Formulization of Cost Estimation in Optimizing Constellation Satellite, Launch Vehicle and Launch Place

By Saeid Kohani [1)] and Peng Zong [2)]
[1)] *Ph.D. candidate, Nanjing University of Aeronautics and Astronautics, Astronautics College, Nanjing, JiangSu, 210016, China*
saeid.kohani@nuaa.edu.cn
[2)] *Professor, Nanjing University of Aeronautics and Astronautics, Astronautics College, Nanjing, JiangSu, 210016, China*
pengzong@nuaa.edu.cn

Abstract

Along with developing of space enterprise, more and more satellites are deployed in a style of constellations which are able to provide efficient application coverage. However, to construct a constellation is still a big cost due to main facts of launching satellite to the orbit. The methodology of launching satellite will seriously influence the system cost. Therefore, it needs a better tool for analyzing and evaluating design of the constellation architectures. and estimating the launching cost The design will be integration of heterogeneous, or multi-orbit, multi-purpose and multifaceted. In the new achievement, a series of constellation satellites are thrown precisely and successfully onto the orbit. Simultaneously, an orbit optimal problem is solved by the numerical binary linear function. The degree of precision is achieved by fully utilizing the capacity of each launcher. Formulations are divided into three different mission areas: Navigation, weather, military. For climate missions, formulation is determined by multifunction and multi-orbit designs. This algorithm has been successfully proved by simulation of 12 satellites in four different orbits with four launchers and placing heterogeneous satellites in the same orbits. For the missions of high precision navigation, it has been proved that 12 variables of configuration, mass and homogeneous orbit are optimized individually. For military mission, the two previous optimizations can be merged to reduce the cost extremely.

Key Words: Satellite, LEO, Launch vehicle, Navigation, Constellation.

1. Introduction

The selection of launch vehicle to deploy satellite constellation significantly influences the cost and mission performance. The cost mostly depends on type of launch vehicle and launching site. As a precise constellation, it is necessary to consider the cost optimization (Shelton, W. L. 2013)[21]. The existing optimizations are still insufficient in operation of constellation in separated orbits. Satellite constellation can be specified as follows: mission and function, or platforms of multiple systems in one or more orbital planes. A key issue of determining the total life of distinct constellations is the cost associations Currently there is no specific method to integrate the constellations design of using different Launchers to put satellites on different orbital planes.

This study intends to minimize the total cost of launching satellite into a constellation in a formulary way. A binary linear function is used to determine an optimal matrix for matching launch vehicle and heterogeneous satellite in constellations from launch place to the orbit. In some cases, binary linear function can produce a numerical solution as optimal result.

The utility of distinct achievements is to find general solutions for complex scientific problems. However, the objective function has a weak point because all restrictions and variables must be linear, in fact that they are in nonlinear form. To compensate this problem, we use a linearization method to transform the equations from nonlinear into linear by preserving the principle relationships in design.

Additionally, constellations are optimized to increase coverage both for academic and political or military purposes. With these input parameters, it allows researchers, launcher makers and satellite designers to develop the project based on a comprehensive considerations.

The main contents are organized as following: The second part will highlight key techniques related to selection of launcher, orbit design and constellation design, that will be taken into account in the optimization. In the third part, formulation will be introduced based on the important decision variables, constraints, target function and sensitive parameters. Also, the computational complexity and architecture of the algorithm are discussed for formulation implementation. In the fourth part, modeling of design algorithm is programmed and evaluated in two stages of simulation, the precise software is developed on distinct constellations in previous research. The fifth part is conclusion that proposed new research areas in the future, it investigates and discovers possible target functions for updating various cost models as well as application software.

2. Literature Review

A. Division and parsing

There are five examples of decomposition methods (U.S. Air Force Space Command, 2013)[25].

1) Classification,
2) Hosted Payloads
3) Functional analysis
4) Multi-orbit decomposition
5) Multi-Domain Parsing.

Classification indicates that networking satellites provide coordination functions to the subsystem or sub-network. For example, constellation satellites work as network nodes to store and transmit data. Hosted Payloads imply commercial satellites transmitting data from one country to another. Benefits of hosted payloads are hostile to being classification. Function analysis divides satellite into smaller subset similar as classification. For example, instead of using a large satellite with weather sensors and remote sensors, a few small satellites are arrayed in the constellation, each satellite has a specific sensor.

Multi-orbital constellation has capabilities of fully completing the mission. An example of multi-orbital constellation is Walker, in which satellites are arrayed in multi-layer orbits. To cover the whole earth, we need separating orbit layers in different degrees of latitude, despite the difference in RAAN and ascending node. Global Positioning System (GPS) is a true decomposed example of a multi-orbital constellation.

Multi-domain parsing is a last sort of decomposition method, from space or non-space facilities, such as at land and in air. This type of segmentation is the presentation of image processing and communication. In this method air systems can be used to carry out the missions like aerial imagery based on the advanced and integrated networks. Paradise and Homogeneous are two types of constellations for regional satellites, which have capabilities to share information between spacecraft and heterogeneous satellites using an integrated network (The Boeing Company Space Division Launch Systems Branch, 1968.)[22].

Separated constellations have many advantages. The first and foremost one is the low cost for launching. Although, launching a separate constellation may require more launchers, cheaper launcher can be used for lower-altitude orbits (Miller, D. E. et al. 2001)[16]. The second advantage is that separated constellations have more flexibility. The third advantage is that the function of constellation can be upgraded with new technologies and more advanced capabilities of satellites (Cortright, Edgar M. 1975)[6].

B. The capabilities of the launcher

Most launch vehicles used to be the military rockets and continue to make commercial contribution. Evolved expendable launch vehicle (EELV) is from Delta and Atlas families and considered as "heavy lift" launch vehicles. The Atlas V can launch over 5000 kg payload to Low Equatorial Orbit (LEO) and Delta IV can launch over 7000 kg payload to geosynchronous equatorial orbit (GEO) (Vandenberg Air Force Base, March 2013)[26]. The best famous up-to-date commercial launcher could be Falcon 9, developed and enhanced by SpaceX, which has can launch over 10,000 kg payload to LEO. Another famous launch vehicle systems are Antares, Minotaur and Athena, which are small and medium size launch vehicles. The lifting capacities of them are between 582 and 4800 kg. In general, their reliabilities are estimated between 71% (Antares) and 98% (Delta II) (Kyle, E., 2014)[15].

Although small and medium-sized vehicles are less expensive, large vehicles have better reliability. In a commercial matter, launching cost is very high, most countries do not own launch vehicle but use other country’s, especially for launching the GEO satellite. Usually the price of launch vehicles in some countries, excluding Western and American, is half of EELV price (Futron Corporation, 2002)[8]. If we divide the metric costs of launching vehicle into the mass of render payloads, then it is concluded that the low cost is the main advantage of small launch vehicles for LEO satellite (Godfey, R. et al. 1970)[9].

Given the cost restriction, the important thing is to design or select the launch vehicle. A research company after studied NASA's plans (Sarsfield, L. 1998)[20] of launch small satellites, found that the cost of launch vehicle was equal to 21 percent of the satellite cost. Also, due to decrease of satellite mass, the cost of dedicated launch vehicle in entire lifecycle is increased (Rumsfeld, Donald. 2011)[19]. So we need some methods to optimize selection of launch vehicle, which can minimize startup costs.

C. Constellation Design

Reliability improvement and cost minimization are important issues of a constellation design. The launch vehicle is one of the main optimal components. Several factors in the overall design of constellation have great impact on selection of the launch vehicle. These factors include orbit altitude, inclinations, number of satellites per plane, mass of satellite, availability of launch vehicle, and total cost (Budianto et al. 2004)[2]. And most importantly, launch vehicle has a huge impact on the overall cost of the project.

More and more researchers have tried to bring the launch factors into constellation design (Chaikin, A. 2016)[4]. To determine the capacity of launch vehicle, Numerical Optimization Programming was carried out by Olds and Budianto (Budianto et al. 2004). According to the data of the previous launchers, the cost of launch vehicle has a constant value, and is independent of orbit, launch site and launching mass. One of the disadvantages in designing Walker constellations is that only homogeneous satellites were considered and not including the constraints.

A hybrid method "multi-objective and multi-disciplinary design optimization systems architecting (MMDOSA)" has been introduced by Jilla to the missions of Planets discovery, Earth observation and communications (Morris, D. Z. 2017)[17]. This new approach evaluates various orbital configurations and homogeneous satellites in optimization of constellation design.

Thompson and colleagues designed and optimized the constellations using a separated multi-orbit and multi-function approach (Thompson, R. et al. 2015)[23]. The method is applied for the weather mission (Thompson, R. et al. 2015)[24]. It benefited from the cost saving of launching LEO satellite in the medium lifting capacity, and is recorded in Space Mission Analysis and Design (Wang, B. 2016)[28].

In fact, apart from orbit and satellite design, selecting a launch vehicle is allowed to design apart from the entire constellation system. When launch vehicle is performed as part of the constellation design, the launch vehicle optimization is done in a duplicate process or calculation as a basic design of the Constellation. In the next part, four practical applications are introduced to optimize the selection of launch vehicle.

D. Optimization of selecting launcher

Firstly filtering method is used to select launch vehicle for a satellite. This method uses the appropriate curve technique to determine the lifting weight of each launch vehicle. Parameters of the international launch vehicle include inclination, optimal reliability, site of launch, orbit, mass of payload and diameter of payload (Kim, M. J. 2017)[14].

Secondly filtering technique is applied to test 14 constraint parameters, on the basis of 14 parameters launch vehicles are selected and recorded step by step. These parameters are: diameter, acceleration limits, launch frequency, possible errors, inclination and mass. (how can be 14?)

When an appropriate vehicle is selected, its parameters will be input a program running optimized target function. Important optimization parameters are: maximum availability, maximum performance, minimum cost, minimum risk and multipurpose function between reliability and vehicle cost (Kim, M. J. 2017).

Both filtering methods are only applicable for one satellite, so they are insufficient for separation or multi-satellite designs. A utility called launch vehicle selection is an independent way to optimize the selection of launch vehicle.

Those design optimizations are considered in formularization of system capability and numerical program for locating the optimization stage in the whole procedure. In the numerical approach, there are some limitations, 1) the restriction of launch vehicle for each satellite, 2) the orbital constraints for launch vehicle that is put on the minimum number of orbit planes, 3) the political constraints, supposed political restrictions in the world is the foreign quota for launch vehicle owned by different countries, 4) availability of limited number and types of launch vehicles (Morris, D. Z. 2017).

In the application of choosing launch vehicle software, objective functions and special parameters are formulated. Jilla used 14 special parameters to check the commercial value between reliability and launch vehicle costs (Morris, D. Z. 2017). Jila method is only applicable to the constellations of homogeneous satellites (Morris, D. Z. 2017). In the mission design, number of launch vehicles are analyzed to be suitable for different mass and size of the satellites. Calculations can be made of launcher and satellite optimizations without taking into account of orbital constraints.

On the other hand, the method of selecting launch vehicle does not consider the capacity of each launch vehicle, which depends on the orbital height and launch site. As an achievement of this method the optimization of launch vehicle selection is integrated with the MMDOSA, which is capable of incorporating these developed methods and it shows that optimization methods are disaggregation from each other.

The unique way of putting heterogeneous satellites into launch vehicles is something like the packaging problem that is supposed to put some things of different sizes and types inside the bags. Target functions are used to reduce the cost to a minimum waste amount, here is the number of bags (Velerio de Carvalho, J. M. 2002, Chan, L. M. A. et al. 1998)[5],[27]. Although the packaging problem seems simple, it is uncertain that the complexity is explained exactly (Diamant, B. L. 1990)[7].

In fact, the issue of selecting launch vehicle is very different from the actual packaging problem, because the number of launch vehicles cannot be determined until the mission starts and the number of satellites is determined. In other words, this is more like a cutting or division problem, as we want to split things into smaller pieces to minimize the waste (Carrasquillo, R. L.1999, Williams, M. 2018, Jones, H. W. 2017)[3],[29].

The fundamental difference between withdrawal or division of stocks and choosing a launch vehicle is that selecting vehicle is to reduce costs, but the division of stocks aims to minimize waste. This theory had been developed by Morgan et al. In a form of formulation, launch vehicles are matched to homogeneous satellites by the constraint. The capacity of the launch vehicle must be greater than total size of the payloads (Jones, H. W. 2017)[12].

Other limitations are also considered, including that different types of satellites do not fit into the same launch vehicle and the particular type of satellites are limited into one launch vehicle.

Morgan and his colleagues also used an innovative simulation in the MATLAB program (Jones, H. W. 2017)[13]. Coding solution method points to the fact that there were no significant effects related to the types of satellites, because the total number of satellites has increased, the actual performance is improved.

An interesting discovery of the innovative experiment was that it's not a priority optimization, but the solution's accuracy is increased or the number of types of launch vehicles are increased (Jones, H. W. 2017). It is worth noting that experiments carried out in the research of Morgan and colleagues only have six launch vehicles. In the new issue, experiments have 10 launch vehicles (Jones, H. W. 2017).

These innovative methods provide us a quick computing solution, even if are not the best way to solve problem. Also, according to the similar method of Jilla (Morris, D. Z. 2017), the solution cannot determine the heterogeneous satellites in different constellations, only can determine satellites that have the same orbit and mass.

3. Procedure and formulation

In order to optimally determine a launch vehicle, a binary linear program is made by using the key points:

exact numeric value of the parameters, the objective function, constraints and effective variables in decision making. The main target of designate functional selector is to minimize the launch costs of constellation using world-class launch vehicles. It separates heterogeneous satellites into different types for the LEO orbits. The overall mission is to determine if the satellites should be placed in the same orbit. The launch vehicle is designated to launch each satellite into right position in orbit.

The so-called "heterogeneous segments" are a set of satellites that do not have the same mass and do not fit in the same orbit. Since the masses of satellites are not equal, and not same as Jilla's model, the capacity of launch vehicle would be divided by satellite mass (Morris, D. Z. 2017). Using a Rounded down method, we can get the total number of satellites that can be mounted on a specific launch vehicle. Also, for the launch vehicle selection of heterogeneous satellites, we need an innovative method similar to the stock capture or stock splitting.

Individual constellations may include satellites placed in different orbits. To analyze this kind of constellation, it should be determined what orbits can be attached to these constellations. For example, the same launch vehicle cannot either send a satellite to an large elliptical orbit or GEO. Formulations are based on the assumption that constellation satellites are located in the similar orbits. The mission includes three designs: adapting launch vehicles to orbits, adapting satellites to launch vehicles, and adapting satellites to orbits. So far, most cost estimation of launching satellites into orbit is only in average and ignores the data of different launch sites.

Finally, the last mission is to determine the mass and volume limits of the launch vehicle. The innovative method is mentioned in reference (Godfey, R. et al. 1970, Greg. 2015)[10], it used a polynomial for approximating mass limits.

In any case, the mass limitation of each launch vehicle is variable in launch position or location. All these constrain problems are described in the formulations. The optimization algorithm is implemented by a binary linear function and run in a Matlab program (Natick, MA, 2013, Armonk, 2016) [1],[18].

A. Assumptions

The hypotheses used to solve this scientific issue problem are:

1) All active satellites must move in the same orbit because they are all launched with by the same launch vehicle.
2) The power capability and or capacity of the a launch vehicle's winner is directly related to the height of the target orbit, the launching location and type ofthe launch vehicle.
3) The total cost of launching depends only on the location of launching and price of the launch vehicle.
4) Cannot have anyL launch vehicles maybe not available at any all launching locations.

In the previous studies that were discussed about them, hypotheses were defined that are different from the hypotheses defined in this researches. According to the previous research that was discussed, only Olds and Budianto (Budianto et al. 2004) pointed out to the launch location, which was designated as a variable, for power and capacity, rather than launch cost as a variable cost of launch. In Tthe previous studies, the sharing limitation between orbital planes is not considered. Itresearch is also not intended todoes not consider change orbit requirements and the limitations of orbital planes, if multiple orbits are set for the same launch vehicle. Also, in previous studies, Nno variation in of orbital height in LEO has been considered either, instead, they considered an the average lifting capacity for of launch vehicleing to LEO. SoThus, with all the assumptions discussed abovut them, the basic formulation of this research is formed.

B. Parameter definitions

The formulation is a mathematical model describing a process that satellites are assigned to launch vehicles and launched to the orbits from the launch sites. The parameters of the process are: launch locations (l), orbits (k), launch vehicles (j) and satellites (i).

i) is the number of satellites in a constellation, from 1 to n. Satellite (i) has an orbit (k) and a mass. So, mass of satellite (i) is m_i. Input of linear function is the parameters of a satellite.

(j) is the number of launch vehicles, from 1 to m, which denotes all aggregate of launch vehicles. To further discussion, this paper focuses on the small and medium size of rockets, including Minotaur I, Minotaur IV, Minotaur IV+, Minotaur VI, Athena Ic, Athena IIc, Antares 120, Falcon 9 Upgrade, Falcon 9 Heavy of Spacex.

In the first stage, all number of launch vehicles of different types are available in the aggregate. For example, the total number of launch vehicles is 400, there are 200 Minotaur IV's and 200 Minotaur I's. Since every launch vehicle has a large number, searching number increases until the number of launch vehicles exceeds the number of satellites. By multiplying the number of different types of launch vehicles with the number of satellites (n) we can obtain the maximum number of launch vehicles (m). For example, if a constellation requires three satellites and two launch vehicles of different types, then six different launch vehicles should be considered. It means that each of three satellites can be mounted on the launch vehicles of the first type or the second type.

The important parameters of the launch vehicle are feasibility, launching cost and lifting capacity. (k) denotes discrete orbits defined by unique altitude level. It is distinct with three parameters: RAAN, altitude and inclination. For circular orbits eccentricity and argument of perigee are always assumed zero. In a constellation of Walker, each plane has a unique RAAN of orbit, For example, GPS constellation needs minimum 24 satellites in total and four satellites on six orbit planes. All orbits are discretized from one to six..

In this optimization, four locations are selected for launching services, thus (l) = 4. The launching sites are Wallops Flight Facility (S1) in Virginia, Cape Canaveral Air Station (S2) in Florida, Kodiak Launch Complex (S3) in Alaska and Vandenberg Air Force Base (S4) in California.

Apart from four independent parameters, there is also a set of other specific parameters: launching cost, lifting capacity and feasibility of the launch vehicle.

(d_{ik}) is assignment that satellite (i) belongs to orbit (k). Besides, (m_{jkl}) defines the lift capacity of launch vehicle (j) at launch location (l) going for orbit (k). (a_{jkl}) defines feasibility of the same launch vehicle, the same location and the same orbit. However, for different types of vehicles have some limitations at the launch locations because of different inclinations. Thus, it may not be available for any launch vehicle to be launched at any launch location.

C. Cost estimations

Parameter (c_{jl}) is launch cost for launch vehicle (j) at launch location (l).

Satellite vendors and launch service providers make the agreement of launch service cost. Calculation and estimation of launch costs depend on various parameters such as: weight of payload, launch site, trajectory, orbital height, manufacturing country and whether this mission is manned or not (Godfey, R. et al. 1970).

Normally the launch costs are estimated on the mass of payload launched to the orbit (Futron Corporation, 2002). For example, in SMAD Space Mission, the cost is calculated by per kilogram weight of launching payload (Godfey, R. et al. 1970). Obviously, the calculations only show average costs, and key costs are not identified, such as costs come from location or launch site. Therefore, in this paper, the cost variations are evaluated on different types of launch vehicles and different launch sites as well as the orbits.

D. Decision variables

Variables and decision factors can affect the outcome of target function and give different results. There are three types of factors or variables that have been formulated in decision-making. The first factor or decision variable determines satellite i assigned to launch vehicle j.

The second factor determines that launch vehicle j is assigned to launch location l. These factors are basis of the objective function, which is discussed in Section F. The last factor determines that launch vehicle j is assigned to orbit k is launching. All factors are formulated in binary method.

E. Constraints

There are five characteristics of limitations in the formulation. The first and most important feature is that launch vehicle should be specified to each satellite, no need to use any type. The first feature is addressed in Limit 1. The second feature of the limitation is that total mass of the payload must be less than lifting capacity of the launch vehicle. The third limitation ensures that a triple mission can be completed by assigning satellites to the launch vehicles and transferring to similar orbits, it is referred to "fast sharing" key segmentation. Important points of the fourth limitation are that any launch vehicle at any location launch may not be assigned to the same orbit. Also, the fifth limitation implies that number of launch vehicles to move to the orbit is same as the number of launch locations. The last limitation relates to describing the decision factors and variables in a binary method.

Limit 1: Launch any satellite.

The first limitation is the need to launch each satellite into the orbit of constellation. Without this limitation, there is at least a launching cost as \$ 0, it denotes that nothing has been launch. This limitation is

$$1 \forall \mathrm{i} = 1, \dots\dots, \mathrm{n} = \sum_{\mathrm{j}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{ij}} \qquad (1)$$

Limit 1 shows that all launch vehicles, j from 1 to m should be specified exactly once for a satellite from 1 to n. A reverse mission, assigning launch vehicle to a satellite, does not need this formula because no launch vehicle is required.

Limit 2: The capacity of launch vehicles.

The capacity of launch vehicle $j,$ must be greater than or equal to the total mass of satellites. This limitation guarantees the masses of all satellites allocated to the launch vehicle j and ensures that they are less than the capacity of launch vehicles j. This limitation of "Big-M" constraint is shown in Eq.(2):

$$m_{jkl} + M\left(1 - y_{jl}\right) + M\left(1 - w_{jk}\right) \geq \sum_{i=1}^{n} m_i x_{ij} \quad \forall j = 1, \dots., m; \ \forall k = 1, \dots\dots, p \quad \forall l = 1, \dots., 4 \qquad (2)$$

Where M represents an enough large number. If the orbital plane and location are selected, right side of the equation should be large enough. For example, the mass constraint of S4 is greater than the launch of S3. "Big M" constraint ensures that the lifting capacity of the launching vehicle for S3 is less than the lifting capacity for S4.

So, the value of M is the total mass of all the satellites.

$$\sum_{i=1}^{n} m_i = M \qquad (3)$$

Limitation 3: sharing ride on the same orbit.

Each launch vehicle should be specified by the satellites that are on the same orbital plane. The following sub-code indicates the procedure that the restriction is considered:

```
IF $i$ is specified to $j(x_{ij} = 1)$
IF $i$ is specified to $k(d_{ik} = 1)$
THEN $i$ is specified to $k(w_{jk} = 1)$
ELSE IF $i$ is NOT specified to $k(d_{ik} = 0)$
THEN $j$ is NOT specified to $k(w_{jk} = 0)$
```

```
END
ELSE IF $i$ is NOT specified to $j(x_{ij} = 0)$
THEN $j$ MAY or MAY NOT specified to $k(w_{jk} = 1\ or\ 0)$
END
```

IF-THEN-ELSE of the limitations needs an extra decision variable. An additional decision factor or variable refers to “an implicit decision that is caused by one or more decision factors" (Zimmerman, R. 2018)[30]. x_{ij} decision is used to determine whether the satellite i is assigned to a launch vehicle, A decision factor creates the new decision for a special constraint that reduces the complexity and ambiguities of the formulation. The "Big M" parameter is only used to limit the restrictions of the launch vehicles on the left side of the equation. It can fix the ambiguity problem and reduces the complexity.

Mission of launch vehicle orbit w_{jk} is equal to 1 if the missions of launch vehicle and satellite orbit are equal to 1. Two limitations create over or less limits on w_{jk} are needed.

Limitation 3.1: Ride equivalent to the lower limit orbit:

$$M(1 - x_{ij}) \geq w_{jk} - d_{ik} \quad \forall\, i = 1, \ldots\ldots, n; \quad \forall\, j = 1, \ldots., m; \quad \forall \quad k = 1, \ldots., p \qquad (4)$$

Decrease Eq. (4) by setting M = 1, Limitation 3.1 becomes

$$w_{jk} - \delta_{ik} \leq 1 - x_{ij} \quad \forall\, i = 1, \ldots\ldots, n; \quad \forall\, j = 1, \ldots., m; \quad \forall k = 1, \ldots., p \qquad (5)$$

Limitation 3.2: Ride equivalent to the upper limit orbit*:*

$$w_{jk} \ \geq \delta_{ik} + M(x_{ij} - 1) \quad \forall\, i = 1, \ldots\ldots, n; \quad \forall\, j = 1, \ldots., m; \quad \forall k = 1, \ldots., p \qquad (6)$$

Decrease Eq. (6) by setting M = 1, Limitation 3.2 becomes

$$x_{ij} + 1 \geq \delta_{ik} - w_{jk} \quad \forall\, i = 1, \ldots\ldots, n; \quad \forall\, j = 1, \ldots., m; \quad \forall k = 1, \ldots., p \qquad (7)$$

Limit 4: Assessment of successful launching possibility.

If launch vehicle j is possible to reach orbit k from location l, then launch vehicle j can only be certain orbit k. The following sub-code indicates the procedure that the restriction is considered:

```
IF $j$ is specified to $k(w_{jk} = 1)$
AND IF $j$ CANNOT launch from $l$ to $k(a_{jkl} = 0)$
THEN $j$ is NOT specified to $l(y_{jl} = 0)$
ELSE IF $j$ is specified to $k(w_{jk} = 1)$
AND IF $j$ CAN launch from $l$ to $k(a_{jkl} = 1)$
THEN $j$ MAY or MAY NOT specified to $l(y_{jl} = 0\ or\ 1)$
END
```

Similar as Limit 3, "big M" is applied in the procedure of the limitation. An enough value M makes the limitation contraction and decreases the complexity as shown in Eqs. (8) and (9):

$$w_{jk} \leq M(1 - y_{jl}) + \alpha_{ikl} \quad \forall\, l = 1, \ldots\ldots, 4; \quad \forall\, j = 1, \ldots., m; \quad \forall \quad k = 1, \ldots., p \qquad (8)$$

Decrease Eq. (8) by setting M = 1, Limitation 4 is

$$w_{jk} - \alpha_{jkl} + \leq 1 - y_{jl} \quad \forall\, l = 1, \ldots\ldots, 4; \quad \forall\, j = 1, \ldots., m; \quad \forall k = 1, \ldots., p \qquad (9)$$

For example, Launch vehicle B is determined to lift-off to sun synchronous orbit (SSO). Launch location has to be the West Coast, S3 or S4. Limitation 4 bans launch vehicle B launching to SSO at the sites of East Coast S1 and S2. This limitation is hard to be decided because it does not mention that S4 is a possible site for launching vehicle B to SSO (α_{jkl} = 1) and launching vehicle B is determined to SSO (w_{jk} = 1), so launching vehicle B is determined at S4. In this circumstance, launch location can be determined not only at S4 but as also at S3 (y_{jl} =1 or 0).

Limitation 5: Compliant mission of launch vehicles.

As described above, the formulation does not limit launch vehicles for the specific launch locations. The limitation determines the launch sites alike that the launch vehicles are determined to the orbits. So, the pattern is compelled to allocate launch vehicles to the launch sites. The limitations are expressed below:

$$\sum_{l=1}^{4} y_{jl} - \sum_{k=1}^{p} w_{jk} = 0 \quad \forall j = 1, \ldots., m \qquad (10)$$

Limitations 6, 7, and 8: Binary limitations.

All determination variables are bound to binary values shown below:

$$x_{ij},\ y_{jl},\ \ w_{jk} \in \{0, 1\} \quad \forall i = 1, \ldots., n, \quad \forall j = 1, \ldots., m, \quad \forall k = 1, \ldots., p, \quad \forall l = 1, \ldots., 4 \qquad (11)$$

For perceptual designs, these eight limitations are enough for the assessment of optimal launching. Other significant limitations, particular in constellation and space vehicle designs, tendency of accumulated volume and launch vehicle volume extents were not considered.

F. Target Function

Target function is used to minimize the whole cost of launching satellite constellation. The cost parameter c_{jl} is a function of launch vehicle and launch site. So, the cost of launching satellite constellation is a function of the number of launch vehicles that are launched at location y_{jl}. This target function is presented in Eq. (12), and proved in the Appendix:

$$min \ \sum_{j=1}^{m} \sum_{l=1}^{4} c_{jl} y_{jl} \qquad (12)$$

The target function does not take into account of any economic criterion, but coalition costs of sharing ride of launching satellite. The economic criterion is responsible for deciding the cost of trading multifold satellite constellations and multifold launch vehicles. The variation of target function in Eq. (12) becomes linear form if target function perfects as formulation of a launch selector in assigning an inharmonious constellation with sharing ride.

G. *Intricacy problems*

Generic integer program are hard for most computers. Actually, the time needed to unravel the generic integer in linear program is an anatomical dependence on amounts of the integer number. For example, a 10-fold increments in the number of determination variables increase the calculation times by 1027 (Zimmerman, R. 2018). Furthermore, the problem is addressed as NP difficulty because it can be decreased to one-dimensional packaging issue in the sample of two satellites launching to the identical orbits (Diamant, B. L. 1990).

Comprehension of measuring the efficacy in intricacy of the pattern helps to represent the extents of the program. To figure out the determinant space, suppose satellites i from 1 to n, launch vehicles j from 1 to m, orbits k from 1 to p, and launch locations l from 1 to 4. Furthermore, let t express the number of launch vehicle, so that the number of launch vehicles j is $m = t * n$.

Numbers of determination variables that make up the determination space are tabloid in Table 1. The number of satellites n is the most efficacy in the number of determination variables. The number of launch vehicles t is the next most important. It is the certain pattern that will become more difficult and lengthy to untangle the number of satellite increments. Few collisions limitations have analogous tendencies as explained in Table 2.

H. *Primary Solution*

Primary solution of the current method helps to discover the optimal solution in math coding. It can aid the computer to discover solutions more faster. In several instances, the computer may have a difficult time to discover the practical solution that the solver parameters are sans. A primary practical solution also assure that the input data of satellite is feasible for prepared launch vehicles. The primary practical solution does not utilize any share of ride but dialectics laws to discover which launch vehicles are available for given satellite. The assembles of low cost solutions are arranged in the list.

The repetitions of this procedure for any satellite in the constellation helps computer work. The primary practical solution caters the satellite as extenders in higher cost assessment.

I. *Model Reliability*

The reliability of developed models caters several outcomes that can be practical in action. A string of limited experiments in the homogeneous constellation have corroborated right treatment and performance. This is an accredited performance of the optimal formulation. The usage of an optimization formulation is to obtain modular priority and limitations, also to defeat the research to be an intricate problem. After reviewing other research works, it accredits rational substantiations and measurements.

TABLE 1

NUMBER OF DETERMINANT VARIABLES

$determinant\ variables$	$relation$
x_{ij}	$n^2t = n * m = n * t * n$
w_{jk}	$ntp = m * p$
y_{jl}	$4tp = m * 4$

4. Applications

The pattern of optimal model created in Part. 3 is practical to three decomposed constellations that did not test a linear solution of optimized launch detector. The three assignments are Protection Weather, Navigation Constellation and Military Constellation.

TABLE 2

NUMBER OF LIMITATIONS RELATION

$limitation$	$relation$
1	n
2	$4ntp = m * p * 4$
3.1	$n^2tp = n * m * p$
3.2	$n^2tp = n * m * p$
4	$4ntp = m * p * 4$
5	$nt = m$
6	$n^2t = n * m$
7	$4nt = m * 4$
8	$ntp = m * p$

A. *Protection Weather*

According to 2015 Pentagon Budget Request, Protection Weather System (PWS) “will catch a decomposed systems come close” (Gruss, M. 2017)[11]. Along with the flexibility of constellations, Thompson et al. (Thompson, R. et al. 2015) designed a multiple functions/multiple orbits and decomposed satellite constellation to join the provisions of the (PWS).

TABLE 4
primary solution for protection weather constellation [a]

Launch vehicle	Satellite	Launch site	Orbit (altitude/inclination)	Excess mass capacity, %
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Falcon 9 Upgrade	Microwave	S4	$298\ km$ / $95\ deg$	22
Minotaur I	Imager	S4	$1200\ km$ / $95\ deg$	77
Minotaur I	Imager	S4	$1200\ km$ / $95\ deg$	77
Minotaur I	Space environmental monitor	S4	$298\ km$ / $95\ deg$	91
Minotaur I	Space environmental monitor	S4	$298\ km$ / $95\ deg$	91
Minotaur I	Space environmental monitor	S4	$1200\ km$ / $95\ deg$	87
Minotaur I	Space environmental monitor	S4	$1200\ km$ / $95\ deg$	87

[a] Total cost to launch primary possible solution is 493.6 million UDSs.

Bygone weather assignments, the Defence Aerology Satellite Plan, Polar Usable Environmental Satellites Plan, and Geostationary Usable Environmental Satellites Plan have exploited big launcher and evolved to be usable launch vehicles. The determination of next descendant of defense weather satellites could have deep impacts on the requirement of small and medium launch vehicles. Table 3 shows the parameters of satellite for the primary constellation expanded by Thompson et al. (Thompson, R. et al. 2015). The primary constellation includes of two Imager satellites, six Microwave satellites, and four Space Surroundings Monitoring satellites.

The primary solution of one satellite on the singular launch vehicle is shown in Table 4. This solution is one to one without sharing the ride, Analogous procedure of Massachusetts Institute of Technology MIT) is that one satellite is refined versus the capacity and accessibility of a launch vehicle to the favorable orbit. Distinct procedure of, MIT,is that the launch location is also specified in the primary solution. This primary solution is a bad feasible cost to launch the constellation, as it does not perform sharing the ride. For a launch plan management, landscape is the high limit in the cost assessment. The optimal launch detector with minimizing the launch cost is displays in Table 5.

TABLE 3
Input amount for protection weather constellation

Satellite name	Satellite mass, kg	Number of planes	Satellites per plane	Orbital altitude, km	Orbital inclination, deg
Microwave	357	3	4	298	95
Imager	61	3	2	1200	95
Space environmental monitor [a]	29	3	2	298	95
Space environmental monitor [a]	29	3	2	1200	95

[a] One environmental monitoring satellite is put in any orbit with the microwave and imaging satellites.

B. *Navigation Constellation*

PWS is a decomposed constellation, and is partly tiny in the quantity of satellites. To exert bigger loading pattern, Diniz divided the homogenous solutions (Greg. 2015) and expanded a navigation assignment. The layout of homogeneous satellites is examined in Walker constellation of different heights. Diniz's inspected different orbital altitudes frome LEO to GEO, finally centralized in 12 examples of LEO constellations.

Using the optimization pattern of launch detector we can expand the navigation constellation. Using a bigger loading pattern yields assurance solution for accrediting the number of decomposed constellations.

In optimal navigation plan, satellites are homogeneous in Walker constellations that have different orbit altitudes. As assurance of the orbit altitude, the masses of satellites and embed various sensors are calculated for the navigation constellations. Table 6 shown the special parameters of 12 constellation plans (Greg. 2015).

TABLE 5
Optimal launch detector, with mass border for PWS [a]

Launch vehicle	Satellite	Launc site	Orbit (altitude/inclination)	Excess mass capacity, %
Minotaur I	Imager, space environmental monitor	S4	1200 km / 95 deg	64
Minotaur I	Imager, space environmental monitor	S4	1200 km / 95 deg	64
Falcon 9 Upgrade	4 microwave space environmental monitor	S4	298 km / 95 deg	7
Minotaur IV	3 microwave space environmental monitor	S4	298 km / 95 deg	7

[a] Total cost to launch primary possible solution is 190.4 million UDSs.

TABLE 6
Navigation constellations parameters

layout	Satellite mass, kg	Number of planes	Satellites per plane	Orbital height, km	Orbital inclination, deg
1	38.876	18	12	908	59.01
2	38.830	15	11	901	59.11
3	38.532	12	13	876	54.02
4	38.599	12	12	878	59.94
5	38.576	12	12	882	55.04
6	38.582	12	11	874	56.02
7	38.577	12	11	879	55.01
8	38.585	12	10	873	57.12
9	38.586	12	10	875	59.07
10	38.724	12	9	869	61.21
11	38.596	12	9	871	56. 98
12	38.691	12	9	870	58.89

Computation of launch capacity produces the number of launch vehicles for the plan. For projects 1, 2, and 12, just one launch vehicle is elected to deploy the constellation. For these projects, the optimizer is not essential to design the launch detector. The massive capacity of launch vehicle is simply divided by the mass of satellite to decide how many launch vehicles are required.

For the remaining designs, the solution optimized by launch detector is that seven available launch vehicles are assigned to four launch locations. In Table 7 the primary solution uses the cheapest launch vehicle to exclusively launch any satellites. This is a possible Non-optimal solution and does not contain multi detectors.

The optimal solution displayed in Table 8 is used to minimize the cost of 12 constellations in the layout space by using launch detector. An optimal solution is obtained by detecting multi satellites on the suitable launch vehicle and replacing the launch vehicle's model (Minotaur IV to Minotaur I on layouts 3, 5, and 7).

C. *Military Constellation*

Constellations combining two applications of navigation and weather can be used for the military purposes, such as guiding the missiles, guiding military drone, guiding fighter, rescuers and more. The importance of the solutions is to reduce implementation cost and time, as well as increase reliability and performance of the constellations. The primary solution displayed in Table 9 uses the cheapest launch vehicle to exclusively launch the satellites.

This is a Non-optimal solution and does not contain multi satellite detectors. This is a possible yet Non-optimal solution and does not contain multi satellite detectors.

5. Conclusions and further discussions

This paper endeavors to formularize an optimal launch detector or selector that minimizes the cost of launching heterogeneous LEO satellites in decomposed constellations. A formulization is required since there is not a method is available to compute an undertaken optimal launch detector for decomposed constellations in multiple functions/multiple orbits. The formulization can adjust satellites to right launch vehicles and allow satellites going to identical orbit.

The limitations for formulization are investigated on the assumptions. The suppositions includes that satellites are launched to the identical orbit and lift capacity of the launch vehicle is larger than the total mass. The lift capacity is a subordinate of the kinds of launch vehicle parameters, such as the height of target orbit and launch location. Launch cost to is supposed a constant value and is also a subordinate of launch vehicle's kinds. The final supposition is that not every launch vehicle is accessible or possible to launch from any location. Possibility was specified by the inclination borders and certain launch position.

Accessibility is the ability for a launch vehicle to take off at specified location. These assumptions are formed in constraints of unique problem, as Limitation 3.1, Limitation 3.2, and Limitation 4. c_{jl} denotes the dependence of launching cost between location l and launch vehicle j.

Furthermore to unparalleled limitations, Limitation 1 needs that any satellite coming in the pattern should be launched. Limitation 2, requires that cutting portion or packing restriction permits satellites to share riding until the masses are overflow the lifting capacity of launch vehicle.

Finally, the binary limitations (5, 6, and 7) confined the determination variables as one or zero, which was an essential component of the mission. Composed of the target subordinate, the limitations are expanded and organized in a integer linear code that is permissible for heterogeneous satellites to share riding in multiple functions or multiple orbits.

TABLE 7
primary possible solution for 12 navigation constellation layouts

layout	*No. of satellites = no. of launch vehicles*	*launch vehicles*	*launch site*
1	210	Falcon Heavy	S1
2	181	Falcon Heavy	S1
3	170	Falcon Heavy	S1
4	159	Falcon 9 Upgrade	S2
5	159	Falcon 9 Upgrade	S1
6	135	Falcon 9 Upgrade	S2
7	130	Minotaur I	S1
8	125	Minotaur IV	S2
9	120	Minotaur IV	S2
10	110	Minotaur I	S3
11	110	Antares 120	S1
12	220	Falcon Heavy	S1

Part 3 presented mission formulization of the optimal design for inharmonious constellation. The procedure is accomplished as anticipated, it allocated satellites put on

TABLE 8
Optimal launch detector for 12 navigation constellation layouts

layout	*No. of launch vehicles*	*Launch detector*	*Launch site*	*Excess mas capacity, %*	*Cost saving from primary possible solution, %*
1	12	Falcon Heavy	S1	74	95.1
2	11	Falcon Heavy	S1	78	95.2
3	10	Falcon 9 Upgrade	S1	58	94.9
4	10	Falcon 9 Upgrade	S2	64	95.13
5	10	Falcon 9 Upgrade	S1	61	91.2
6	11	Minotaur IV	S2	68	92.7
7	11	Minotaur IV	S1	67	90.1
8	11	Minotaur IV	S2	69	91.4
9	12	Minotaur IV	S2	69	91.1
10	12	Minotaur I	S3	12	90.5
11	12	Antares 120	S1	92	91.2
12	9	Falcon Heavy	S1	72	95.8

TABLE 9

Optimal launch detector for 12 navigation constellation layouts

$layout$	$No. of\ launch\ vehicles$	$Launch\ detector$	$Launch\ site$	$Excess\ mass\ capacity, \%$	$Cost\ saving\ from\ primary\ possible\ solution, \%$
1	13	Falcon Heavy	S1	75	96.3
2	11	Falcon Heavy	S1	79	96.1
3	9	Falcon 9 Upgrade	S1	53	95.3
4	9	Falcon 9 Upgrade	S2	69	96.1
5	11	Falcon 9 Upgrade	S1	67	92.6
6	11	Minotaur IV	S2	63	93.6
7	11	Falcon 9 Upgrade	S1	69	91.2
8	12	Minotaur IV	S2	64	92.4
9	11	Minotaur IV	S2	67	92.5
10	12	Minotaur I	S3	18	91.1
11	11	Antares 120	S1	96	91.6
12	11	Falcon Heavy	S1	79	96.2

several orbits and masses onto series of launch vehicles that are accessible at numbers of launch locations. Since the formula is a linear coding integer and the pattern is completely solved, the solution is dependable and desirable. Thus it has more superiority than the exploratory procedures such as genetic algorithms.

This investigation endeavors a novelty because the expanded pattern is prime way to optimize coding of launch detector for inharmonious, multiple functions and multiple orbits. The formulization can also decide which launch site is specified for the launch vehicle, because the mass restriction, the inclination borders, and cost related with any launch vehicle are all affiliated to the launch site. In conducting subsequent research, the endeavors can discover the cost factors of launch locations and append target functions or limitations, so as to obtain how several determinations effect on selecting the launch location and launch vehicle.

The new method expanded in this investigation does not optimize satellites and launch vehicles themselves, but assigns different satellites to different orbits and different kinds of launch vehicles at different launch sites. The important quotas of subsequent researches are lifting capacity, launch vehicle accessibility, inclination extents, information of launch cost, and limitations of sharing ride.

The supposition of the target function is that the cost of launching satellite is a constant value only relying on the position of launch site and the kind of launch vehicle. Extra target functions can be taken into consideration, like adding integration costs (for multi detector), which increasing dependability as a second target. It will take into account of economic criterion (reduce launching production costs), and adding launch timing for second target (capability to obtain big numbers of decomposed satellites rapidly approaching the orbit from multi launch positions). The next steps will integrate launch optimization with layout optimization of decomposed constellation and/or the GEO transmission orbits.

Appendix: Formulization of Optimization

$$min \sum_{j=1}^{m} \sum_{l=1}^{4} c_{jl}\, y_{jl}$$

Topic to

$$1 = \textstyle\sum_{j=1}^{m} x_{ij} \quad \forall i = 1, \ldots., \qquad \text{(A1)}$$

$$m_{jkl} + M\left(1 - y_{jl}\right) + M\left(1 - w_{jk}\right) \geq \sum_{i=1}^{n} m_i x_{ij} \quad \forall j = 1, \ldots., m;\ \forall k = 1, \ldots, p\ \ \forall l = 1, \ldots, 4 \qquad (A2)$$

$$\sum_{i=1}^{n} m_i = M$$

$$w_{jk} + x_{ij} \leq 1 + \delta_{ik} \quad \forall i = 1, \ldots, n; \quad \forall j = 1, \ldots., m; \quad \forall k = 1, \ldots, p \ \ (A3.1)$$

$$w_{jk} + x_{ij} \geq \delta_{ik} - 1 \quad \forall i = 1, \ldots, n; \quad \forall j = 1, \ldots., m; \quad \forall k = 1, \ldots, p \ \ (A3.2)$$

$$w_{jk} + y_{jl} \leq 1 + \alpha_{ikl} \quad \forall l = 1, \dots, 4; \quad \forall j = 1, \dots., m; \quad \forall k = 1, \dots, p \quad (A4)$$

$$\sum_{l=1}^{4} y_{jl} - \sum_{k=1}^{p} w_{jk} = 0 \quad \forall j = 1, \dots., m \qquad (A5)$$

$$x_{ij} \in \{0,1\} \quad \forall i = 1, \dots, n, \quad \forall j = 1, \dots., m \qquad (A6)$$

$$y_{jl} \in \{0,1\} \quad \forall j = 1, \dots, m, \quad \forall l = 1, \dots., 4 \qquad (A7)$$

$$w_{jk} \in \{0,1\} \quad \forall j = 1, \dots, m, \quad \forall k = 1, \dots., p \qquad (A8)$$

where i is Satellite number from 1 to n; j is launch vehicle number from 1 to m; k is divided orbit number from 1 to p; l denotes the number of launch location from 1 to 4 related to S4, S2, S3, and S1;

x_{ij} is the devolution of satellite i to launch vehicle j (DV); w_{jk} is the devolution of launch vehicle j to orbit k (DV); y_{jl} is the devolution of launch vehicle j to location of launch l (DV); d_{ik} is the devolution of satellite i to orbit k;

coding input; a_{jkl} is the possibility of launch vehicle j to launch to orbit k from launch location l; mi is the mass of satellite I; and m_{jkl} is the lifting capacity of launcher j to orbit k from launch location l.

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