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The Research on The Time-Dependent Evaluation Model of Space Debris Removal

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Abstract. In this paper, we build the *Time-Dependent Alternatives Evaluation Model* to determine the best alternative or combination of alternatives to remove the space debris. The model is consist of three small models, such as *Costs, Risks and Benefits models* which are time-dependent models. After consulting some researches, we discover five basic alternatives: S1, S2, S3, S4, S5. Using measure parameters of the alternatives, we obtain specific quantities of *Costs, Risks and Benefits*. Considering the factors, we qualitatively analyze five alternatives by *Borda Count Method*. S2 (ground-based laser) might be the best alternative.

Introduction

There are a number of alternatives to remove the space debris including small, space-based water jets and high energy lasers etc. To get the best alternative, it is necessary to put forward several alternatives by evaluating some important factors such as *costs*, *risks* and *benefits*. Then, the best alternative or the combination of alternatives can be determined. In addition to evaluate directly by the factors, the method of approaching ideal point is performed.

What's more, *time* is an significant variable. In this paper, *time* express different year, it is discrete. The important factors such as *costs*, *risks* and *benefits* are influenced by *time* directly or indirectly. Therefore, we establish a time-dependent alternatives evaluation model.

Time-Dependent Alternatives Evaluation Model

Alternatives of space debris removal:

By referring to information, some technical alternatives are collected: *space-based laser(S1), ground-based laser(S2), solar sail(S3), resistance-increased device(S4), electric cable(S5)*. The specific alternative or combination is shown as follows:

Table 1: the character of different alternatives

Alternatives	Target orbit	Removing ability	Volume	Quality	Spending of time	Lifetime
S1	LEO/MEO/GEO	0.01	50	200	15	20
S2	LEO	0.01	0	0	15	50
S3	LEO/MEO/GEO	3	80	250	80	10
S4	LEO	2	80	300	120	10
S5	LEO	2	200	300	120	5
S2+S3	LEO/MEO/GEO	10	80	250	15	40
S3+S5	LEO/MEO/GEO	10	280	550	100	15
S1+S5	LEO/MEO/GEO	5	250	500	30	25
S1+S2	LEO/MEO/GEO	1	50	200	7	40

We define $C(t)$, $R(t)$, $B(t)$ stand for the time functions about *costs*, *risks*, *benefits* respectively. And then, we should establish three models to analysis and evaluate these alternatives.

Risks Model:

According to the model, *risks* should meet the equation as follows:

$$R(t)=e^{(j+P(t))}+G(q)\cdot M \; ; \qquad (1)$$

Where $p(t)$ is the probability of a satellite being hit by space debris within a year. j is a collision parameter. So $e^{(j+P(t))}$ is used to measure the risk of debris impact to the alternatives. $G(q)$ is a function of the satellite's fault.

There are three orbits that we should consider. If we regard their heights are 5000km, 6000km and 36000km, then discuss the probability of collision happened in different orbits. From model I, diameters of most of debris are less than 10cm. In the paper we only consider most debris.

Costs Model:

According to the model, *costs* should meet the equation as follows:

$$C(t)=m(i)\cdot A\cdot h+round\left[\frac{\upsilon_1}{\upsilon_2}\right]\cdot E(i)+D\cdot V\int_0^1 F dl\cdot t_d\cdot round\left[\frac{\upsilon_1}{\upsilon_2}\right]+k\left[t_d\cdot round\left[\frac{\upsilon_1}{\upsilon_2}\right]\Big/Y\right] \qquad (2)$$

Among them, $m(i)$ represents the quality of the satellite in different alternatives. A is the transmission coefficient, h is the height in different alternatives. So the physical meaning of $m(i)\cdot A\cdot h$ refers to the *costs* that a company launch a satellite to remove the debris.

υ_1 is the total area where debris need to be removed, and υ_2 is capability of removing the debris(the area where the satellite can remove all debris once). If $E(i)$ is the cost that debris to be removed once, $round\left[\frac{\upsilon_1}{\upsilon_2}\right]$ indicates the number of times to remove. Then $round\left[\frac{\upsilon_1}{\upsilon_2}\right]\cdot E(i)$ is the cost using alternative i.

To get $E(i)$, we scan the paper from others**[1]**:

$$E(i)=\frac{V_{\cos t}}{N_{total}} \; ; \qquad (3)$$

$$N_{total}=N_{cata\log e}\cdot\frac{F}{F'} \; ; \qquad (4)$$

Where N_{total}=402000 , $F=0.0084,0.0032,0.0053$ and $F'=0.0032,0.0027,0.0016$. F and F' are obtained from model I. $V_{\cos t}$ is the fixed cost of private firm. By calculation, $V_{\cos t}$ equals to $\$164.349$, $\$231.923$ and $\$315.779$ in different orbits.

$k\left[t_d\cdot round\left[\frac{\upsilon_1}{\upsilon_2}\right]\Big/Y\right]$ expresses the depreciated cost, k is a depreciated parameter. And Y is lifetime of a satellite.

Benefits Model:

As the model shows, *benefits* should meet the equation as follows:

$$B(t)=\sum_{i=1}^{2}E_i \; ; \qquad (5)$$

In this model, benefits are divided into two parts, $E(1)$ and $E(2)$:

$$E(i)=\begin{cases} E(1)=E_m(h) \cdot e^{\alpha F} \\ E(2)=C \cdot round\left[\frac{\upsilon 1}{\upsilon 2}\right] \cdot E(i) \end{cases}; \qquad (6)$$

Where $E(1)$ represents the space value of different heights. $E(2)$ is the private firm's charges of removing space debris. In $E(1)$, $E_m(h)$ is a function of space value. C is called value coefficient. $e^{\alpha F}$ represents the influence to the space value caused by the flux of space debris. $E(i)$ is the unit price of space removing. $round\left[\frac{\upsilon 1}{\upsilon 2}\right]$ indicates the number of times to remove the debris.

Borda Count Model:

Solutions based on risks, costs and benefits are obtained, we can use Borda Count model **[2]** to make the qualitative order of the multiple attribute solutions. Then We can determine the optimal ordering.

The basic idea of the model is to establish an evaluation set $D=\{d_1,d_2,\ldots d_n\}$, where d_n is the corresponding ranking. Every d_n weighs differently. $w(d_i)$ is used to express it. Borda count is the sum of all $w(d_i)$:

$$B(i)=\sum_{i=1}^{n} w(d_i)D(i), i=1,2,\ldots n; \qquad (7)$$

By contrast of Borda count, we get the best order.

Conclusions:

According to the result of Borda count model, we obtain table 2and table 3.

Table 2: The rank of each character

Alternatives	Risks	Costs	Benefits	Borda Count
S1	2	3	1	18.33
S2	3	1	2	16.33
S3	9	5	6	4.33
S4	4	6	7	6
S5	5	7	3	7.66

Table 3: The Borda counter

Alternatives	Borda Count
S1	18.33
S2	16.33
S5	7.66
S4	6
S3	4.33

Ranking these *Borda values*, we get the best order in different orbits(from the best to the worst):

$$S1 \rightarrow S2 \rightarrow S5 \rightarrow S4 \rightarrow S3$$

Finally, we can find the best alternative is S1. It means space-based laser is the best alternative to removing space debris if we take risk, cost and benefit into consideration.

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