sensing application includes revisit time (Figure 10), local time (Figure 9), sensor calibration (Figure 11), overlap criteria (Figure 9), and regional coverage (Figures 9 and 12).

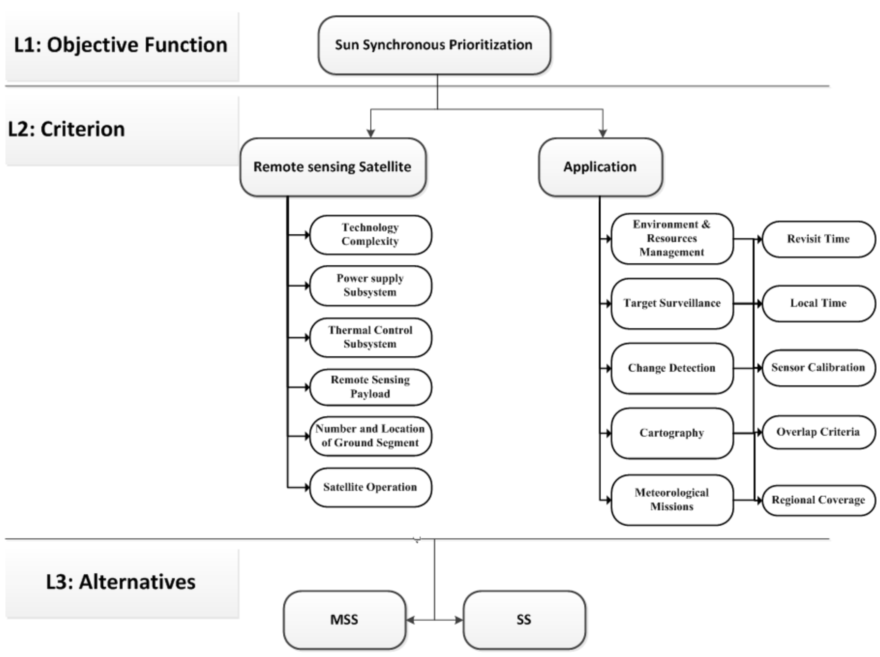

Figure 3 Schematic of AHP modeling applied to the decision making problem

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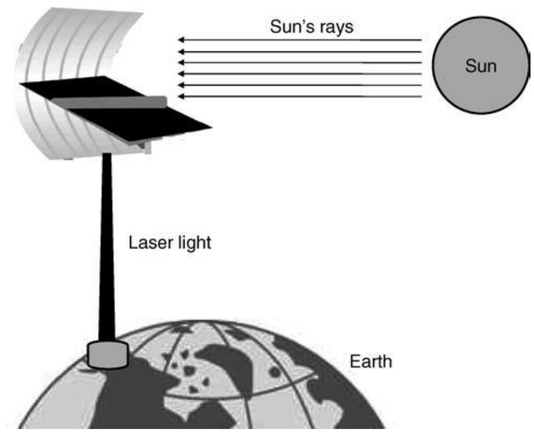

Figure 4 Space based laser concept (technology complexity) of JAXA and Osaka University (Maini A. K. et. al., 2011)

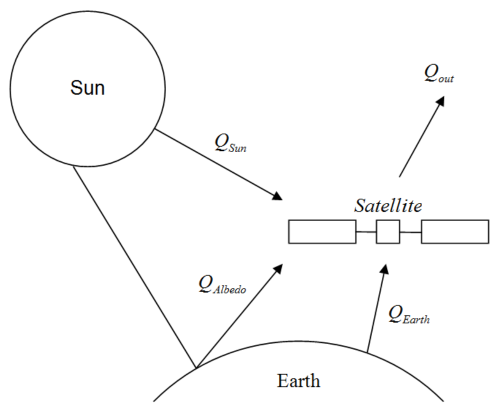

Figure 5 Thermal control subsystem and types of received energy (Maini A. K. et. al., 2011)

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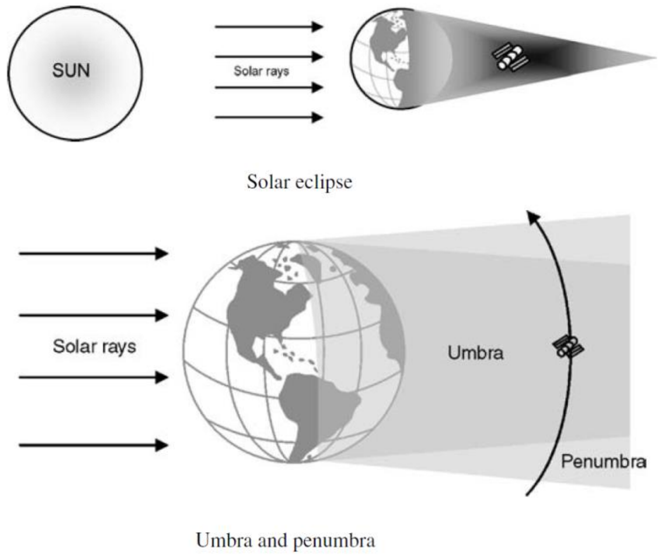

Figure 6 Power supply subsystem performance in eclipse (Maini A. K. et. al., 2011)

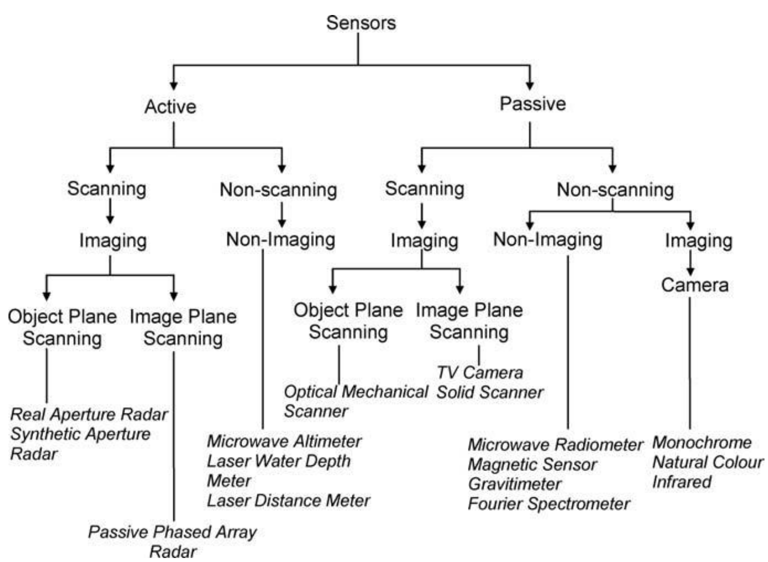

Figure 7 Payload (type of sensors) (Maini A. K. et. al., 2011)

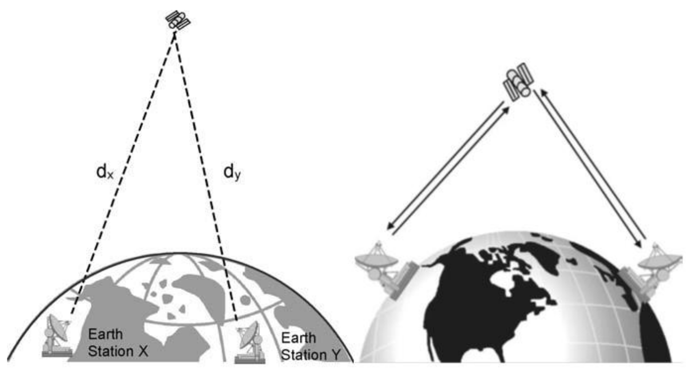

Figure 8 Number and location of ground segment (Maini A. K. et. al., 2011)

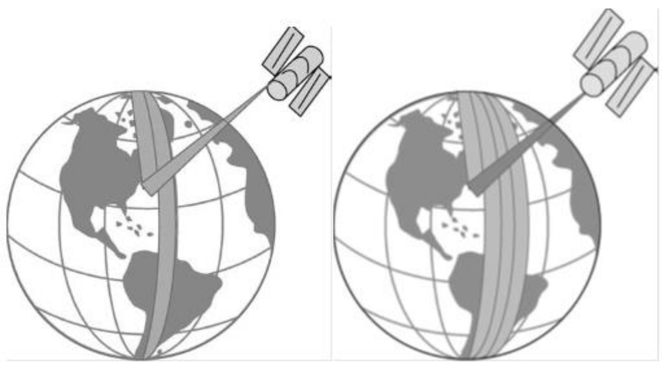

Figure 9 Earth observation and coverage (Maini A. K. et. al., 2011)

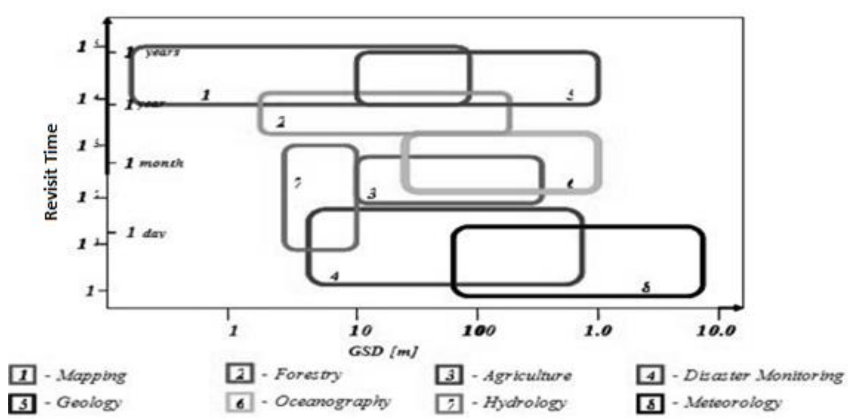

Figure 10 Revisit time versus Ground Sampling Distance or GSD (Naseh H. et. al., 2016)

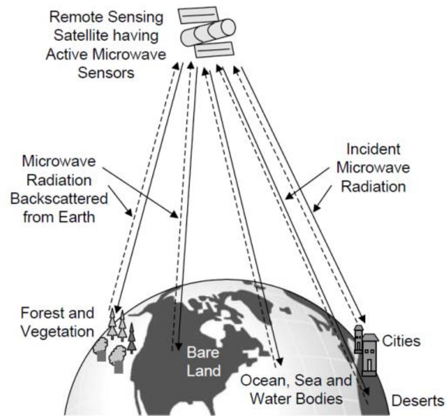

Figure 11 Active sensor calibrations (Maini A. K. et. al., 2011)

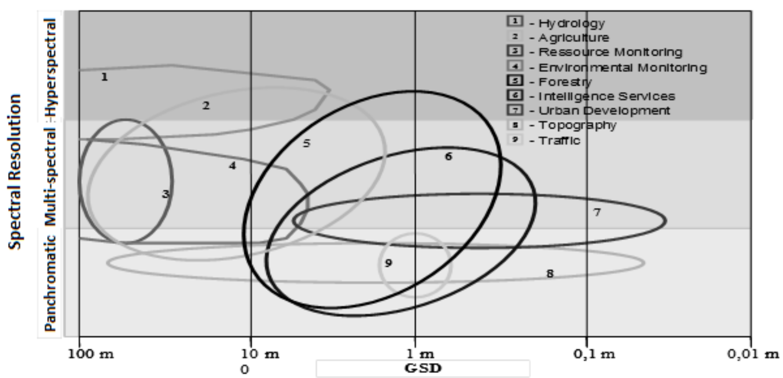

Figure 12 Spectral resolution versus ground sampling distance or GSD (Naseh H. et. al., 2016)

The alternative capability with respect to the criterion is listed in Table 1. Thus, the pairwise comparison matrix of criterion on a qualitative scale is obtained based on expert knowledge and system configuration. In this decision making problem the knowledge of ten experts with more than 10 years related academic experience was utilized and the average achieved scores were used. Next, it was determined that the AHP analysis was achieved between the acceptable ranges of inconsistency. To this end, the pairwise comparison matrix of alternatives is presented in Table 2. The decision making problem model in the Expert Choice software is presented in the Figure 13, and samples of pairwise comparison tables are shown in the Figure 14.

Table 1
Alternative capability with respect to the criterion

row	Criteria	SS	PMSS
1	Commercial Applications	Very Good	Good
2	Region Coverage	Global	Local
3	Revisit Time	Lower	Higher
4	Revisit Time in specific local time	Periodic	Non Periodic
5	Upper stage	Required	No required
6	Ground Segment for guidance, Navigation and Control	Variety	limited
7	Satellite Design Complexity	No complexity	Complexity in Power Supply and Thermal Control
8	Monitoring, Recognition and Surveillance	Suitable	Non suitable

Table 2
Pair wise comparison matrix of criterion on a qualitative scale

Row	Commercial Application	Region Coverage	Revisit Time	Revisit Time in specific local time	Ground Segment for guidance, Navigation and Control	Satellite Design Complexity	Monitoring, Recognition and Surveillance
Commercial Application	0.2	0.2	0.2	0.2	1	0.2	0.14
Region Coverage	0.2	0.2	0.14	5	5	0.2	0.14
Revisit Time	0.2	0.2	0.14	0.2	5	5	0.14
Revisit Time in specific local time	0.2	0.2	0.2	1	5	5	0.14
Ground Segment for guidance, Navigation and Control	1	0.2	0.2	0.2	0.2	0.2	0.14
Satellite Design Complexity	7	7	7	7	7	7	1
Monitoring, Recognition and Surveillance	5	0.14	0.14	0.2	5	1	0.14

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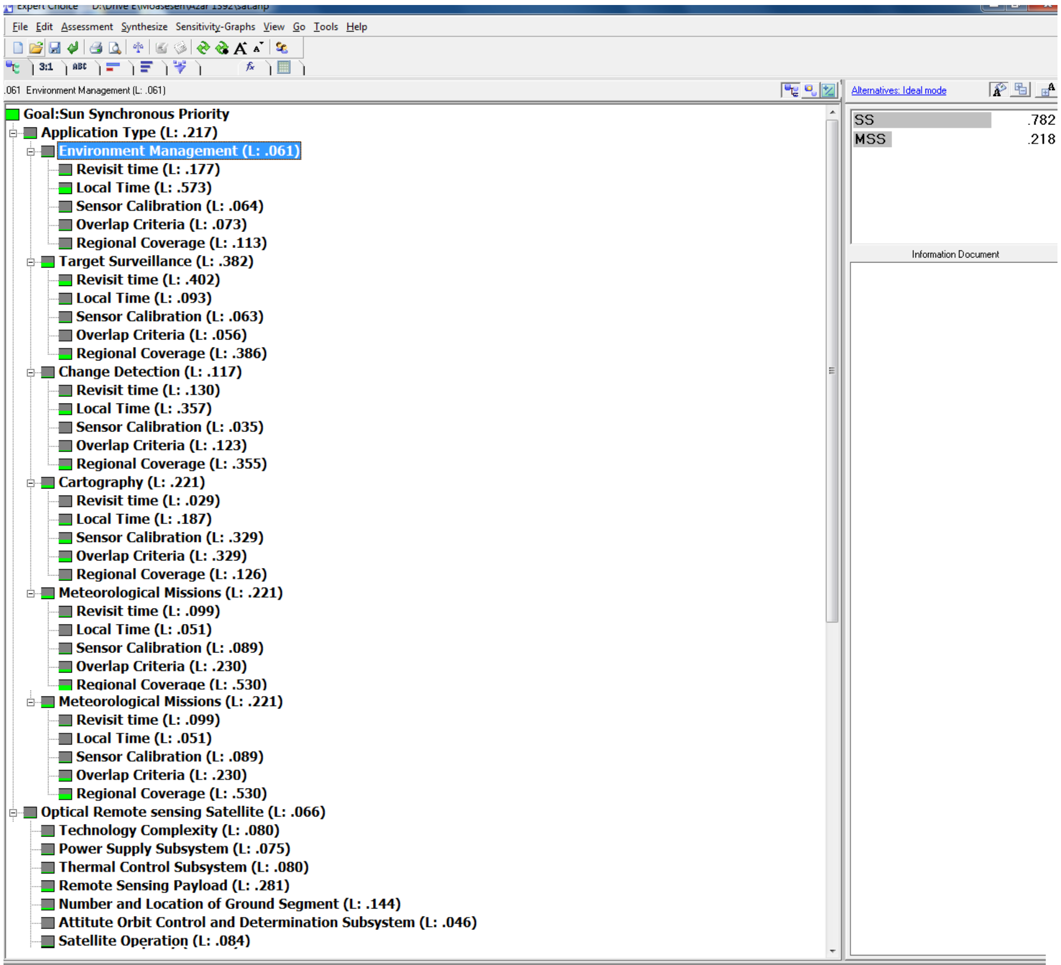

Figure 13 Decision making problem model in the Expert choice software

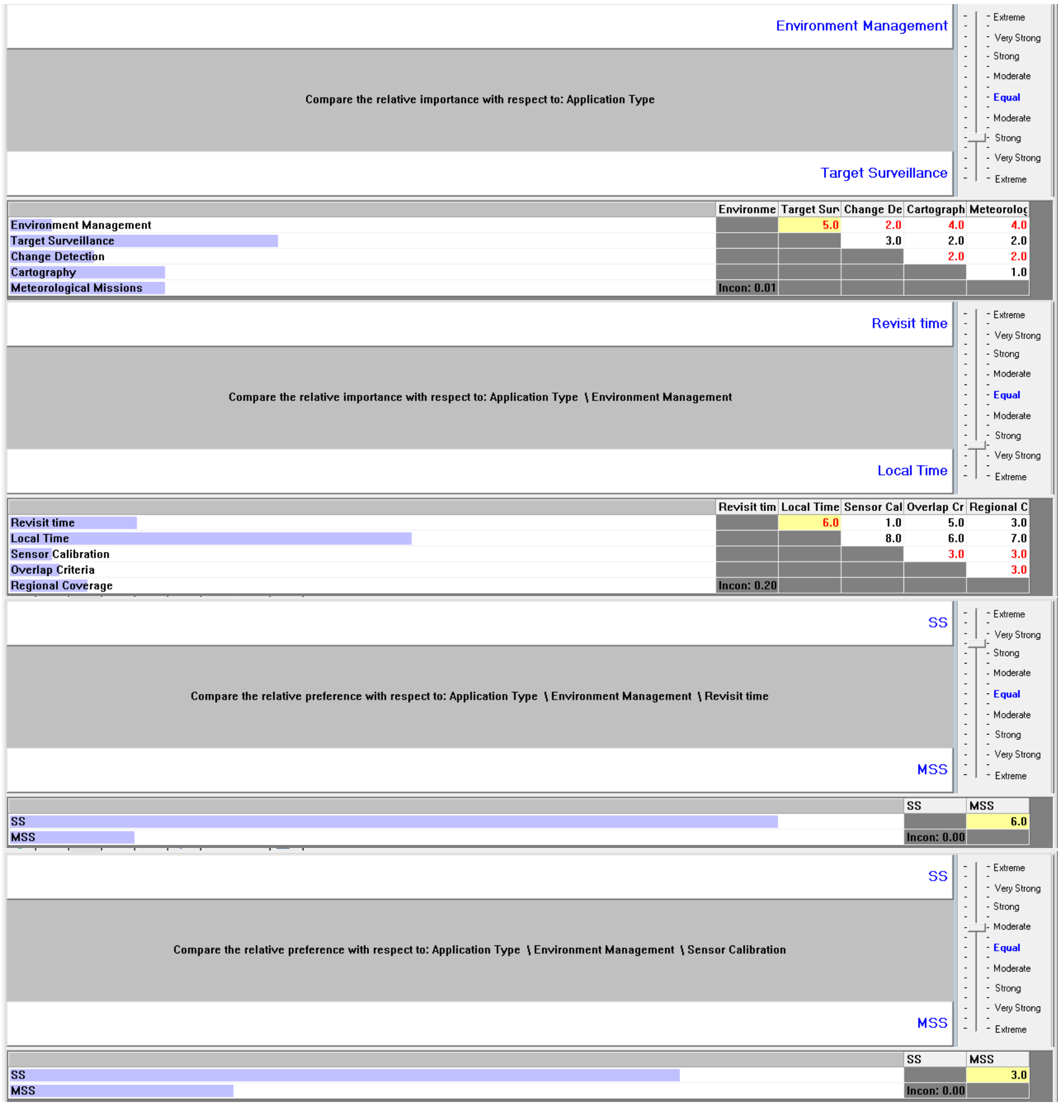

Figure 14 Samples of pairwise comparison tables

4. Result presentation and validation

The application of the AHP to the decision problem was presented in the previous section, and this section presents the results of the decision making process. The methodology is modeled in the Expert Choice software. The results are shown in Figures 15 to 22 from any criteria aspect that was presented in the Figure 3.

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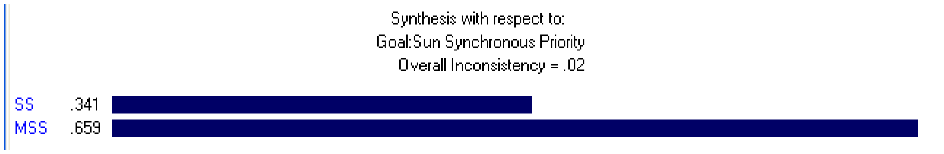

Figure 15 Sun synchronous orbit prioritization (overall in space missions)

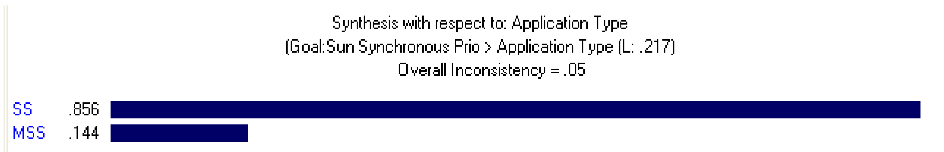

Figure 16 Sun synchronous orbit prioritization (from application type criteria aspect)

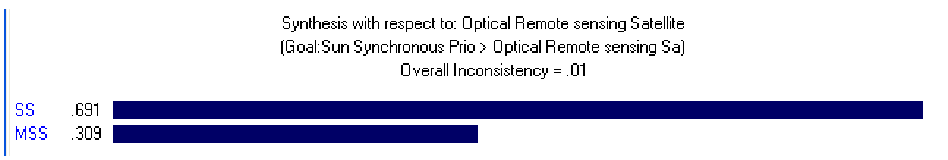

Figure 17 Sun synchronous orbit prioritization (from optical remote sensing criteria aspect)

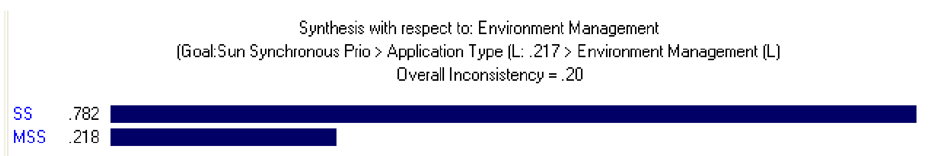

Figure 18 Sun synchronous orbit prioritization (from environment management criteria aspect)

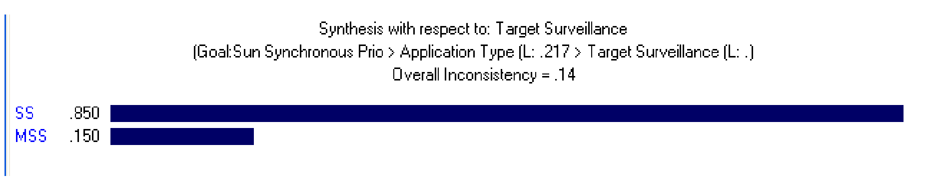

Figure 19 Sun synchronous orbit prioritization (from target surveillance criteria aspect)

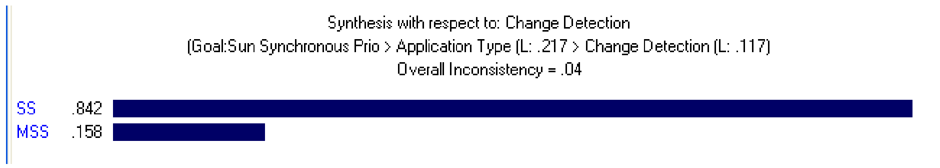

Figure 20 Sun synchronous orbit prioritization (from change detection criteria aspect)

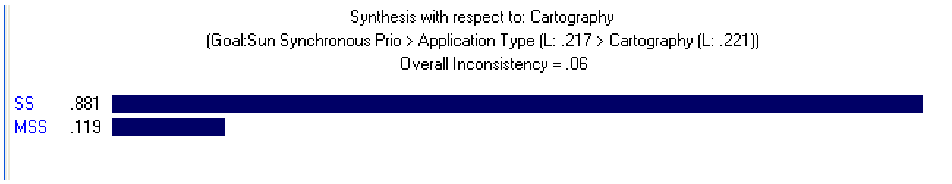

Figure 21 Sun synchronous orbit prioritization (from cartography criteria aspect)

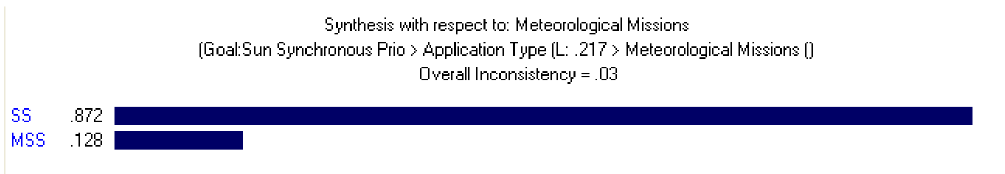

Figure 22 Sun synchronous orbit prioritization (from meteorological criteria aspect)

5. Conclusions

In this paper, an application of AHP for space mission definitions (from orbit and application aspects) is presented. The schematic of AHP applied to the decision making problem is shown in Figure 3. Based on this and Table 2, which shows the pairwise comparison matrix of criterion on a qualitative scale, the methodology was implemented and the results are shown in Figures 15 to 22 (using Expert Choice software). The figures 15 to 22 show that SS and MSS orbits each have a higher priority for the various missions. For example, Figures 16, 17, 18 and 19 illustrate that SS orbits have higher priority for the application type, optical remote sensing, environment management and target surveillance, respectively. Furthermore, Figure 15 shows the higher priority of the MSS orbits in the overall decision making (overall aspects) with the AHP's objective (when time and cost affect the mission analysis). The methodology verification is performed based on the overall inconsistency in the results (Figures 15 to 22) which is lower than 0.2. Finally, SSO in the meteorological missions has the most priority in the applications.

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APPENDIX

Decision model definitions

Remote sensing satellites: The satellites are used for performing three types of space missions: monitoring missions, recognition missions and surveillance missions.

Technology complexity: Remote sensing satellites have a variety of technologies in payloads, such as high resolution optical camera, Synthetic Aperture Radar (SAR), laser optic imaging and etc.

Power supply subsystem: The power supply subsystem has a very important role in the decision making because the remote sensing satellite will not be able to perform any mission without power.

Thermal control subsystem: The thermal control subsystem has a very important role in the remote sensing satellite because the performance of payload in the remote sensing satellite is influenced by the temperature and the thermal control subsystem and must provide a suitable range of temperature.

Remote sensing payload: There are a variety of remote sensing payloads in the space mission that can be selected based on the needs. For example, the SAR payload selected for the remote sensing mission independent of local time (every time can be imaging from the earth) and optical camera selected for the remote sensing mission depending on local time (the earth imaging just performed in the day, not night).

Number and location of ground segment: the number and location of the ground segment is very important for communication aspects. Communication approaches can be selected online or in the store and used in the remote sensing satellite. In the store and forward must be considered the hardware limitations for saving data.

satellite operation, the type of scenarios for covering the earth for decision making regarding the overlap/without overlap of imaging in each repeat.

Application: There are various types of applications in the remote sensing satellite that will be able to service humans. These applications are environment and resources management, target surveillance, change detection, cartography, and meteorological missions. Furthermore, these applications are selected based on human needs.

Revisit time: The revisit time is the elapsed time between the first and second tracking from the target region.

Local time: The local time is used for optical imaging.

Sensor calibration: Sensor calibration is used for clearing the ephemerids drifts.

Overlap criteria: The overlap criteria is important for repeat ground tracking.

Regional coverage: The SSO can be earth global coverage, and MSS can be regional coverage.

Sun Synchronous (SS): These orbits allow the observation of a given region of the planet at regular time intervals (periodic orbits) with approximately the same solar illumination conditions (Sun-Synchronism).

Multi-Sun Synchronous (MSS): The MSS orbits form a general category of orbits that are characterized by two periodicity conditions. The first condition is related to the observation of a given area (periodic orbit), and the second refers to the solar illumination, which repeats itself at regular time intervals (Multi-Sun Synchronism).