

Service-oriented weapon systems of system portfolio selection method

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Abstract: Weapon system portfolio selection is an important combinatorial problem that arises in various applications, such as weapons development planning and equipment procurement, which are of concern to military decision makers. However, the existing weapon system-of-systems (SoS) is tightly coupled. Because of the diversity and connectivity of mission requirements, it is difficult to describe the direct mapping relationship from the mission to the weapon system. In the latest service-oriented research, the introduction of service modules to build a service-oriented, flexible, and combinable structure is an important trend. This paper proposes a service-oriented weapon system portfolio selection method, by introducing service to serve as an intermediary to connect missions and system selection, and transferring the weapon system selection into the service portfolio selection. Specifically, the relation between the service and the task is described through the service-task mapping matrix; and the relation between the service and the weapon system is constructed through the service-system mapping matrix. The service collaboration network to calculate the flexibility and connectivity of each service portfolio is then established. Through multi-objective programming, the optimal service portfolios are generated, which are further decoded into weapon system portfolios.

Keywords: weapon system portfolio selection, service-oriented, multi-objective programming.

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1. Introduction

The weapon system-of-systems (SoS) architecture, which consists of system components and the relationships among them, serves as the guideline for the design of weapon SoS over time. Thus, the modeling of weapon SoS actually involves selecting a feasible weapon system portfolio from the perspective of systemic modeling to meet required capabilities and fulfill combat missions, which is of great military significance.

Markowitz first proposed the portfolio theory in 1952, opening a new era of utilizing mathematical approaches in finance study [1]. In the field of management science and operations research, the portfolio decision theory is a possible method for resource optimization allocation, which is widely used in project investment [2], product production [3], technology research and development [4], and defense procurement [5]. The project portfolio selection field is another important area where the portfolio selection theory has been widely applied and developed in depth. The project portfolio selection compares the candidate project portfolio schemes to identify their pros and cons and selects the optimal project portfolio that meets the criteria. The commonly used methods include the goal planning method (GP) [6], such as the 0-1 integer programming method [7], and hybrid or dynamic programming. In addition, the genetic algorithm, the Monte Carlo (MC) simulation method, and the Lagrangian relaxation method are often applied to the solution process, because it is a matter of determining the feasible projects or super subsets of capital based on specific resource constraints. From the perspective of the modeling framework, the scenario-based planning method (SPM) is gradually gaining attention. It studies the foreground probability, describes the uncertainties with the desired future scenario, and develops strategies that match these uncertainties. Christopher, James, and other scholars introduced the scenario analysis and the multi-criteria decision theory to project portfolio selection in the military and industrial facilities [8].

In past applications of portfolio selection in the military field, much effort has been put in the selection of system R&D, purchase, and deployment. One typical application in portfolio decision-making is the wave model for the system evolution and capability portfolio model for SoS, proposed by researchers at Purdue University in the United States [9]. In the latest research, the weapon and equipment systems were generally evaluated from the perspectives of capability, effectiveness, risk, technical feasibility,

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evolution process, and the impact of the new technology introduced to the system [10–13].

However, there exists a long-standing problem always bothering the decision-makers in architecture modeling, that is, the mapping relation from the combat capabilities to the weapon systems is very complex. Furthermore, in weapon SoS, information resources of weapons are provided by different developers at different periods. Considering that the development language, operating system, and development platform used by each developer are different, there is significant interface heterogeneity among the information resources for the weapons. The heterogeneity of systems and the tight couplings between them even complicate the description of this relation, which will lead to two problems in weapon system portfolio selection. First, the theoretical candidate weapon may not be called because of interface inconsistency. Second, especially when the number of candidate weapon systems increases, and the already complex system construction process becomes even more complex, the complexity of the selection of the weapons system index exponentially increases, which can be categorized under the classic NP-hard problem.

Therefore, service is introduced as an intermediary to try to connect capabilities and systems. The Department of Defense (DoD) Architecture Framework (DoDAF) Working Group first mentioned the idea of service view in its DoDAF 1.5 [14] in April 2007 and further emphasized the role of service by officially conceptualizing the service view in the release of DoDAF 2.0 [15] in May 2009. Influenced by the actions of DoD, the U.K. Ministry of Defence (MoD) added content about service in its updated version of MoD Architecture Framework (MoDAF) 1.2 [16] in September 2008. In November 2007, NATO Architecture Framework (NATOAF) v3.0 [17] released by the NATO Consultation, Command and Control Board specifically described the service-oriented view, aiming at providing theory and technology support for military resource integration for member countries. Thus, it is believed to be a necessary attempt to conduct weapon system portfolio selection from the angle of service-orientation.

The study of this paper aims at establishing the mapping relation between the combat mission and system selection, and transferring the weapon system selection to service portfolio selection. The service-oriented analysis model for weapon systems consists of two stages as shown in Fig. 1: the value modeling based on the mapping between the system portfolio and the service portfolio, and portfolio selection optimization. In the first stage, the relation between the service and the task is described through the service-task mapping matrix so all the services required

to implement a certain task will be achieved; the relation between the service and the weapon system will be constructed through the service-system mapping matrix to target all the weapon systems to support the specific services. Afterward, the task-service-weapon interaction network model will be established. The above network will be decomposed into a service collaboration network, where the flexibility and connectivity features of the service will be extracted. In the second stage, multi-objective programming will be used to seek the optimal portfolios for weapon system selection.

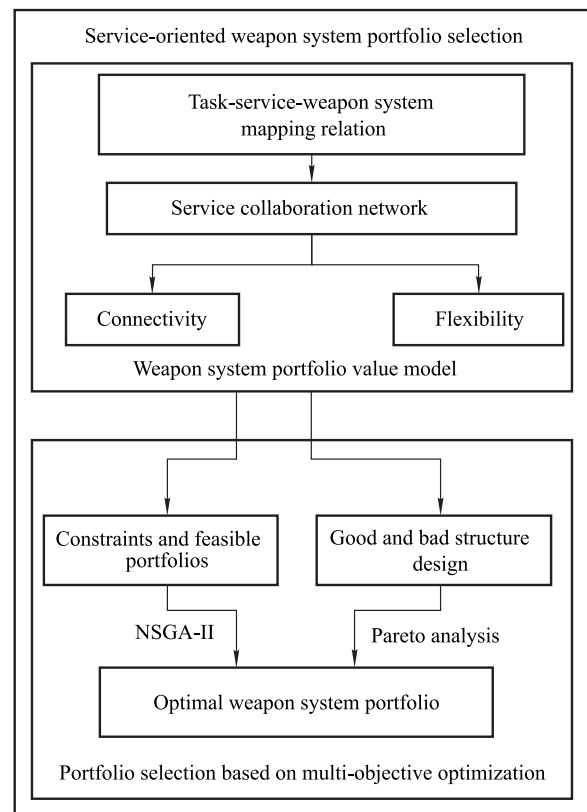


Fig. 1 Framework of service-oriented weapon system portfolio selection

The rest of the paper is structured as follows: Section 2 defines related concepts and describes the problem to be studied. Sections 3.1 and 3.2 elaborate the service-oriented system portfolio selection model, including a detailed mapping analysis of the relation between the system portfolio and the service portfolio, the construction of the service network, and the value model based on the extracted features for the weapon system portfolio selection. The service-weapon mapping decoding process is explained in Section 3.3. In Section 3.4, the optimization procedures of portfolio selection are presented. The procedures are designed with multi-objective programming where the optimal service portfolios can be obtained with

certain constraint assumptions. Through mapping decoding, the final weapon system portfolios are then generated. An illustrative example is presented in Section 4 to prove the feasibility of the proposed model and method, then the results are explained and discussed. Finally, in Section 5 we make a conclusion.

2. Problem description

Definition 1 Mission

The mission is decomposed by the national security strategy to describe the highest expectations of decision makers.

Definition 2 Task

The task is undertaken by the military to achieve the intended mission.

Definition 3 Service

By combining various resources such as humans, materials, finance, and equipment to form a specific function or mechanism, the core is to dynamically combine the static personnel consumables and equipment to form a dynamic service to support the completion of tasks.

Weapon system portfolio selection is intrinsically an optimization problem. The priority is to determine the optimization objective to measure the values of the roles of the systems or portfolios. This is where the service-oriented analysis will be adopted to calculate the values and construct the objective.

In the Gulf War, the communications service was provided by many systems, including the current BeiDou navigation satellite system (BDS) in China. It can be seen

that providing services through a systems portfolio has become an urgent need. Combining the function of a single weapon into a system-level service provides a higher-level value standard for weapon system development planning, making the value of the weapon systems portfolio closer to the actual combat.

The mapping of the weapon portfolio to the service portfolio is primarily based on the following aims:

(i) Simply splicing the corresponding capabilities of the weapons does not necessarily achieve the effect of the service portfolio. The level of interconnection between the weapons, the technical difficulty of the interface, the reliability and other uncertain factors reduce the service level of the weapon portfolio.

(ii) Under the current situation of China's military-civilian integration policy, the advantages of military resources will be fully utilized through service combinations to achieve integrated utilization and reorganization and optimization of the two, making it possible to integrate and reorganize the military-civilian system resources oriented by service portfolio selection.

(iii) The single weapon system is expensive. It is costly to build a complete weapon system with all different types of weapons. It is not necessary to purchase the weapon system when setting up the service but choose to purchase some services.

Table 1 explains the concepts and elements in the service portfolio corresponding to the ones in the weapon system portfolio.

Table 1 Mapping relation between system portfolio and service portfolio

Weapon system portfolio	Relation	Service portfolio
Weapons (equipped, developed, or to be developed)	Construct	Elements of the bottom level in the service portfolio
Weapon portfolio (all, feasible or optimal)	Provide	Service
Multi-task combat	Correspond	Multi-scenario
Objective	Correspond	Objective
Selection	Determine	Availability of the elements
Collaboration between weapons	Correspond	Interconnection between elements
Scale of weapons	Determine	Number of elements

Weapon SoS is a group of weapon systems gathered together to fulfill a certain combat mission. The combat mission can be further decomposed into several combat tasks which need to be accomplished by various weapon systems.

In traditional research, the support provided by the weapon systems for the combat task is not direct, but by using the capability to connect these weapon systems with the requirements of the task. Assume that we have to use two combat tasks to complete a combat mission, but also need to ensure that there is good information exchange be-

tween the two tasks. Weapon A provides the capability A and Weapon B provides the capability B. When the information exchange between the two weapons is achieved, they can cooperate well to promote the combat mission. However, if one of the weapons (A or B) has a problem, it is unable to provide the ability. Due to the tight coupling relationship between the weapons and the task, and the non-dynamic characteristic of the capability, it is very difficult and complicated to replace a new weapon resource, which will obviously bring disadvantages to the successful completion of the mission. This obviously does not benefit the

successful completion of the mission.

After the service is used as the media from the task to the weapon, due to the loose coupling of the service itself, the resource data, application and function in the weapon system can be encapsulated. It can also effectively reduce the heterogeneity of the system structure due to different development technologies and development platforms of various developers. Therefore, the dynamic joining and exiting of weapon systems caused by problems of weapons can take advantage of the dynamic characteristic of services and ensure that alternative services have consistent functions and interfaces, thus solving the problem that cannot be solved by using capabilities as a media.

In other words, weapon systems are combined properly to provide services for combat missions. Therefore, the idea of services can be used as an intermediary, establishing mapping relations between tasks and required weapon systems in the weapon system portfolio selection. The hierarchical structure of this mapping relation, task-service-weapon system, is shown in Fig. 2.

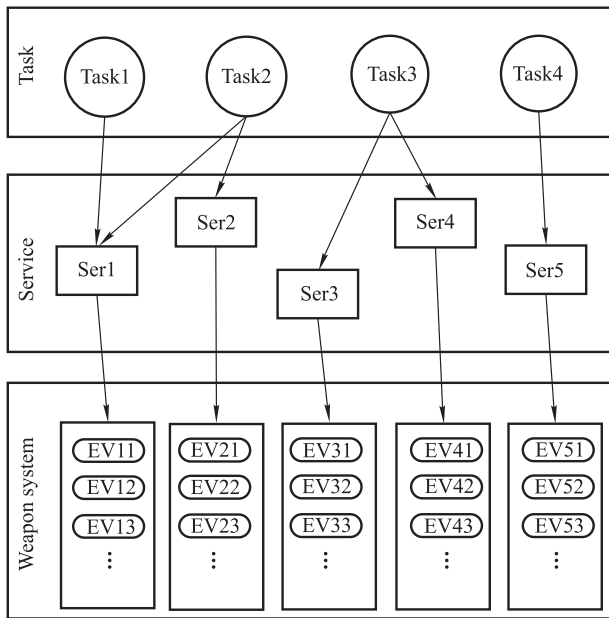


Fig. 2 Task-service-weapon system mapping relation

There are three levels in the mapping relation structure: task level, service level, and weapon system level. Each level consists of a different number of elements which are connected by arrowed solid lines between different levels. The pointing direction of the lines indicates the supporting relations. In Fig. 2, EV12 means the second weapon system that supports Ser1. As seen from Fig. 2, the weapon system portfolio selection has been transformed into first seeking the services that support certain tasks. Afterward, once the services are determined, the weapon system port-

folio will be generated according to the relations between services and weapon systems.

3. Service-oriented portfolio selection model

On the basis of the structure in Fig. 2, the subnetworks, task-service, will be transformed into a service collaboration network where the features of flexibility and connectivity are extracted to quantify the value of the service portfolio.

3.1 Service collaboration network

Considering the task-service network as a set of co-citation relations that are similar to the reference network, use the co-citation method to build a service co-citation network. As in the co-citation network, if two papers are cited at the same time, there is a co-citation relation between the two papers. Similarly, in the “task-service” network, if two services are called by one task at the same time, they are considered to have a collaborative relationship, and a collaboration edge is drawn between them with a weight equal to the number of times called.

Specifically, assume that the task-service network $T = (a_{ij})_{m \times n}$ consists of m tasks and n services where $a_{ij} = 1$ indicates task i calling service j , and the service collaboration network is represented by $S = (s_{tl})_{n \times n}$ where s_{tl} is the time when services t and l are called at the same time. If services t and l are called at the same time by task k , then $a_{kt}a_{kl} = 1$ or $a_{kt}a_{kl} = 0$. Thus,

$$s_{tl} = \sum_{k=1}^m a_{kt}a_{kl}. \tag{1}$$

It is easy to prove that $S = T^T T$ and the diagonal elements are subject to

$$s_{tt} = \sum_{k=1}^m a_{kt}^2 = \sum_{k=1}^m a_{kt}. \tag{2}$$

In fact, s_{tt} is equivalent to the number of the tasks pointing to the service t in the task-service network, which is called the incoming degree of service t . An illustrative example is presented in Fig. 3.

As shown in Fig. 3, task 1 needs to call services 1 and 2, task 2 needs to call services 1, 2, 3, and 4, and task 3 needs to call services 2, 3, and 4. After being transformed into a service collaboration network, services 1 and 2 are co-cited twice, services 1 and 3 are co-cited once, services 1 and 4 are co-cited once, services 2 and 3 are co-cited twice, services 2 and 4 are co-cited twice, and services 3 and 4 are co-cited twice.

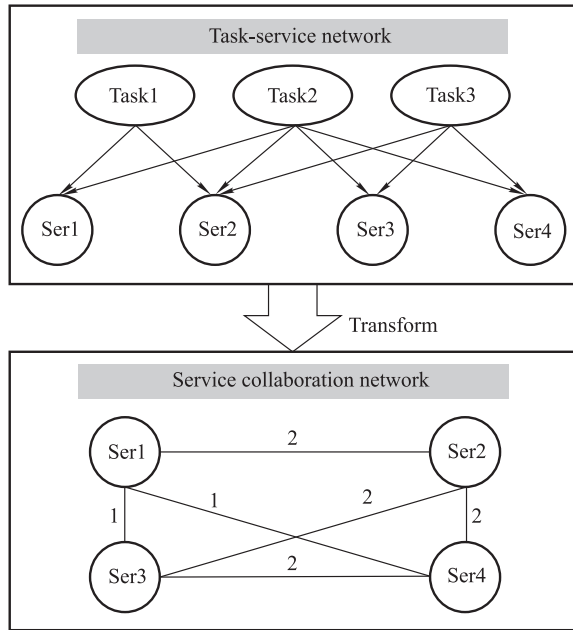


Fig. 3 Transformation from “task-service” network to service collaboration network

3.2 Feature extraction

According to the transformation from the task-service network to the service collaboration network, we complete the transition from the double-deck network to a single-deck network, and thus we can estimate the service collaboration network from some network indicators.

Flexibility: Flexibility describes the redundancy of a service group. When a task calls a service group, it does not necessarily need all the services in the group, which means some services are considered redundant for this task. The bigger the group is, the higher the redundancy is. Similarly, considering two extreme cases A and B, case A is of high redundancy because all the services are included in the group, while there is no redundancy in case B because every service group called consists of only one service. The flexibility can be calculated as

$$\text{flexibility} = 1 - \frac{\sum_{i=1}^m \text{Unused}(\text{task}_i)}{\sum_{i=1}^m \text{UnSupport}(\text{task}_i)} \times \sum_{i=1}^m \text{RequiredBy}(\text{task}_i) \quad (3)$$

where $\text{Unused}(\text{task}_i)$ represents the number of redundant services in the service portfolio that task i

calls, $\text{UnSupport}(\text{task}_i)$ represents the number of services that do not support task i in the network, and $\text{RequiredBy}(\text{task}_i)$ represents the number of service portfolios that task i needs to call.

Connectivity: Using the concept of network natural connectivity is required here [18]. Assume that the service collaboration network obtained after the transition is G and its adjacency matrix is $A(G)$, $a_{ij} \in A(G)(i, j = 1, 2, 3, \dots, N; a_{ij} \in [0, 1])$ represents the connectivity between services. The networks of service portfolios in solutions are G_1, G_2, \dots, G_M . M represents the number of portfolios, and their adjacency matrix can be obtained from $A(G)$. Previous literatures [19] and [20] have proved that the network natural connectivity is strictly monotonic with respect to adding or removing edges, which means that natural connectivity can accurately describe the nuances of network connectivity after adding or removing nodes. The following method is used to calculate the natural connectivity of network G_I ($I = 1, 2, \dots, M$) [18].

$$\bar{\lambda}_I = \ln \left(\frac{1}{N} \sum_{i=1}^N e^{\lambda_i} \right) \quad (4)$$

where λ_i is the eigenvalue of adjacency matrix $A(G_I)$. Thus, for the service portfolio solutions, the connectivity of the solution can be calculated by the following method:

$$\text{connectivity} = \sum_I^M \bar{\lambda}_I \quad (5)$$

3.3 Service portfolio-weapon system portfolio decoding

The service view product in DoDAF 2.0, service-system mapping matrix (SvcV-3a), is combined with the service collaboration network to decode the preselected service portfolio into supporting weapon systems. SvcV-3a is able to describe the relationship between systems and services and support rapid assessment on potential versatility and redundancy.

SvcV-3a can be used to summarize the interaction between systems and services and to implement the management of service interfaces. Its description model can effectively manage the development of solutions, integration of new functions and technologies, and recombination and distribution of systems, services, and functions under the ever-changing evolution of operational requirements and capability requirements.

SvcV-3a products are usually presented in the form of a matrix where the services are listed in the first row of the

matrix and the systems are listed in the first column. The cells in the matrix represent the relationships and interactions between the systems and the services.

An SvcV-3a product is formed as in Table 2.

Table 2 Example of an SvcV-3a product

System	Service		
	Service 1	Service 2	Service 3
System 1	<u>Symbol</u>	-	-
System 2	-	<u>Symbol</u>	-
System 3	-	-	<u>Symbol</u>

In Table 2, symbols can be chosen from “very poor”, “poor”, “general”, “good,” or “excellent”.

In Fig. 4, the service collaboration network consists of five services, and its service-system mapping matrix is shown in Table 3. The degree to which a weapon system supports a service is represented by a number in [0,1] for illustrative simplification. Assume that services 1, 3, and 4 make up a service portfolio and services 1 and 5 constitute another service portfolio, then according to the mapping matrix, the support of weapon systems to the services can be clearly seen in Fig. 5.

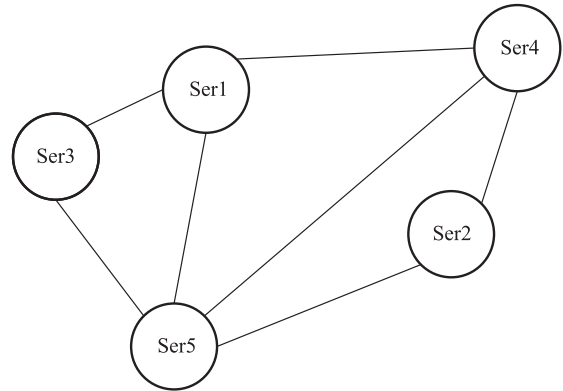


Fig. 4 Service collaboration network

Table 3 Service-system mapping matrix

System	Service				
	Ser1	Ser2	Ser3	Ser4	Ser5
A	1	0	0	1	0
B	1	1	0	0	1
C	0	1	1	1	0
D	0	0	1	0	0
E	1	0	1	0	0
F	0	1	0	1	1
G	1	0	0	0	1

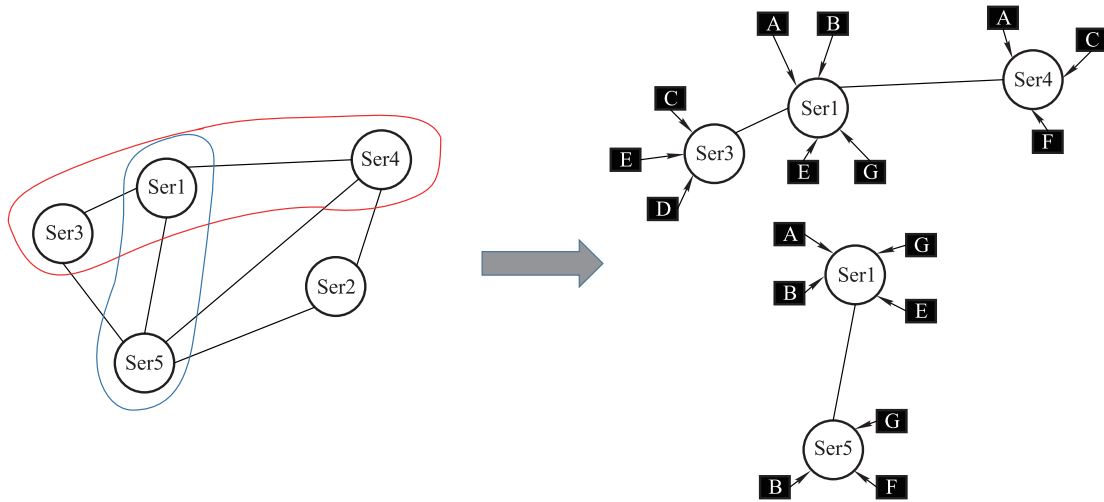


Fig. 5 Support of weapon systems for services

A service portfolio can generate a variety of different weapon system portfolios by selecting different weapon systems at different nodes, that is, the process of the service portfolio. It means that multiple selections of the weapon system portfolio can support the implementation of the same service portfolio, which improves the robustness of weapon selection. If $E_j (j = 1, 2, \dots, \text{Num}(E)_i)$ is the weapon system that supports the service, and $\text{Num}(E)_i$ is the number of weapon systems that support the service, then the number of possible weapon system portfolios for each service portfolio is

$$\prod_{i=1}^n \text{Num}(E)_i, \quad i = 1, 2, \dots, n$$

where n is the number of services in the service portfolio. Then the weapon system portfolio can be represented by

$$\text{Ser}V = \{E_j^1, E_{j+1}^2, \dots, E_k^n | j \in [0, \text{Num}(E)_1], j + 1 \in [0, \text{Num}(E)_2], \dots, k \in [0, \text{Num}(E)_n]\}. \quad (6)$$

In the example above, there are 12 possible weapon system portfolios for the service portfolio constructed by ser-

vices 1 and 5, which are

$$\text{Ser}V = \left\{ \begin{array}{l} \{A, B\} \\ \{A, G\} \\ \{A, F\} \\ \{B, B\} \\ \{B, G\} \\ \{B, F\} \\ \{G, B\} \\ \{G, G\} \\ \{G, F\} \\ \{E, B\} \\ \{E, G\} \\ \{E, F\} \end{array} \right\}. \quad (7)$$

Similarly, there are 36 possible weapon system portfolios for the service portfolio constructed by services 1, 3, and 4. In order to decode and obtain better weapon system portfolios, we return to the service-system portfolio selection problem in the three-deck network of Fig. 2.

The service portfolios exhibit different performances towards the task. To measure the performance, an indicator, service quality, is proposed. The quality of the service, which is affected by the extent to which the weapon systems support the service, can be formulated as

$$\text{quality} = \sqrt[n]{\prod_{j \in [1, \text{Num}(E)_i]}^{i=1} q_{ij}} \quad (8)$$

where q_{ij} is the extent to which the j th weapon system supports the i th service.

Further, the response time of service portfolios for the task varies as well. The response time of the service portfolio, which is determined by the response time of the weapons to the services, is calculated as

$$\text{time} = \text{avg} \left(\sum_{j \in [1, \text{Num}(E)_i]}^{i=1} t_{ij} \right) \quad (9)$$

where t_{ij} is the response time of the j th weapon system to the i th service.

3.4 Optimal service portfolio calculation

In single-objective constrained optimization, there is usually only one optimal solution, which can be found simply by using commonly used heuristic algorithms. However, it does not work the same way for the service-oriented portfolio selection, because the portfolio selection is a multi-objective optimization problem with conflicts between each objective and there is no such solution that makes all objectives reach the optimal. Thus, the solutions for multi-objective optimization are usually presented as a set of non-inferior solutions — Pareto solution.

NSGA-III is a third-generation non-dominated sorting genetic algorithm developed on NSGA-II, which has proven to produce good results in the optimization of multiple objects. According to the characteristics of the task-service-weapon system mapping relation in Fig. 2, the following NSGA-III-based algorithm of twice portfolio selections is designed.

Step 1 Define the population size, number of iterations, probability of mutation and crossover, number of objective functions, etc., and set the counter to 0. Define the object and constraints.

$$\min y = (r(\mathbf{X}_i)), f(\mathbf{X}_i), \quad \mathbf{X}_i \in \mathbf{X}$$

$$\text{s.t. } \mathbf{X}_i - \mathbf{X}_j \neq 0$$

$$\mathbf{X}_i, \mathbf{X}_j \in \mathbf{X}; i = 1, \dots, 80; j = 1, \dots, i-1, i+1, \dots, 80$$

$$\left\{ \begin{array}{l} \sum_{m=1}^{12} x_{m1} \geq 1 \\ \vdots \\ \sum_{m=1}^{12} x_{m12} \geq 1 \end{array} \right. \quad (10)$$

where $x_{mn} = (\mathbf{X}_i)_{mn}$ ($i = 1, 2, \dots, 80; m, n = 1, 2, \dots, 12$), $\mathbf{X} = \{\mathbf{X}_i | \mathbf{X}_i = (\mathbf{X}_i)_{12 \times 12}, x_{mn} = 0, 1\}$.

Step 2 If there are m candidate services, we can get an initial population of length $m \times m$ when making a service portfolio selection. Rows represent the number of candidate services, and columns represent different service portfolios in the service portfolio solution. Because the algorithm is for twice portfolio selections, systems portfolio selection is required when determining service portfolio solutions. Results from the former can be used to generate the initial population of the system. Rows represent the service which system supports, and columns represent the number of candidate systems. We can obtain initial population P_1 with a size of N using the operation above. The coding form of the initial population is shown in Fig. 6.

Step 3 Using the genetic operator (including crossover and mutation) to operate the initial population and obtain population P_2 of size N , and mixing population P_1 with population P_2 , a new population P_3 is obtained. The population size at this time is $2N$. The crossover and mutation operations are as follows.

(i) Crossover

In order to enrich the diversity of the population, each individual of the child is replaced with a parent with a certain probability. Crossover can selectively retain new and old individuals and increase the diversity of the population. The specific steps are as follows:

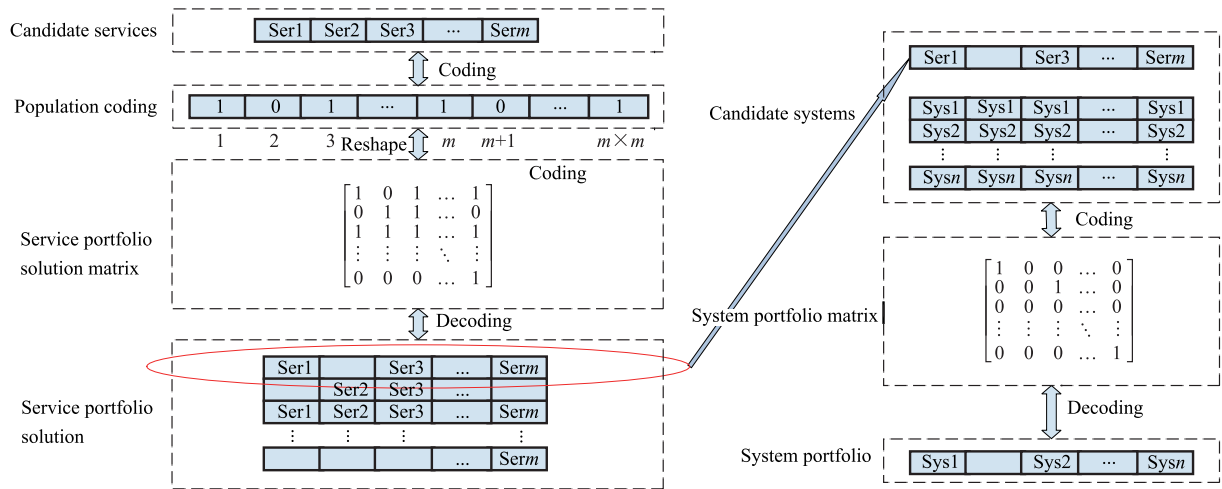


Fig. 6 Coding form of the initial population

$$C_{i,j}(G + 1) =$$

$$\begin{cases} P_{i,j}(G + 1), & \text{rand}l_{ij} \leq \text{CR or } j = \text{rand}(i) \\ x_{i,j}(G), & \text{rand}l_{ij} > \text{CR or } j \neq \text{rand}(i) \end{cases} \quad (11)$$

where CR is the crossover factor; rand(*i*) is a random integer in [1, *n*]; and rand_{*l*_{*ij*}} is a random decimal in [0, 1]. This crossover approach ensures that at least one feature in child *C_i*(*G* + 1) is provided by parent *P_i*(*G* + 1).

(ii) Mutation

*r*₁, *r*₂, and *r*₃ are three distinct individuals randomly selected from the current population. *r* is the current individual, *r*_{gebest} is the current global optimal solution, and *r'* is a new temporary individual resulting from the mutation operation. rand is a random integer in [1, *n*].

$$r' = r + \text{rand} \cdot (r_{\text{gebest}} - r_1) + \text{rand} \cdot (r_2 - r_1) \quad (12)$$

Step 4 Via non-dominated sorting of new population *P*₃, we can obtain multi-deck individuals with non-dominated levels of 1, 2, 3, ..., *k*. Adding these individuals to population *P*₄ of the next generation of child in order of deck, when the individual of the non-dominated level *L* joins the population *P*₄ and the population size is more than *N*, results in *K* individuals being found from the *L* level, so that the sum of all the previous levels of *K* is *N* [21].

Step 5 Function scalar operation. Normalize the multi-target value and calculate the minimum value on each target dimension *i* in the objective function *Z_i^{min}*. The collection of *A* can then be used as an ideal point set *Z_i^{min}*. After the ideal point set is obtained, the extreme point is selected, and for each target dimension, all individual target values in the population are calculated and traversed to find the smallest extreme point. According to the specific value of

the extreme point, the intercept on the corresponding coordinate axis is obtained and recorded as *a_i*. The value of the objective function is then normalized based on the obtained *a_i* and *Z* [21].

$$f_i^n(x) = \frac{f_i(x) - Z_i^{\min}}{a_i - Z_i^{\min}}, \quad i = 0, 2, 3 \quad (13)$$

Step 6 Establish an individual association reference point. Taking three objective functions as an example, the principle of reference point selection is shown in Fig. 7 [22].

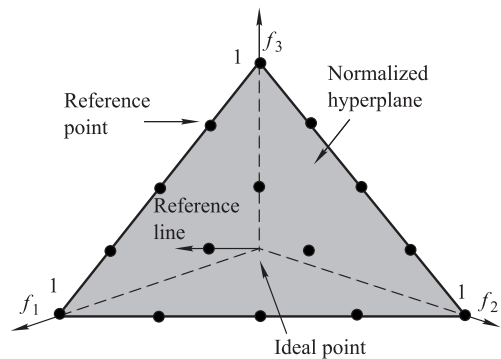


Fig. 7 Reference point distribution [22]

The principle of selecting reference points is to go up one by one, step by step, and recursively.

Step 7 Calculate the distance to the reference point. As shown in Fig. 8, construct the vector from the reference point to the origin, calculate the distance to all the vectors by traversing each individual in the population, find the nearest reference point from each individual of the population, and record the corresponding shortest distance at this time [22].

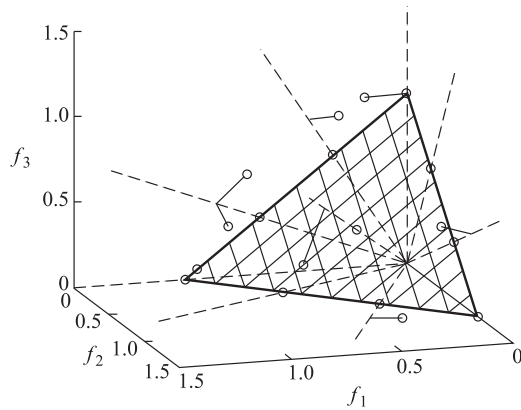


Fig. 8 Building a reference point vector [22]

Step 8 Filter the children and delete the reference points. A reference point may be associated with multiple individuals. The non-dominated solutions are sorted, and the total number of population members from the first non-dominated level to the FL level exceeds the population size N for the first time. At this point, we can define as a collection that contains all the individuals in the FL . Because the size of set K_{t+1} exceeds the set value, it is necessary to perform screening. First, search all the reference points to determine the number of references in which there is no K_{t+1} containing FL . Next, record the reference point with the least number of citations, which is the reference point with the least number of associations among the population individuals. If the number of singular individuals associated with a reference point is 0, but the individual associated with the reference point vector can be found in the FL set, the individual with the smallest distance reference vector should be extracted and placed in the next generation population. If no individual is associated with this reference point in the FL set, the individual is deleted; if the number of individuals associated with the remaining reference points is greater than 0, the reference point with the smallest distance is selected, and the algorithm ends when the population size is N [22].

4. Illustrative case study

4.1 Case and data description

A simulated example is presented to demonstrate the service portfolio selection and decoding in this section. In this example, there are five tasks to be completed: precision strikes, air defense, antimissile, special operations, and striking warships (represented by Task1–Task5). There are also radar reconnaissance services, airborne warning and control system (AWACS) reconnaissance services, satellite reconnaissance services, wireless communication services, wired communication services, satellite communication services, warcraft strike

services, missile strike services, special operations services, air refueling service, logistics support services, and unmanned aerial vehicle (UAV) services (represented by Ser1–Ser12), where the supporting relationship is explained in Table 4. The corresponding service collaboration network after transformation is shown in Fig. 9.

Table 4 Task-service mapping relation in the case

Service	Task1	Task2	Task3	Task4	Task5
Ser1	1	0	0	0	0
Ser2	1	0	0	0	0
Ser3	0	0	1	1	0
Ser4	1	0	0	0	0
Ser5	0	0	1	1	1
Ser6	0	0	1	1	1
Ser7	0	0	0	0	1
Ser8	0	0	0	0	1
Ser9	1	1	0	1	1
Ser10	0	0	1	0	0
Ser11	0	1	0	0	0
Ser12	0	1	0	0	0

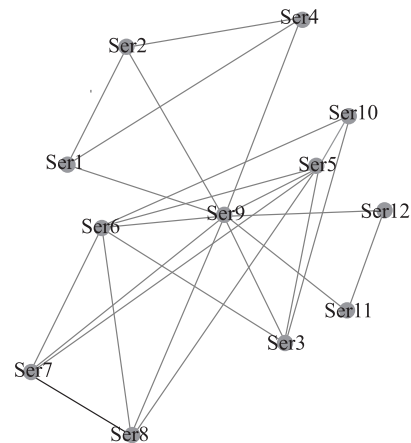


Fig. 9 Service collaboration network in the case

If two services are invoked by one task, they are considered to have a collaborative relationship, which means services in the same column with the value 1 have a synergistic relationship in the table. We can see that there are many connections in the middle of the network, such as Ser5 and Ser9. There are many synergistic relationships, which are in a more important position among the candidate services, indicating that it is more likely to be selected in the service portfolios.

According to the service collaboration network from Fig. 9, its adjacency matrix is easy to obtain. By expressing some elements in the matrix to a random number of either 0 or 1 to represent the connectivity between the two candidate services, we can finally determine $A(G)$.

$$A(G) = \begin{bmatrix} 1 & 0.42 & 0 & 0.42 & 0 & 0 & 0 & 0 & 0.04 & 0 & 0 & 0 \\ 0.42 & 1 & 0 & 0.58 & 0 & 0 & 0 & 0 & 0.12 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0.90 & 0.64 & 0 & 0 & 0.78 & 0.13 & 0 & 0 \\ 0.42 & 0.58 & 0 & 1 & 0 & 0 & 0 & 0 & 0.75 & 0 & 0 & 0 \\ 0 & 0 & 0.90 & 0 & 1 & 0.92 & 0.22 & 0.66 & 0.11 & 0.75 & 0 & 0 \\ 0 & 0 & 0.64 & 0 & 0.92 & 1 & 0.14 & 0.73 & 0.69 & 0.45 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.22 & 0.14 & 1 & 0.40 & 0.07 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.66 & 0.73 & 0.40 & 1 & 0.19 & 0 & 0 & 0 \\ 0.04 & 0.12 & 0.78 & 0.75 & 0.11 & 0.69 & 0.07 & 0.19 & 1 & 0 & 0.48 & 0.53 \\ 0 & 0 & 0.13 & 0 & 0.75 & 0.45 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.48 & 0 & 1 & 0.29 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.53 & 0 & 0.29 & 1 \end{bmatrix}$$

Assuming that there are five weapon systems to provide the services, the service-weapon system mapping matrices in terms of service quality and response time are listed

in Table 5 and Table 6, respectively. The range of service quality is [0,1], and the response time lies between 0 and 10.

Table 5 Service-weapon system mapping matrix in terms of service quality

System	Ser1	Ser2	Ser3	Ser4	Ser5	Ser6	Ser7	Ser8	Ser9	Ser10	Ser11	Ser12
Sys1	0.00	0.00	0.91	0.00	0.28	0.00	0.00	0.00	0.97	0.00	0.00	0.00
Sys2	0.42	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00	0.00	0.00	0.00
Sys3	0.71	0.28	0.10	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.49
Sys4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00
Sys5	0.75	0.51	0.00	0.00	0.00	0.00	0.15	0.84	0.81	0.93	0.00	0.25

Table 6 Service-weapon system mapping matrix in terms of response time

System	Ser1	Ser2	Ser3	Ser4	Ser5	Ser6	Ser7	Ser8	Ser9	Ser10	Ser11	Ser12
Sys1	0.0	0.0	5.7	0.0	9.8	0.0	0.0	0.0	6.8	0.0	0.0	0.0
Sys2	8.2	0.0	0.0	0.0	0.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0
Sys3	4.9	8.4	1.8	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	2.6
Sys4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0
Sys5	8.5	8.2	0.0	0.0	0.0	0.0	1.5	4.6	5.7	4.8	0.0	6.9

4.2 Calculation and analysis for service portfolio solutions

In NSGA-III, the size of population is set as Pop = 1 000

and the iteration times as MaxIt = 200. The probabilities of crossover and mutation are 0.5. Based on the above parameters, the selection results are shown in Table 7.

Table 7 Service portfolio computing result

No.	Service portfolio	Number of portfolios	Connectivity	Flexibility
1	{Ser1,Ser2,Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser11,Ser12}	1	1.761 4	0.000 0
2	{Ser10,Ser11,Ser12}	12	1.619 9	0.379 4
	{Ser6,Ser7,Ser8,Ser9,Ser12}			
	{Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser11,Ser12}			
	{Ser4,Ser5,Ser7,Ser8,Ser9,Ser11}			
	{Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser11,Ser12}			
	{Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser11,Ser12}			
	{Ser2,Ser3,Ser5,Ser6,Ser9,Ser11}			
	{Ser2,Ser3,Ser4,Ser5,Ser6,Ser8,Ser9,Ser10,}			
	{Ser2,Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser11,Ser12}			
	{Ser1,Ser2,Ser3,Ser5,Ser6,Ser7,Ser8,Ser9,Ser11,Ser12}			
3	/	12	1.313 0	0.676 3
4	/	12	1.592 7	0.542 4

Continued

No.	Service portfolio	Number of portfolios	Connectivity	Flexibility
5	/	12	1.611 3	0.493 2
6	/	12	1.451 3	0.602 7
7	/	12	1.564 4	0.549 1
8	/	12	1.362 3	0.664 4
9	/	12	1.213 1	0.719 9
10	/	12	1.525 6	0.586 4
11	/	12	1.396 5	0.634 3
12	/	12	1.479 7	0.599 5
13	/	12	1.218 1	0.704 3
14	/	12	1.614 8	0.464 3
15	/	12	1.613 5	0.491 1
16	/	12	1.523 0	0.596 0
17	/	12	1.262 7	0.688 7
18	/	12	1.269 8	0.678 9
19	/	12	1.465 1	0.601 9
20	/	12	1.446 0	0.631 8
21	/	12	1.104 4	0.727 3
22	/	12	1.253 0	0.694 4
23	/	12	1.365 7	0.641 2
24	/	12	1.538 9	0.553 6
25	{Ser10,Ser11,Ser12} {Ser6,Ser7,Ser8,Ser9} {Ser5,Ser7,Ser8,Ser9,Ser11,Ser12} {Ser5,Ser6,Ser9} {Ser4,Ser5,Ser6,Ser8,Ser9,Ser12} {Ser3,Ser4,Ser5,Ser6,Ser9,Ser10,Ser11} {Ser2,Ser5,Ser6,Ser9} {Ser2,Ser4,Ser6,Ser9} {Ser2,Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser12} {Ser1,Ser6,Ser9} {Ser1,Ser5,Ser6,Ser9} {Ser1,Ser2,Ser3,Ser6,Ser9}	12	1.393 5	0.636 0

In the NSGA-III algorithm, the choice of the target value is as small as possible, so when the algorithm is running, the target value is replaced. Flexibility is replaced by 1 – flexibility, while connectivity is replaced by 1/connectivity. As seen from Table 8, the original values are displayed. There are 25 non-dominated service portfolio solutions to this problem. When the first solution is excluded, the remainder all have 12 service portfolios, which

are not easy to display in the table. Thus, we only take the details of No.1, No.2, and No.25 solutions as examples. In addition, the NSGA-III algorithm divides a population of 80 into three non-dominated layers, as shown in Fig. 10. The horizontal and vertical coordinates in the first picture are the target values in the algorithm processing, and are the original values in the second picture.

Table 8 System portfolio computing result

No.	Connectivity	Flexibility	No.	Connectivity	Flexibility	No.	Connectivity	Flexibility	No.	Connectivity	Flexibility
2	4.974 8	4.303 5	12	5.332 1	4.736 8	22	5.168 1	4.598 1	32	4.779 4	4.038 2
3	5.054 2	4.505 0	13	5.312 0	4.697 9	23	5.167 6	4.517 3	33	5.357 7	4.779 3
4	5.582 5	5.056 7	14	5.157 2	4.512 5	24	4.849 1	4.144 2	34	5.358 1	4.796 5
5	5.331 2	4.722 5	15	5.007 6	4.414 7	25	4.877 8	4.219 1	35	5.371 6	4.827 4
6	5.679 7	5.125 4	16	5.247 1	4.609 0	26	5.473 3	4.920 2	36	5.841 7	5.316 9
7	5.909 6	5.406 5	17	4.266 7	3.497 5	27	5.257 7	4.650 7	37	5.776 0	5.149 0
8	5.439 7	4.829 8	18	5.559 0	5.031 2	28	5.792 1	5.265 1	38	5.521 3	4.948 6
9	5.776 8	5.196 5	19	4.798 3	4.133 0	29	5.442 7	4.846 3	39	5.466 0	4.886 1
10	5.943 3	5.429 9	20	5.688 4	5.125 7	30	5.556 7	4.989 6	40	5.603 8	5.107 7
11	5.550 5	4.950 1	21	5.301 2	4.661 6	31	5.865 0	5.363 1			

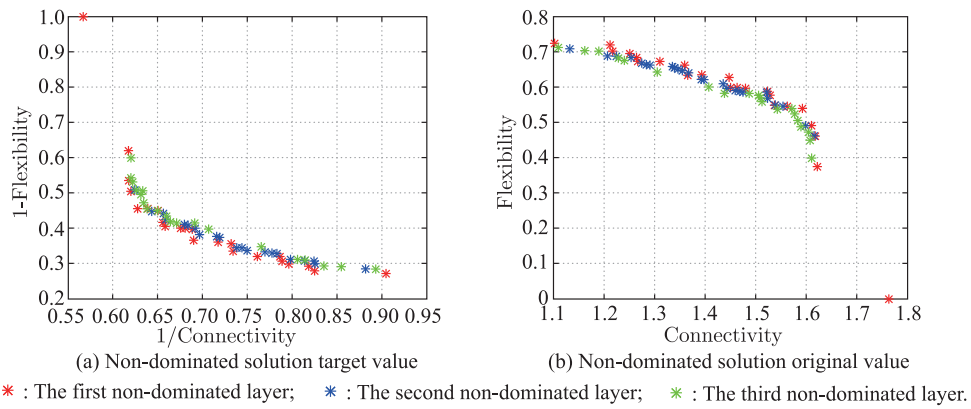


Fig. 10 Non-dominated solution target value and original value of the service population

There is a special case to note wherein a solution in the upper-left corner of the left picture is located in the first non-dominated layer; its value of 1/connectivity is the smallest in the population, so it is put into the first non-dominated layer by the algorithm, but its value of 1 – flexibility rises to the top at 1. In other words, its flexibility is 0 in the right picture, which is actually not advisable. Therefore, we remove this solution. Beyond that, the algorithm has a great effect on the selection of the population.

To visualize the results, these portfolios are displayed in the form of matrix as shown in Fig. 10. The area is divided into multiple blocks by service portfolios and ser-

vices. The color of the block indicates if the corresponding service is selected in the service portfolio. In this way, one can clearly see the internal structure of the non-dominated service portfolios and intuitively perceive the law hidden in all non-dominated solutions through the color blocks. According to the color blocks in Fig. 11, the black blocks are mainly concentrated in the middle part, and the white blocks are mainly concentrated on both sides, which reflect that among the non-dominated service portfolio solutions, more portfolios select services 4–10 and fewer select 1, 2, 11, and 12.

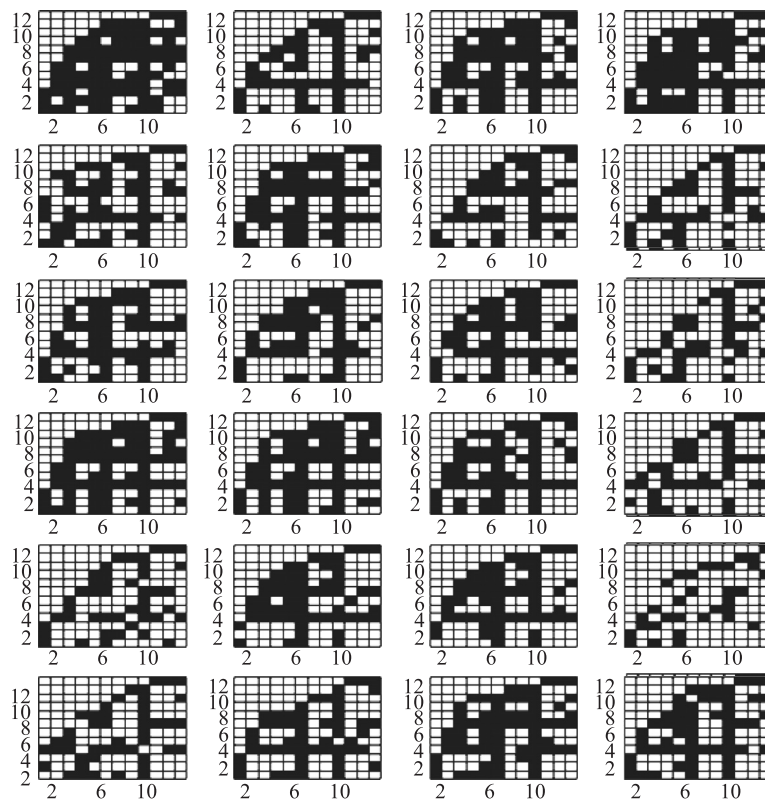


Fig. 11 Non-dominated service portfolio structure black-and-white block diagram

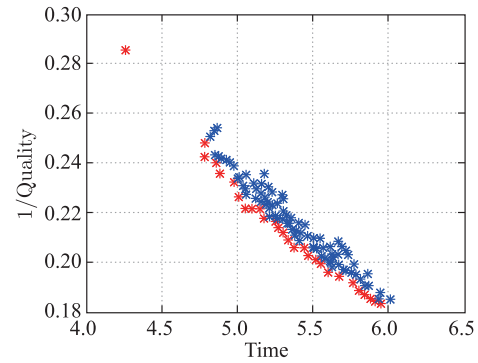
4.3 Calculation and analysis for system portfolio solutions

Using the same method, the size of population is set at $Pop = 300$, and the selection results are shown in Table 8.

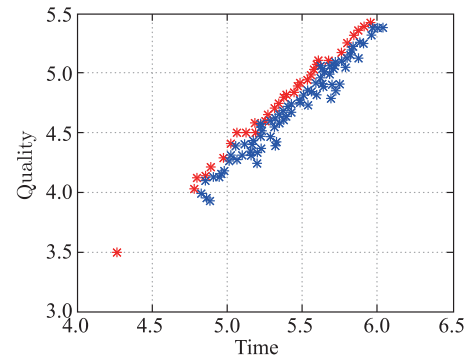
With regard to the choice of the target value in NSGA-III, the smaller is considered to be the better, and the quality is replaced by $1 - Quality$. There are 40 non-dominated system portfolio solutions for 24 service portfolio solutions, and each solution has 12 portfolios. Thus, the original values are displayed only in Table 8.

Furthermore, the NSGA-III algorithm divides a population of 300 into 12 non-dominated layers. We divide the layers into the first non-dominated layers and other non-dominated layers, as shown in Fig. 9. The horizontal and vertical coordinates in the left picture are the target values in the algorithm processing, and are the original values in the right picture. Through the distribution of scatter points in Fig. 12, the algorithm is shown to have a great effect on the selection of the population.

After gaining the system portfolio solutions, we can restore the mapping decoding process of the service portfolio selection to the system portfolio selection. Taking No. 5 service portfolio solution as an example, the illustration of decoding is presented in Table 9.



(a) Non-dominated solution target value



(b) Non-dominated solution original value

* : The first non-dominated layer; * : Other non-dominated layers.

Fig. 12 Non-dominated solution target value and original value of the system population

Table 9 Service portfolio-weapon systems decoding

Service portfolio	Weapon system selection
{Ser10,Ser11,Ser12}	{Sys5,Sys3,Sys3}
+	+
{Ser7,Ser8,Ser9}	{Sys3,Sys5,Sys5}
+	+
{Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser11,Ser12}	{Sys2,Sys1,Sys2,Sys5,Sys4,Sys5,Sys3,Sys3}
+	+
{Ser3,Ser5,Ser6,Ser8,Ser9,Ser10}	{Sys3,Sys1,Sys2,Sys4,Sys5,Sys5}
+	+
{Ser3,Ser5,Ser6,Ser8,Ser9,Ser12}	{Sys3,Sys1,Sys2,Sys4,Sys1,Sys3}
+	+
{Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser11,Ser12}	{Sys3,Sys4,Sys1,Sys2,Sys5,Sys3,Sys5,Sys3,Sys5}
+	+
{Ser2,Ser3,Ser4,Ser5,Ser6,Ser9}	{Sys3,Sys3,Sys2,Sys1,Sys2,Sys1}
+	+
{Ser2,Ser3,Ser4,Ser5,Ser6,Ser8}	{Sys3,Sys3,Sys2,Sys1,Sys2,Sys5}
+	+
{Ser2,Ser3,Ser4,Ser5,Ser6,Ser7,Ser8,Ser9,Ser10,Ser11,Ser12}	{Sys3,Sys3,Sys2,Sys1,Sys2,Sys5,Sys3,Sys1,Sys5,Sys3,Sys5}
+	+
{Ser1,Ser3,Ser6,Ser9}	{Sys3,Sys1,Sys2,Sys5}
+	+
{Ser1,Ser3,Ser4,Ser5,Ser6,Ser9}	{Sys3,Sys3,Sys4,Sys1,Sys2,Sys5}
+	+
{Ser1,Ser2,Ser3,Ser4,Ser5,Ser6,Ser9}	{Sys3,Sys3,Sys3,Sys2,Sys1,Sys2,Sys5}

According to the service-weapon system mapping relationship, the support of weapon systems for the services is visualized in Fig. 13 after extracting the service portfolio from the service collaboration network. Taking two portfolios in the No. 5 service portfolio solution as an example, the service portfolios and the system selection can

be clearly seen. This study has greatly reduced the scope of the solutions. There should be $2^{12 \times 12} \times 5^{12}$ solutions, and our service-oriented weapon system portfolio selection method can reduce it to 40 for decision makers, which reflects the advantage of the service-oriented structure in loose couplings.

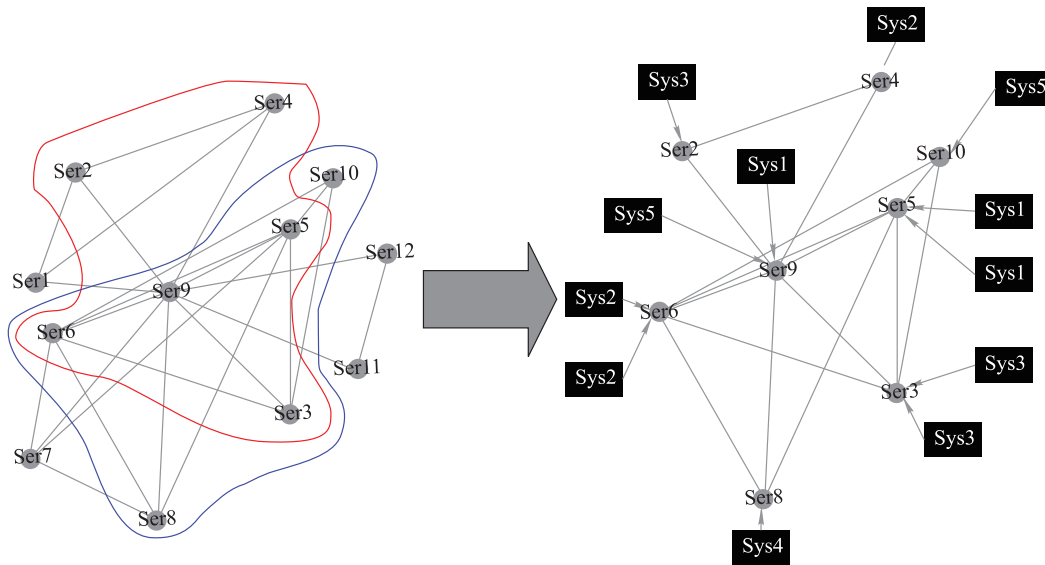


Fig. 13 Non-dominated service portfolio service-equipment selection decoding

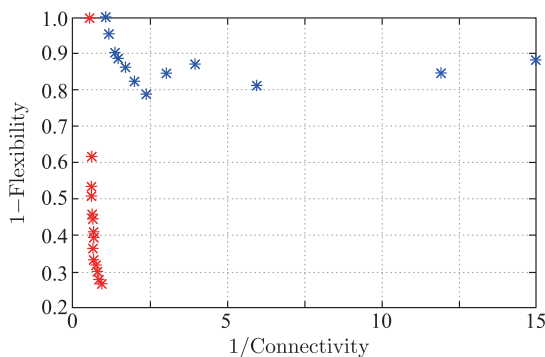
4.4 Comparison with other method

The NSGA-II algorithm is another commonly used method for solving multi-objective optimization problems. It uses a fast non-dominated sorting mechanism to reduce the computational complexity of non-dominated sorting, and introduces elite mechanisms into the algorithm to improve the performance of the algorithm. In order to maintain the diversity of the population, the crowding distance is used to rank individuals in the same non-dominated sequence.

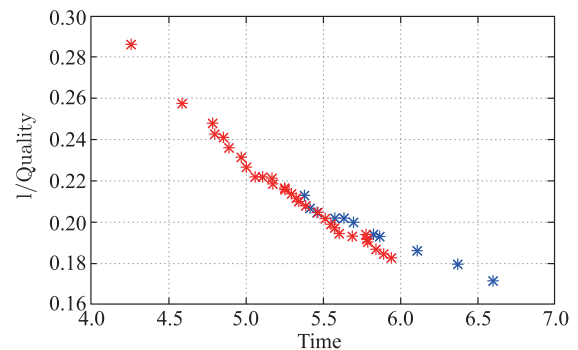
In NSGA-II, The main parameters are consistent with the parameters in NSGA-III, Pop = 1 000 and the iteration times at MaxIt = 200. The probability of mutation is 0.5 without crossover. Twelve selection results are obtained finally.

The difference between the non-dominated solutions obtained by the two algorithms is compared from the four indicators, and the results are shown in Fig. 14.

In the evaluation of flexibility and connectivity, the results of the NSGA-II algorithm are completely dominated by the results of NSGA-III.



(a) Comparison of flexibility and connectivity



(b) Comparison of quality and time
* : NSGA-III; * : NSGA-II.

Fig. 14 Comparison of NSGA-III and NSGA-II calculation results

Comparing the two indicators of time and quality, the NSGA-II algorithm performs slightly better. There are two sets of solutions that are not dominated by the results of the NSGA-III algorithm, but not better than the non-dominated solution set of NSGA-III.

It can be seen that compared with the NSGA-II algorithm, the NSGA-III algorithm can obtain better non-dominated solutions, which may be due to the fact that the NSGA-II algorithm lacks the crossover step in the process, so it is not good enough to save the characteristics of excellent individuals. Therefore, the NSGA-III algorithm is more suitable for the service portfolio selection problem studied in this paper.

5. Conclusions

This study attempts to build a bridge between combat tasks and system selection by mapping weapon system selection to service portfolio selection. Firstly, the relationships between the service and the task, and the service and the

weapon system are obtained through the service-task mapping matrix and the service-system mapping matrix, so the task-service-weapon system hierarchical network is constructed. Secondly, the above network structure is transformed into the service collaboration network, where the characteristics of flexibility and connectivity are extracted to describe the service portfolio structure and establish the value function. In the optimization, the NSGA-III algorithm for twice portfolio selections is applied to generate the Pareto optimal service portfolios. Finally, the service portfolios are decoded into weapon system portfolios through mapping relationship. To illustrate and validate the proposed model, a simulated example is presented and the results are analyzed.

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