Endogenous factors affecting the cost of large-scale geo-stationary satellite systems*

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Abstract. This work proposes the use of model-based sensitivity analysis to determine important internal factors that affect the cost of a large-scale complex engineered systems (LSCES), such as geo-stationary communication satellites. A physics-based satellite simulation model and a parametric cost model are combined to model a real-world satellite program whose data is extracted from selected acquisitions reports. A variance-based global sensitivity analysis using Sobol' indices computationally aids in establishing internal factors. The internal factors in this work are associated with requirements of the program, operations and support, launch, ground equipment, personnel required to support and maintain the program. The results show that internal factors such as the system based requirements affect the cost of the program significantly. These important internal factors will be utilized to create a simulation-based framework that will aid in the design and development of future LSCES.

Keywords: Advanced high frequency satellite · cost overrun · cost modeling · model-based sensitivity analysis · endogenous factors.

1 Introduction

A system associated with large-scale projects involving a vast number of stakeholders with high complexity is a large-scale complex engineered system (LSCES) [10]. Acquisition of an LSCES in the aerospace and defense industry undergo processes of design, engineering, construction, testing, deployment, sustaining, and disposal of the system [5, 8, 31]. Due to the high costs and risks involved, these systems are often acquired by large organizations, such as the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD), in the United States using the defense acquisition system (DAS) [28, 1]. The costs involved during the acquisition process of LCSES are reported quarterly to the congress using the selected acquisition reports (SARs) [9].

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Every year, the aerospace industry's cost overruns grow at least twice the estimated costs by the end of the program due to longer schedules and the system's high complexity [9]. Past research has shown that highly complex systems undergo costs and schedule overruns often exceeding 40% of their initial estimated costs [35]. SARs also demonstrates the trend of higher estimated costs for the space programs [35].

Cost overruns in LCSES may be due to the high complexity, size of the project, various stakeholders, organizations, political disruptions, and changes in requirements and scope [27]. The factors which affect the cost overrun are not clearly explained in the SARs and often described as to be caused due to underestimation of initial costs [10]. Although many factors go into the overall cost of a project, it is known that systems engineering efforts can reduce the costs [8]. But to use systems engineering frameworks, it is fundamentally essential to understand the factors affecting the cost overrun of the system [37]. The two main types of factors that affect the cost overrun are the exogenous and endogenous factors. Exogenous factors are factors not belonging to the system, and endogenous factors are within the program's realm [6]. Both factors play a significant role in the cost and schedule overrun and the DoD data can be used to validate it. Examples of endogenous factors are design errors, change in scope, and complexity of the system. In contrast, exogenous factors are changes due to natural disasters, political dynamics, warfare, and the scientific world [8, 33, 29]. Changing the factors within the system may or may not have a significant impact on the cost. The factors affecting the cost overrun are often identified by experts or using surveys, but they are often prone to error [34]. Global sensitivity analysis (GSA) has been used to identify critical factors in systems [30, 7].

In this work, a variance-based GSA is used to determine the effects of different factors on the program's cost [36]. Specifically, GSA is performed on a geo-stationary satellite system model by combining a physics-based simulation model with a cost model and evaluating the effects of its input parameters on the output parameter, in this case, the overall system cost. A geo-stationary communication satellite program is used as an example of a LCES program. In particular, the advanced extremely high frequency (AEHF) satellite program. A parametric cost-based model, the unmanned spacecraft cost model (USCM8), is used [40]. GSA with Sobol' indices is used to quantify how the internal factors affect the system's overall cost.

The remained of the paper is organized as follows. Next section introduces the AEHF satellite system and the data from SARs. The following section describes the methods used to construct the satellite physics model and the cost model as well as Sobol's method. The numerical results are presented in the following section. Lastly, the conclusions and suggestions for future work are presented.

2 The AEHF Satellite System

A geo-stationary communication satellite's mission is to relay telecommunication signals using transponders between the satellite and different ground stations,

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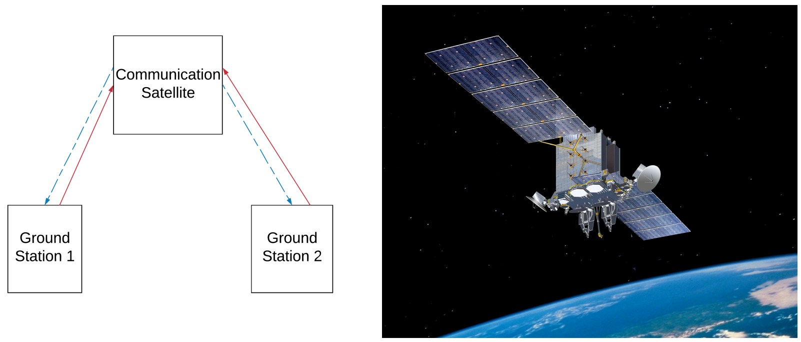

(a) (b)

Fig. 1: A geo-stationary communication satellite: (a) block diagram of the system, and (b) the advanced extremely high frequency satellite (AEHF) [2].

as shown in Fig. 1(a). The objective is to transmit the signals from one ground station to another ground station efficiently and effectively. The example satellite program used in this work is the AEHF shown in Fig. 1(b).

The AEHF program consists of six geo-stationary communication satellites, and it is operated by the United States Air Force Space (USAF) command [3]. The expected lifetime of a satellite is 14 years [3]. The program baseline cost data is extracted from the selected acquisition reports (SARs) [1, 3] and is shown in Fig. 2. The changes in the estimated costs during the development of AEHF are due to various internal and external factors to the system. In this work, a conceptual model of a satellite program is utilized to reveal how the internal factors affect the overall cost by utilizing GSA.

3 Methods

This section describes the development of a physics based model of a geo-stationary satellite, along with its cost model. Both the models have parameters that are internal to the system. A variance-based GSA model using Sobol' indices is constructed to study the effect of different internal factors on the cost of the system [36]. The workflow of the method is provided in the next subsection, followed by the satellite model, the cost model, and the variance based sensitivity analysis

3.1 Workflow of the model-based cost sensitivity analysis

A flowchart for exploring the effect of the systems cost due internal factors is shown in Fig. 3. The first step is to model the physics of the satellite. The mass of different subsystems is fed into the cost model to calculate the cost of the system. The satellite model and the cost model are then made to fit a real

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satellite program data from the SARs. This is followed by the variance-based GSA to determine the important internal parameters.

3.2 Satellite model

In this work, the satellite system designed in this paper is conceptual. Generally, a communication satellite system includes a communication satellite, a launch station, and ground stations to accomplish the mission objective. The satellite system consists of the payload, including transmitting and receiving transponders for communication, subsystems such as power system, propulsion, ground support, and launch vehicle. The satellite system also follows a top-down hierarchical decomposition and this is shown in Fig. 4.

The satellite system is highly coupled with linear and nonlinear couplings. In this work, the physical satellite is defined by nine continuous parameters.

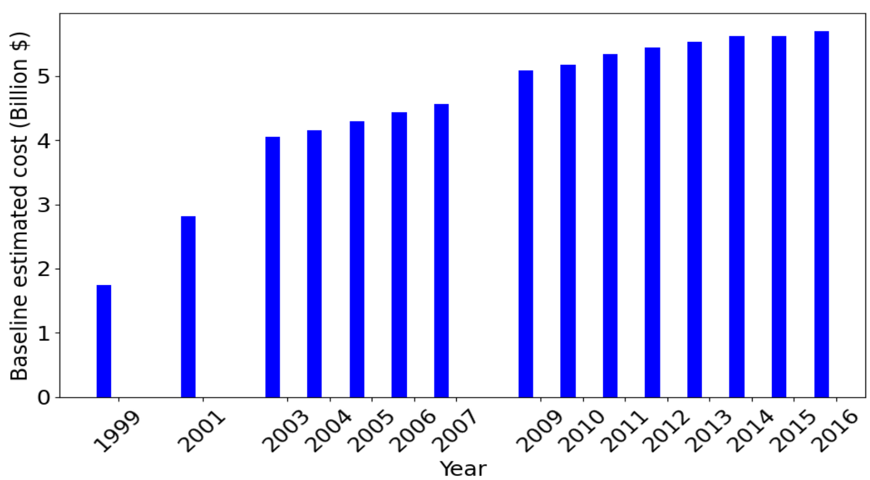

Fig. 2: The yearly baseline cost estimation of the advanced extremely high frequency satellite system (data obtained from [1, 39, 11–24]).

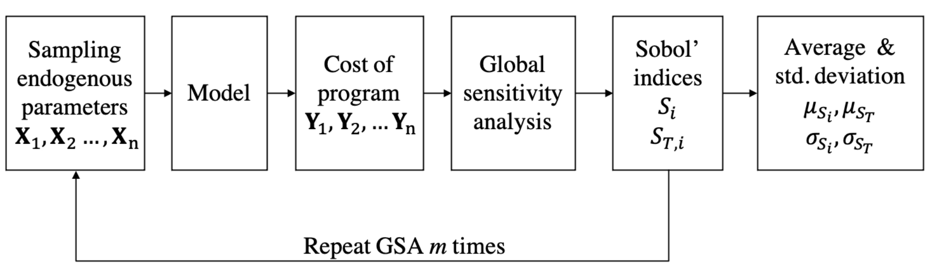

Fig. 3: Workflow of the model-based cost sensitivity analysis.

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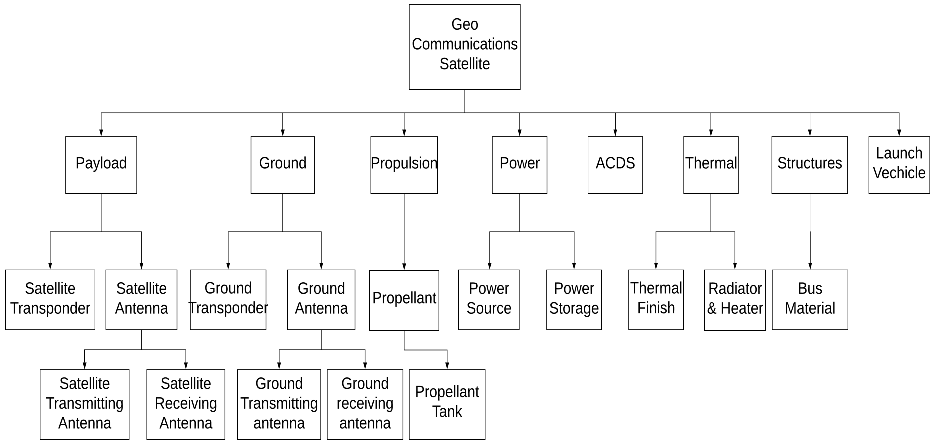

Fig. 4: System diagram of geo-stationary communication satellite.

The bounds used for the satellite's parameters are provided in Table 1. The data for AEHF satellite used in this work is also provided in table. Data for the AEHF satellite is classified and, hence, assumptions for those parameters are also provided in Table 1.

The inherent couplings in the satellite system is represented using a design structure matrix (DSM) and this can be found in Kannan *et al.* [26] along with a detailed description of the parameters of the satellite system [25].

3.3 Cost model

This section describes the cost model constructed with the inputs from the satellite system. Traditional cost models are based on the mass of the system. In this paper, a parametric cost estimation model, USCM8 developed by Telecote Research for the US Air Force, is used to calculate the cost of the satellite pro-

Table 1: Geo-stationary communication satellite parameters

Parameters	**Lower Bound**	**Upper Bound**	**AEHF Data**
Downlink frequency (GHz)	1	100	20 [38]
Uplink frequency (GHz)	1	100	44 [38]
Satellite Transmitter power(Watts)	300	3,000	1,500 (assump)
Watts Ground Transmitter power (Watts)	300	30,000	15,000 (assump)
Satellite transmitting antenna diameter(m)	0.5	2.5	1.0 (assump)
Satellite receiving antenna diameter (m)	0.5	2.5	1.0 (assump)
Ground receiving antenna diameter (m)	2	20	0.3
Ground transmitting antenna diameter(m)	2	20	0.3
Energy density of the battery $(W-hr)/kg$	35	350	200

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gram [40]. USCM8 is mass-based cost and the mass of the system are provided from the previous satellite model. There are different costs involved in the design and development of a system. In this conceptual design, the cost involved are the cost of research and development, cost of the units, cost of operations and support and cost of launching the satellite. The total cost of the satellite system is

$$C_{total} = C_{r\&d} + C_{units} + C_{operations} + C_{launch}, \tag{1}$$

where C_{total} is the total cost of the satellite program, $C_{r\&d}$ is the cost of research and development of a satellite, C_{units} is the cost per unit of a satellite, $C_{operations}$ is the cost of operations and support of the program and C_{launch} is the cost of launching a satellite. The equations involved in calculating the cost of the research and development and the first unit of the satellite systems using USCM8 can be found in Wertz *et al.* space mission analysis and design [40].

USCM8 involves the cost of the first unit and other units separately, the total cost of the satellite system is modified as

$$C_{total} = C_{r\&d} + C_{first-unit} + C_{other-units} + C_{operations} + C_{launch} + C_{estimating}, \tag{2}$$

where C_{units} is divided to $C_{first-unit}$ cost of first unit and $C_{other-units}$ is the cost of other remaining units.

The cost estimation of the research and development is

$$C_{r\&d} = \sum C_{subsystems} + C_{integration} + C_{Ground-Equipment}, \tag{3}$$

where $\sum C_{subsystems}$ is the sum of all the subsystem costs, $C_{integration}$ is the cost of integration of the subsystems and $C_{Ground-Equipment}$ is the cost of ground equipment required for the program.

The cost estimation of the first unit is determined by

$$C_{first-unit} = C_{subsystem} + C_{integration}, \tag{4}$$

where $C_{subsystem}$ is the cost of the subsystem within the satellite and $C_{integration}$ is the cost of integration of the subsystems.

The next step is to estimate the cost of other units. The cost of other units is extrapolated by using a learning curve representing the relationship between experience producing a good and efficiency of production learning curve is given by

$$L = N^{1-(log(1/S)/log(2))}, \tag{5}$$

where N is the number of units and S is the learning curve percentage. In this work, the learning curve percentage is assumed to be 90%. The cost estimation of other units is

$$C_{unit-cost} = C_{first-unit} \cdot (L - 1), \tag{6}$$

where L is the learning curve calculated from (5) and $C_{first-unit}$ is obtained from (4).

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The launch costs are recurring and it depends on the launch vehicle and the number of the number of satellites. The launch cost is calculated as

$$C_{Launch} = C_{launch-vehicle} \cdot N, \tag{7}$$

where N is the number of units. In this paper, the launch costs for Falcon 9 is utilized.

The operations and support cost are essential for a system to sustain its life cycle. These costs involve the personnel cost to operate the system, maintenance of the system as well as the facilities cost. The equations used in the estimation of operations cost is provided in the Space Mission Engineering textbook [40].

Estimating costs depends on various factors. In this paper, the estimating cost is obtained from the Technology Readiness Levels (TRL). These levels measure the maturity level of a particular technology. The estimating costs is calculated as follows

$$C_{estimating} = C_{units} \cdot Y_{Ef}, \tag{8}$$

where C_{Units} is the cost of a single unit and Y_{Ef} is the estimating factor which selected based on the TRL level. In this paper, the TRL level is assumed to be TRL 6 which has a multiplying factor of 1.

3.4 Sensitivity analysis

A variance-based global sensitivity analysis, called Sobol' indices, is used to determine the internal parameters which affect the cost of the system [30, 36]. Sobol' indices uses variance decomposition to find the sensitivity index. For a function $Y = f(\mathbf{X})$, with $\mathbf{X}$ as vector of n input parameters, the model response is provided as follows

$$y = f_0 + \sum_{i=1}^{n} f_i(\mathbf{X}_i) + \sum_{i<j}^{n} f_{i,j}(\mathbf{X}_i, \mathbf{X}_j) + ... + f_{1,2,...,m}(\mathbf{X}_1, \mathbf{X}_2, ..., \mathbf{X}_n), \tag{9}$$

where f_0 is a constant,n are first order function (f_i), $\sum_{i<j}^{n} f_{i,j}(\mathbf{X}_i, \mathbf{X}_j)$ second order functions and so on. All the decomposed terms are orthogonal which can be further decomposed in terms of conditional expected values

$$f_0 = E(f(\mathbf{X})), \tag{10}$$

$$f_i(\mathbf{X}_i) = E(f(\mathbf{X}|\mathbf{X}_i) - f_0, \tag{11}$$

and

$$f_{i,j}(\mathbf{X}_i, \mathbf{X}_j) = E(f|\mathbf{X}_i, \mathbf{X}_j) - f_0 - f_i(\mathbf{X}_i) - f_j(\mathbf{X}_j). \tag{12}$$

The variance of (9) is

$$Var(f(\mathbf{X})) = \sum_{i=1}^{n} V_i + \sum_{i<j}^{n} V_{i,j} + ... + V_{1,2,...,m}, \tag{13}$$

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where V_i is $Var[E(f(\mathbf{X}|\mathbf{X}_i)]$ and $V(f(\mathbf{X}))$ represents the total variance. The Sobol' indices are obtained by dividing (13) by $V(f(\mathbf{X}))$ to obtain

$$1 = \sum_{i}^{n} S_i + \sum_{i<j}^{n} S_{i,j} + ... + S_{1,2,..n} \tag{14}$$

where S_i represents the first-order Sobol' indices as

$$S_i = \frac{V_i}{Var(f(\mathbf{X}))}. \tag{15}$$

The total-effect Sobol' indices are given as

$$S_{T_i} = 1 - \frac{Var_{\mathbf{X}_{\sim i}}(E(f(\mathbf{X})|\mathbf{X}_{\sim i}))}{Var(f(\mathbf{X}))}, \tag{16}$$

where $\mathbf{X}_{\sim i}$ gives the set of all the parameters except $\mathbf{X}_i$. By using the Sobol' indices S_i and S_T, the effect of $\mathbf{X}_i$ can be computed, thus, providing added information about the parameter interactions.

3.5 Parameter sampling

Model-based GSA involves the sampling of the input parameters and then performing the corresponding evaluations of the simulation model. The sampling needs to be performed for several combinations to capture the model response trend. In this work, the internal factors are sampled from the physics model as well the cost model. Eleven parameters are used to identify which factor affects the cost of the system. Table 2 includes the parameters and their bounds (assuming a uniform distribution) which are used in the GSA using Sobol' indices. Generation of the samples for this study is performed using random samples from a uniform distribution within the bounds provided in Table 2 [4]. A Monte Carlo-based numerical procedure is used to compute the Sobol' indices [32].

4 Results

The calculated cost of the AEHF along with the estimated costs from SARs data [39, 11–24] of the program are provided in Fig. 5. The calculated costs of AEHF match well in general with the data. From Fig. 5, it is seen that there is a mismatch for some years. This is due to the various assumptions made in the cost model (cf. Sec. 3.3) of the satellite program. Changing the assumptions to match the costs for the years 2003 to 2007 will change the costs in other years. Therefore, for the simplicity of calculations, the assumptions are retained and the model is considered accurate enough for performing the GSA.

The cost model is then used to determine the different internal factors which have an effect on the total cost by using sensitivity analysis. The GSA needs $n = 10^6$ samples to reach convergence on the Sobol' indices (Figs. 6 and 7). The

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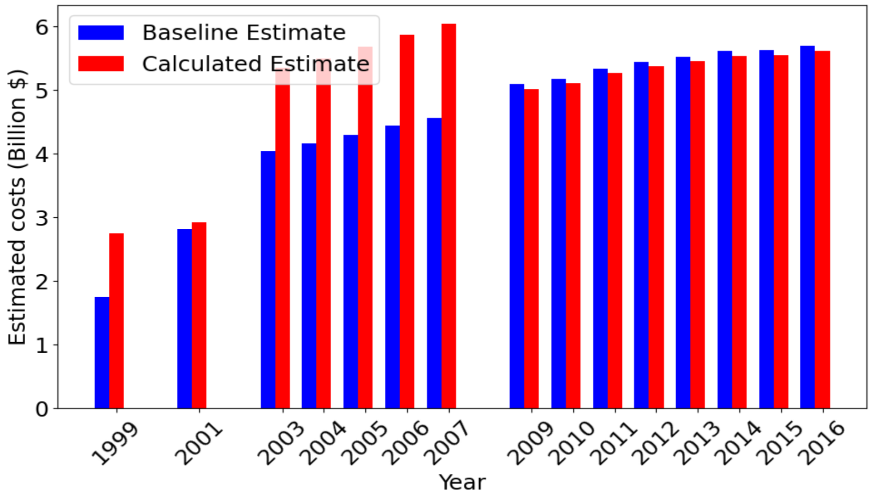

Fig. 5: Calculated yearly cost estimate and baseline estimated costs of AEHF satellite (data obtained from [1, 39, 11–24]).

GSA is repeated $m = 10$ times to obtain the mean and standard deviation of the Sobol' indices estimates (Fig. 8).

From Fig. 8 it is seen that the parameters X_1 (number of transponders), X_2 (power of the satellite), X_7 (technology readiness level(estimating cost), X_8 (learning curve) and X_{11} (number of units) have significant effect on the cost of the program. Other internal parameters used in this program have negligible impact on the cost. It is also seen that X_1 (number of transponders) and X_2 (power of the satellite) have the highest impact on the cost and these factors are a part of the physics-based satellite model.

Table 2: Internal parameters used in GSA

Parameters	**Description**	**Lower Bound**	**Upper Bound**
X_1	Number of transponders (units)	2	20
X_2	Power of the satellite (Watts)	2	30,000
X_3	Salary of the engineers and technicians ($)	100x10^3	300x10^3
X_4	Number of engineers (units)	2	20
X_5	Number of technicians (units)	2	20
X_6	Years of operations (number)	5	30
X_7	Estimating cost (TRL) (number)	0.1	4
X_8	Learning curve (number)	0.6	0.95
X_9	Percentage of Hardware operations (%)	1	40
X_{10}	Percentage of PMSE (%)	1	20
X_{11}	Number of units	1	10

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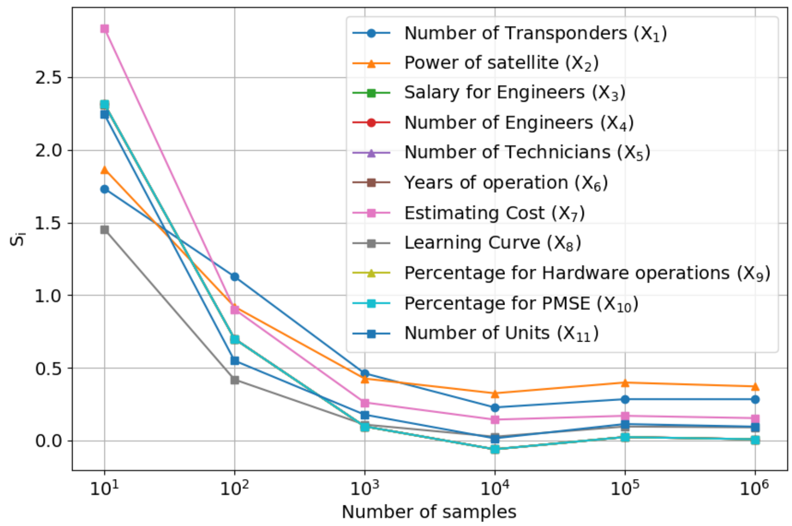

Fig. 6: Sobol' indices of 1st-order of the endogenous parameters.

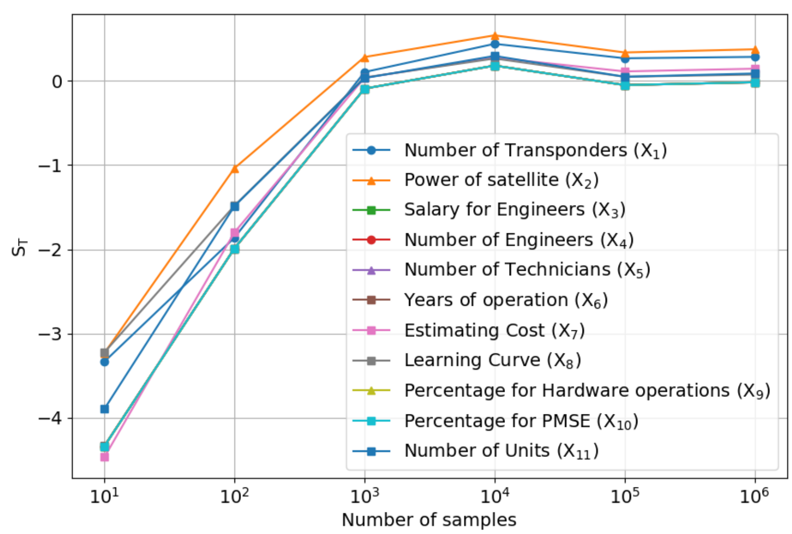

Fig. 7: Total-order Sobol' indices of the endogenous parameters.

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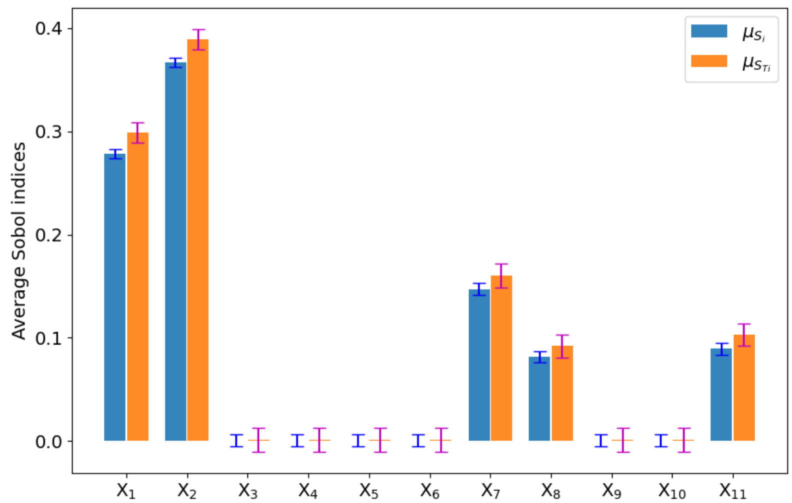

Fig. 8: Average and standard deviation of the first- and total-order Sobol' indices.

5 Conclusion

In this work, model-based global sensitivity analysis (GSA) is used to determine the effects of large-scale satellite program's, the advanced extremely high frequency (AEHF) satellite, endogenous (internal) parameters on the program overall cost. A physics-based satellite model and a cost model were been used to estimate the cost of AEHF.

Sobol' analysis performed on eleven internal factors shows that parameters such as the number of transponders and power of the satellite have the most significant impact on the satellite's cost. This study shows that GSA can be used to determine the system's internal factors and helps in determine which internal parameters affect the cost the most. These results will be used in future work to determine the effects of both internal and external parameters on the program's actual cost.

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