OPTIMIZATION OF DUAL-USE SYSTEM ARCHITECTURE USING SEQUENTIAL QUADRATIC PROGRAMMING METHOD

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ABSTRACT

For large and complex systems, such as space applications, there exist several cases wherein civilian and defence stakeholders enable interoperability and data sharing with each asset. For this reason, there is concern that both stakeholders are hesitant to architect a dual-use system. This study aimed at optimization by searching for points where a compromise can be reached when developing a civilian and defence dual-use system. Specifically, we modelled the relationship of information sharing between civilian and defence stakeholders, and then performed calculations in the dual-use space situational awareness system by using the sequential quadratic programming (SQP) method. We focused on the relative changes in the risk and profit of each player in the dual-use system. To find a compromise between profit and risk, we formulated an information sharing model by defining appropriate preconditions. Consequently, by defining profit and risk as prerequisites, we were able to converge to a point where both sides reached a compromise. The result of this study provides a quantitative optimal solution that can determine how much information should be provided mutually when constructing a dual-use system. In other words, we established a quantitative validation method to derive a compromise between conflicted profit relationships in a dual-use system.

KEYWORDS: *dual-use, civilian, defence, space situational awareness, system architecture, sequential quadratic programming, optimization*

I. INTRODUCTION

For large-scale and complicated systems, the efficient utilization of assets that comprise the structural elements of a system is an important theme in systems architecture. Generally, if two players mutually provide their respective resources for dual-use, each player can benefit from the entire system because they can effectively utilize the limited resources against single use. In particular, dual-use operations of defence and civilian stakeholders often co-exist in large-scale systems, such as space assets, as a means of improving efficiency[1][2]. For example, the US Air Force's global positioning system (GPS) provides high-precision positioning information to the defence sector. But the civilians were not simultaneously released GPS data with the positioning accuracy until 2000 [3][4]. Additionally, the Italian Cosmo-SkyMed dual-use satellite system is responsible both for environmental observation and regional surveillance for civilian users and national security objectives [5][6].

Thus, civilian and defence dual-use systems are already implemented in various space applications. However, in cases where conflict arises between the players, various disadvantages are induced. For example, there exist various actual tasks with regard to information sharing in the space situational awareness (SSA) system [7][8]. The need to track space objects and provide information regarding space activities is increasingly becoming critical to the prevention of collision or debris-related damage to space assets. This type of activity is known as SSA. Rendleman et al. have argued that to employ a coordination framework and operate parallel, coordinated, international, commercial, and US Department of Defense (DoD) SSA systems, is a powerful approach and a necessary measure to improve the accuracy of orbital information [7]. However, Chow has pointed out that information related to defence objectives is untimely and inaccurate, and that "in sharing information on orbital positions to foreign and commercial users, they worry about the program's potential to compromise confidential or sensitive data about satellites that supply key U.S. military needs, specifically those related to intelligence and reconnaissance" [9]. This related study also reported that civilian satellite operators are concerned about revealing proprietary trade secrets. Thereby, when providing information collected by defence sensors to civilians, it is necessary to simultaneously satisfy the requirements of the defence stakeholders, who do not wish to disclose the collected SSA information, in addition to satisfying the requirements of civilians who wish to obtain as much SSA information as possible and use it in business and practical applications. To this end, it is necessary to consider how much information can be kept confidential by the defence stakeholders, and ultimately satisfy both requirements with a single system. Consequently, if dual-use system architecture is able to make some profit as a single system, it can be said that dual-use will have achieved optimization. Therefore, the amount of information that can be provided mutually will be the maximum profit of the complete and optimized system. When developing a dual-use system, it is necessary to conduct research in advance, and achieve a compromise between the players.

This study clarified how to balance SSA information sharing between civilian and the defence stakeholders, and how we can build a dual-use system when applying defence and civilian assets. For example, when defence and civilian players participate in a dual-use system, they may receive profits in addition to taking risks. Because the precision data from the abovementioned GPS system was only used by the US forces and not disclosed to civilians until Clinton's administration, it was considered that the defence stakeholders receive some profit by keeping the GPS data undisclosed. Moreover, it can be said that risks exist because the data are released to civilian users with reduced accuracy. However, because civilian users are sufficiently profitable, even with lower data accuracy, as long as there is acceptable profit, the entire system can be profitable.

It is desirable to evaluate profits and risks in terms of total optimization with regard to the qualitative examination of the extent that information sharing can be achieved in a dual-use SSA system. Therefore, first, we considered a situation wherein each player received data obtained by observation through civilian and defence sensors in the dual-use SSA system, and the players took risks and received profits, simultaneously. Second, we clarified the constraint conditions based on the specific contents of the profits and risks, and formulated a profit and risk relationship model. Third, the sequential quadratic programming (SQP) method was used to obtain the optimal solution of the mathematical formula [10]. The SQP method has been proven to be highly effective in solving constrained optimization problems with smooth nonlinear functions in the objective and constraints. For the qualitative task of SSA, the SQP method can be considered as a mathematical method to quantify the profits and risks. By applying the constraint condition to the SSA model, we can investigate a compromise, with regard to the task assigned to the model, by using the SQP method. After confirming that a quantitative solution can be obtained by the SQP method, it can be said that a capable method of quantitatively evaluating the total system optimization for the dual-use model will have been established.

II. DUAL-USE SSA SYSTEM

In this section, we consider a dual-use model for the mutual use of SSA information by two players [11]. In this study, the details of the model were investigated by assuming the use of civilian and defence sector radar sensors, which are actually employed in civilian and defence aerospace activities in Japan.

2.1. SSA System Activity Flow

The abovementioned SSA activities include searching and tracking for satellites or space debris with dedicated, collateral, and contributing sensors, the analysis of their orbits, and the cataloguing and distribution of information. The SSA activity functions include the following: (a) observation planning, (b) space observation, (c) data collection and analysis, and (d) distribution of information to end-users. Figure 1 shows the SSA activity flowchart, which demonstrates these functions. First, we establish an observation plan to permanently obtain the debris orbital data. Second, we conduct space observation by using SSA sensors, such as a radar and optical telescope. Third, we collect the SSA data, analyse it, and accumulate information. Finally, we distribute the SSA information to users worldwide.

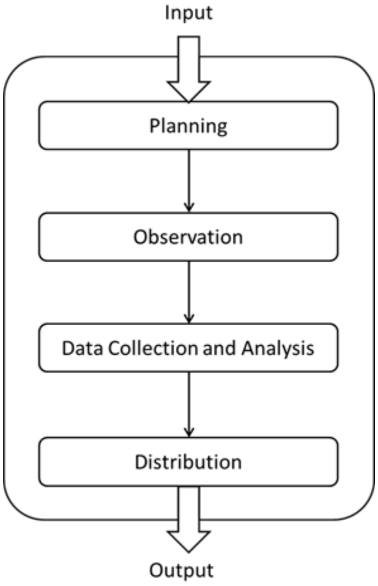

Figure 1. SSA activity flowchart

2.2. Dual-Use SSA System Activity Flow

Here, we explore the dual-use SSA flow of activities performed by civilian and defence players. The effect expected from the civilian and defence sector dual-use SSA activity is to observe more detailed SSA data with multiple SSA sensors, and increase the reliability of the SSA information. Figure 2 shows the dual-use SSA system activity flow. Here, both civilian and defence stakeholders are within the SSA system boundary that provides information mutually, while maintaining the independent system shown in Fig. 1. The civilian and defence SSA is mutually involved in distributing the corrected information. Here, the profit earned when civilian players receive information from defence players is termed as P_{12}, and the profit earned when the defence players receive information from civilian players is termed as P_{21}. Moreover, the risk of distributing information to defence players is represented by R_{12}, while the risk of distributing defence information to civilians is represented by R_{21}.

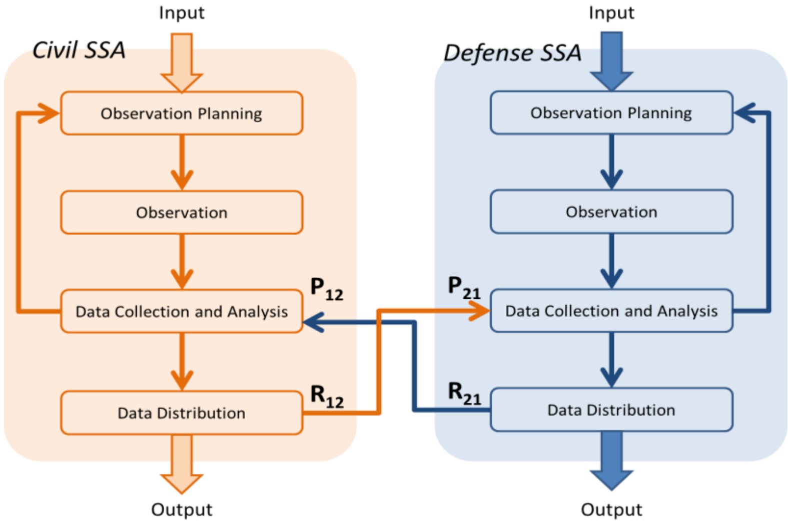

Figure 2. Dual-use SSA system activity flow

2.3. Analysis of Profit and Risk in Dual-Use SSA System

In the flowchart shown in Figure 2, it can be seen that the defence stakeholders have to allow risks, such as decrease in confidentiality, by providing information to a less secure system. Civilians may also have to consider compliance issues and confidentiality obligations as risks when operating on the same system as the defence stakeholders. Thereby, information sharing can result in various profits and risks for both parties. But what are the indicators of potential profits and risks? Although there are multiple factors to consider in risk analysis, four risk and profit indicators are listed in Table 1 as representative examples. Moreover, there exists a concern according to which information sharing risks in a dual-use system may impair accessibility and interoperability. Additionally, efficiency and redundancy are more profitable.

Table 1. Risk and profit indicators of dual-use SSA system.

Indicators	Index	Description
$R_{\_access}$	Accessibility	Civilian users have access to data obtained from defence sensors, and vice versa. Negative evaluation constraints such as membership registration and identity verification.
$R_{\_inop}$	Interoperability	Operational or not, for both stakeholders. Negative evaluation if both operational requirements cannot be satisfied.
$P_{\_eff}$	Efficiency	Dual-use assets can improve efficiency. Positive evaluation if there exist differences in human and material cost, in comparison with a single use system.
$P_{\_red}$	Redundancy	Positive evaluation with regard to increasing the number of sensors and expanding the observation area.

Here, R and P are expressed qualitatively by Equations (1) and (2), respectively, as follows:

$$R = f(R_{\_access} + R_{\_inop} + ... + R_n) \quad (1)$$

$$P = f(P_{\_eff} + P_{\_red} + ... + P_n) \quad (2)$$

The calculations required to quantify and present these qualitative representations are complicated, owing to the consideration of many variables. Therefore, solving these equations is a difficult task. Thus, we attempted to carry out quantification with regard to a simplified SSA information sharing model, as described below.

2.4. Simplified Dual-Use SSA Data Exchange Model

In a dual-use system, the information flow shared by civilian and defence stakeholders can be simplified as shown in Figure 3, where it can be seen that the profit and risk relationship model expresses the SSA information exchange by focusing on shifting from civilian to defence or from defence to civilian information exchange. Therefore, the information transferred from defence to defence and from civilians to civilians is not subject to any risks or profits. The abbreviations used in this figure are defined in Table 2. When the amount of SSA data S_1, which is obtained from a civilian sensor, is provided to the defence stakeholders, the profit P_{21} is generated for the defence stakeholders along with the distribution ratio multiplication factor f_{21}. Moreover, the civilian side generates risk R_{12} with the coefficient risk factor r_{12}. Conversely, even when the amount of SSA data S_2, which is obtained from the defence side, is provided to civilians, the civilian profit P_{12} and the defence risk R_{21} are generated simultaneously.

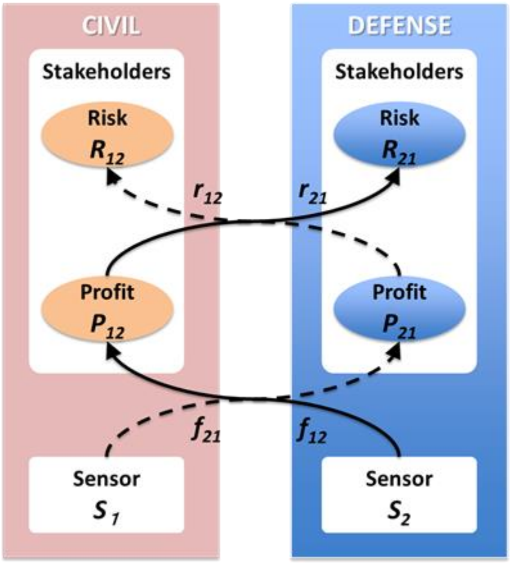

Figure 3. Profit and risk relationship model

Table 2. List of variables and parameters.

Symbol	Variables and parameters
S_1	Resource of civilian stakeholders; space observation data from civilian SSA sensors
S_2	Resource of defence stakeholders; space observation data from defence SSA sensors
P_{12}	Profit of civilian stakeholders obtained by transaction with defence stakeholders
P_{21}	Profit of defence stakeholders obtained by transaction with civilian stakeholders
R_{12}	Risk of civilian stakeholders caused by transaction with defence stakeholders
R_{21}	Risk of defence stakeholders caused by transaction with civilian stakeholders
f_{12}	Multiplication factor for transaction from defence stakeholders to civilian stakeholders
f_{21}	Multiplication factor for transaction from civilian stakeholders to defence stakeholders
r_{12}	Risk factor caused by transaction from defence stakeholders to civilian stakeholders
r_{21}	Risk factor caused by transaction from civilian stakeholders to defence stakeholders

III. OPTIMAL CALCULATION WITH SQP METHOD

3.1. Concept of Optimal Calculation

Civilian and defence stakeholders have SSA information and receive both profit and risk by providing the information to each other. Both players can only make qualitative decisions about how much information they can provide to their opponents and whether this will be the best action for themselves. To quantitatively explore the trade-off point, describe the exchange of information as a differentiable equation, and set its proper preconditions, it is possible to quantitatively calculate the trade-off point to be optimized for each side. In this study, to compute the equation under such conditions, we used the SQP method to converge to some extent with high accuracy. This concept of optimal calculation is described in Figure 4. In this figure, the horizontal axis represents the trade-off point and the vertical axis represents the risk value. Here, each player is supposed to provide a certain amount of information to each other. Then, for example, a defence player is willing to decide not to increase the information given to others because the risk value increases sharply. That point becomes a trade-off point for the defence player. When the proportion of providing information to others varies, the point of increase of the risk value also changes. Functions that show the relationship between the increasing risk and the trade-off can be represented by the mathematical formulas presented in Figure 4.

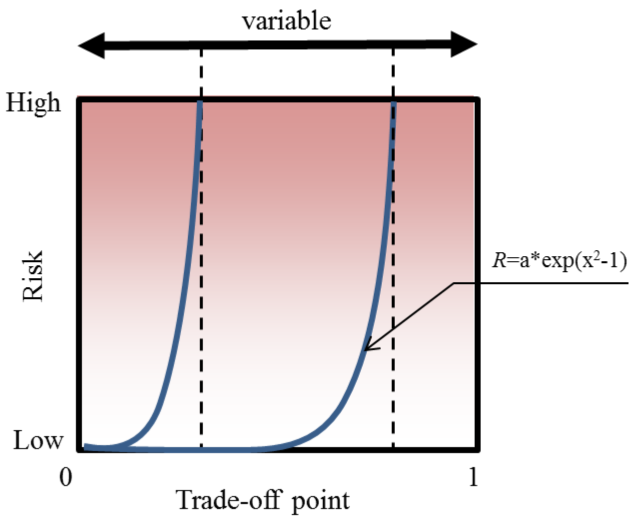

Figure 4. Trade-off point between civilian and defence players

3.2. Fundamental Equations

This section describes the optimization problem of calculating the model shown in Figure 3, so as to arrive at a point of compromise that minimizes the overall risk and maximizes profit. We attempted to formulate the model accordingly, as follows: let S_1 be the data resources obtained by the civilian sensor, and S_2 be the data resources obtained by the defence sensor, the profit P_{12}, when civilians obtain information from defence, is expressed as follows:

$$P_{12} = f_{12} \cdot S_2 \quad \textbf{(3)}$$

Here, the input of S_2 depends on factors such as the number of observation sensors, sensor performance, and observation frequency. The profit P_{21}, which is obtained by the defence sector when the defence stakeholders obtain civilian information, is expressed as follows:

$$P_{21} = f_{21} \cdot S_1 \quad \textbf{(4)}$$

Here, f_{12} and f_{21}, which represent the proportion of distributed information from each sensor, satisfy the following inequalities, respectively:

$$0 < f_{12} < 1 \quad \textbf{(5)}$$

$$0 < f_{21} < 1 \quad \textbf{(6)}$$

The risk R_{12}, which exists when civilians obtain defence information, is expressed as follows:

$$R_{12} = R_{10} + r_{12} \cdot P_{21} \quad \textbf{(7)}$$

Likewise, the risk R_{21}, which is obtained when defence stakeholders obtain civilian information, is expressed as follows:

$$R_{21} = R_{20} + r_{21} \cdot P_{12} \quad \textbf{(8)}$$

where R_{10} and R_{20} are the independently existing initial risks for the defence and civilian stakeholders with regard to information distribution. In this dual-use model, the objective is to minimize the risk of the total system, while maximizing profit. Therefore, the objective function f is expressed as follows:

$$f = (R_{12} + R_{21}) / (P_{12} + P_{21}) \rightarrow \min \quad \textbf{(9)}$$

3.3. Parametric Investigation

The objective of this study was to explore where the SSA dual-use model can achieve a compromise between profit and risk for civilian and defence stakeholders. To this end, we employed the SQP method, which is a popular general-purpose optimization algorithm that is widely used to solve equations such as those presented above. The preconditions for the calculation are defined below.

The number of sensors has a large influence on input. As shown in detail in Figure 1, it can be assumed that the observation performance of the defence sector is more extensive than that of civilians. According to the number of sensors, performance level, and width of the frequency band, the S_1 and S_2 values expressed by Equations (3) and (4) are given as 10 and 50, respectively. The civilian side has two sensor sets, five performance levels, and one frequency band; therefore, the value of S_1 is determined as the dimensionless number of 10. The defence side has one sensor set, 10 performance levels and five frequency bands; therefore, the value of S2 is determined as the dimensionless number of 50.

Civilian sensor: [two sets/five performance levels/one frequency band]; total: 2*5*1=10

Defence sensor: [one set/10 performance levels/five frequency bands]; total: 1*10*5=50

The initial risk values R_{10} and R_{20} in Equations (7) and (8) are R_{10} = 5.0 and R_{20} = 50.0, assuming that the risk of information disclosure by the defence stakeholders is ten times larger than the same risk for civilians.

In the differentiable Equations (10) and (11), r_{12}=0.10 and r_{21}=0.90, assuming that there hardly exists any risk for civilians that occurs with the profits of the defence stakeholders. Additionally, we assume that a_{12}=1.0 and a_{21}=10.0. This is because, if risk occurs for the defence stakeholders, the possibility of risk expansion is larger than that on the civilian side. These two equations are differentiable expressions for the application of the SQP method.

$$r_{12} = a_{12} \cdot (\exp x(1)^2 - 1) \quad \textbf{(10)}$$

$$r_{21} = a_{21} \cdot (\exp x(2)^2 - 1) \quad \textbf{(11)}$$

3.4. Numerical Results of SQP Method

In this section, we describe the calculation of the model shown in Figure 2 by the SQP method. Figure 5 shows an optimization process that is carried out by using the SQP calculation result. In this figure, $x(1)$ is on the horizontal axis and F is on the vertical axis, where F is the objective function. Here, when the calculation starts from 0.001 with the typical initial value of $x(1)$, it jumps to the maximum value of $x(1)$ = 1.0, and returns to the average value of these two points. As a result of repeating these iterations by the Newton-Raphson method in the SQP method program, the object function F becomes a minimum value and $x(1)$ converges to 0.31 after four iterations.

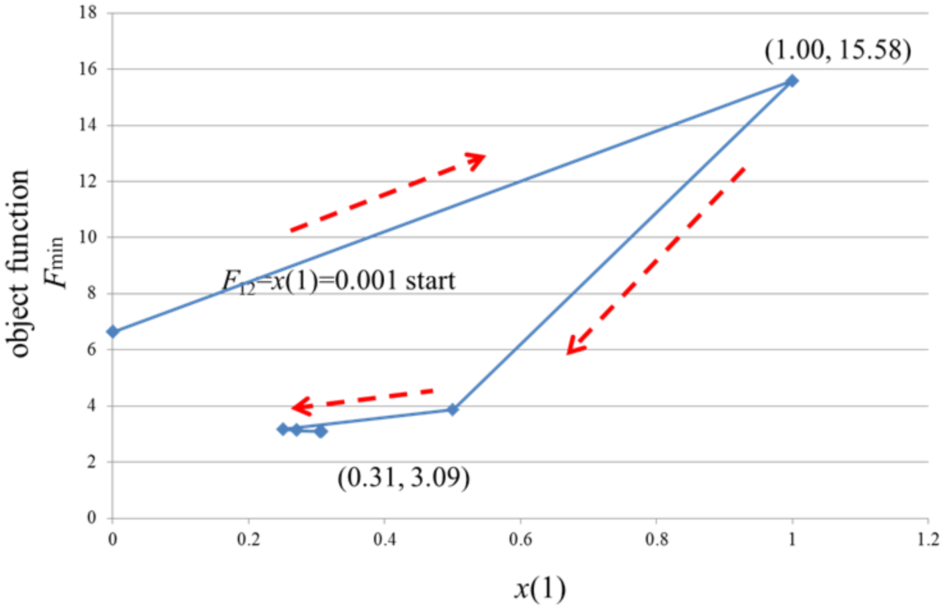

Figure 5. SQP optimization process

Figure 6 shows one of the calculated results. This figure shows $x(1) = F_{12}$, $x(2)=F_{21}$, an object function multiplied by 0.1 on the vertical axis, and the iteration number on the horizontal axis. In this case, $x(1)=F_{12}$ starts from the initial value of 0.10, $x(2)=F_{21}$ starts from the initial value of 0.30, and the other coefficients represent the same conditions. The converged value of $x(1)$ indicates the trade-off of the SSA information exchange from the defence to the civilian stakeholders, while $x(2)$ indicates the opposite situation. We observed that the converged value was $x(1)=0.309$, which is in line with the defence sector's negative intention. However, the converged value $x(2)=0.833$ is also a suitable value for the civilians' intention to obtain as much data as possible. Even when the initial value of $x(1)$ changes, the objective function converges to a reasonable value. Frequently, many SQP calculation results do not converge under certain conditions. However, this result indicates that the object function converged under the present constraint conditions.

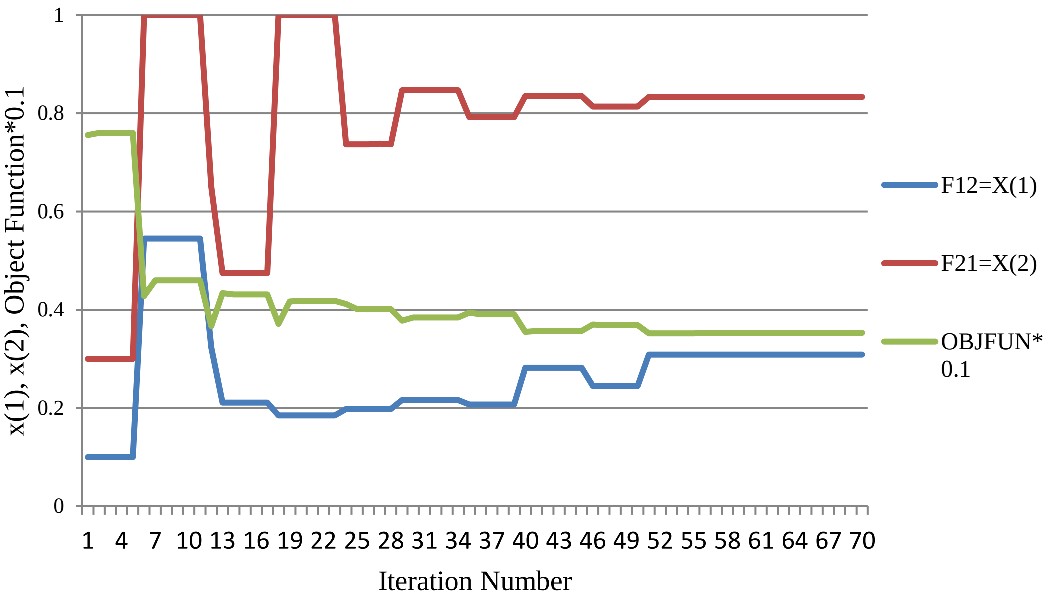

Figure 6. Calculation result

3.5. Discussion

In the dual-use SSA operation, we demonstrated that this method can quantitatively evaluate the content of cooperative relationships that are reasonable for both the civilian and defence stakeholders. To optimize more precisely for SSA by focusing on the profit and risk of both parties, it is necessary to set appropriate conditions that belong to the actual SSA assets. In this study, we succeeded in clarifying the mathematical formula of these conditions. Because only four types of R and P were selected and calculated at this time, the precise validation of the dual-use SSA system to increase the types of parameters will be the object of future work. However, in this case, the mathematical expressions will become more complex. It was also found that the prerequisites necessary for calculation are not easy to set from the viewpoint of consistency with the actual SSA system. However, it was a great achievement to prove that civilian and defence players converge to a reasonable value by setting appropriate parameters. Additionally, the validity of this conclusion could be evaluated.

For application to other systems, mutual operation by multiple subjects is a prerequisite. For example, the Italian observation satellite system Cosmo-SkyMed is a typical dual-use system. Although this study developed a model with a focus on information sharing, the model can be applied to other cases, such as the Cosmo-SkyMed, without changing specific numerical values. For other subjects, it will be necessary to develop a different model.

IV. CONCLUSIONS

The characteristics of defence and civilian systems are inherently different; thus, they are not easy to optimize. From an efficiency viewpoint, attention has been given to managing these systems as a single dual-use system. However, research on the management approach has not been conducted. This investigation is significant as a case study, wherein two subjects with different characteristics are defined as a dual-use SSA system, and an optimal solution is obtained with the SQP method by searching for points where a compromise can be reached when developing a civilian and defence dual-use system. We found that by converting the dual-use information sharing model into a mathematical expression reflecting the characteristics of the actual SSA assets, and by expressing it as an optimization variable with preconditions, the model converges to a reasonable value by the SQP method. In other words, we were able to visualize the amount of information sharing between two parties and the overall benefit.

V. FUTURE WORK

In future work, appropriate validation must be carried out by increasing the types of risk and profit parameters to use the SQP method. Additionally, this optimal calculation process will be applied to other cases, such as an earth observation satellite system [15] or a hosted payload system [16][17], to validate the architecture of the dual-use system.

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