A Hypercube Model based on DSM/DMM for Armament System of systems Modeling and Evaluation

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Abstract - *A hypercube model based on DSM/DMM is presented for armament system of systems （ASoS） modeling and evaluation. The dependency and relation of the ASoS can be described with the structure of the hypercube model, and the DSM/DMM matrix is here to show the elements component and numeric constriction. This paper analyzed the dependency flow and value flow in ASoS from different dimensions of the model. Also it evaluated the ASoS from technology maturity, technology integration and capability supply. And an illustrative example with an analysis of Air-Defense ASoS of its technology effect, integration effect and scale effect was given.*

Keywords: Armament System of systems, Hypercube Model, DSM/DMM, Modeling and Evaluation, Air-Defense ASoS

1 Introduction

Armament System of Systems (ASoS) is generally regarded as a kind of SoS composed by multiple armament systems, which are usually geographic distribution, operational and managerial independent. Just as SoS, ASoS has many complex features, such as nonlinearity, emergent behavior, multiple dependency, and that makes it really difficult to be modeled and evaluated[1]. There are plenty of evaluation methods, such as classic ADC method, exponent method, Lanchester method[6], expert evaluation method, ANP method[11], VFT method[8,10], fuzzy analysis method[9], and many other methods.[2-7] Typically, the researcher Lei Liu evaluated the ASoS with VFT method focused on the strategy target satisfaction degree of different time, then process with an overall view of time to get the total satisfaction degree[8]. Researcher Minghe Liu improved this method with fuzzy theory, and proposed a fuzzy value focused thinking (FVFT)[9]. Yu Shu set up an evaluation index of six capabilities and combined these capabilities with ANP method[11]. Ben Chen start from the relation between the capability need of the mission and the capability providing of the ASoS, the result obtained by gathering from the individual bottom to the top[2]. Doctor Guangzhi Bu proposed a model based on information flow to combined the effect of each single system to ASoS level[1,12,13].

Most of the models and methods are proceed with a specific index system for evaluation or focused on a specific dependency of the armament systems. And the models considering of multiple dependency and relation between different systems is still very rare. And the hypercube model based on DSM/DMM considering different dependency and relation form a higher dimension view.

Dependence Structure Matrix（DSM）, which is also called as Design Structure Matrix, is a useful system analysis tool based on matrix to describe the interdependencies and interactions among the elements of a system. A simple DSM displays the relationships between components of a system with a matrix, in which each row and corresponding column are identified with identical component labels. DSM theory was firstly proposed by Steward, and due to its supporting to the system structure analysis in the limited knowledge condition, it has been proved valuable and efficient by a great number researchers in production design, task scheduling, project management, and system analysis and design fields. This notwithstanding, the components of DSM are limited to a mono-field, which cannot meet the overall needs in the interdependencies and interactions modeling among complex systems with multi-flied components. So Danilovic and Browning proposed a Domain Mapping Matrix (DMM) model based on DSM and it was a matrix in which each row and corresponding column are unnecessarily identified to each other. DMM is proven to be a perfect complement to DSM in complex systems analysis, for the former focuses on the components in the same field but the later focuses on these between the different ones.

We proposed a DSM/DMM hypercube model combined with DSM and DMM to describe the systems portfolio elements from various fields. In DoDAF 2.0, the core elements of a system of systems in multi-view perspective are activity (A), capability (C), system (S) and technology (T). In our paper, the ASoS elements definition is enhanced based on the DoDAF 2.0, which are comprised of capability (C), system (S), function (F) and technology (T). In addition to these elements, the DSM/DMM hypercube model. Also contained portfolio (P), the exact armament system component of ASoS. With this definition, the hypercube model can systematically model the ASoS elements, including describe the relationship and evaluate the value.

2 Problem Description

From the perspective of operational research, the problem can be simply described as a multiple criteria assessment problem with the constrains of complete capabilities, structure independence, and elements interactions.

Considering to evaluate the ASoS in a based-scenario for a specific purpose. Let P be the systems portfolio of the whole ASoS. And S be the systems, C be the capability, F be the functions of each system, T be the technology in each functions, TM_p be the technology maturity of the pth portfolio, TI_p be the technology integration of the pth portfolio, and the CS_p be the capability supply of the pth portfolio.

We assumed that to complete this mission need some capabilities, $C=(C_1,C_2,...,C_n)$, C_i represents the ith capabilities value. And each of the capability C_i can be complete by some different functions F_i. We called this kind of mapping C-F Mapping,

$$F_i=(f_1,...,f_n), f_i=\begin{cases}0, \text{ no i th function}\\ 1, \text{ contain i th function}\end{cases}$$

Also each system S_i have some functions F_i ,we called S-F Mapping, each function are supported by some different technologies T_i. We called F-T Mapping.

$$T_i=(t_1,...,t_n), t_i=\begin{cases}0, \text{ no i th technology}\\ 1, \text{ contain i th technology}\end{cases}$$

Still there are many other mappings. And all these constrain are described in dependence structure matrix (DSM) and domain mapping matrix (DMM) and will be discussed in chapter 3.1. The ASoS (portfolio) is comprised of some systems S_i , and the portfolio P is $X_p=(x_1,x_2,...,x_n)$. The evaluate framework can be simply shown in figure 1.

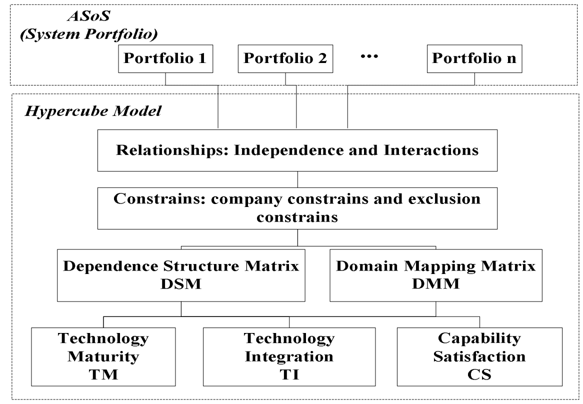

FIGURE 1: Flow chart of the evaluation

3 Methodology

A DSM/DMM Hypercube Model is a method focused on the independence and interactions of each kind of elements in ASoS, which can describe the dependency and relations of the ASoS vividly. And the DSM/DMM matrix is here to show the restrains, such as elements dependency and numeric constriction, among capability (C), system (S), function (F) and technology (T) and portfolio (P).

3.1 A Hypercube Model base on DSM/DMM method

DSM is used to describe the interdependencies and interactions among the elements of a system. A simple DSM model, BDSM, can be formulated as $DSM=<E,A>$, where $E=\{e_1,e_2,\ldots\ldots, e_n\}$ is a set of n system components and

$$A=\{a_{ij},i,j\le n\},$$

$$aij=\begin{cases}1, & \text{there exists a directional dependency from } e_j \text{ to } e_i\\ 0, & \text{otherwise}\end{cases}$$

Based on the DSM/DMM, the hypercube model showed us all the possible interdependencies and interactions defined as 9 mapping. They are T-T mapping, F-F Mapping, F-T mapping, S-F mapping, C-F mapping, S-C mapping, P-S mapping, S-S mapping and C-P mapping.

The elements of system portfolio and mapping among them are described as follows:

1) *T-T Mapping Definition*: It appears as a numerical DMM which describes the integrations among all the technologies (T) included in the whole ASoS.
2) *F-F Mapping Definition*: It appears as a numerical DMM which describes the integrations among all the functions (F) included in the whole ASoS.
3) *F-T Mapping Definition*: It appears as a BDSM which describes the dependencies between the technologies (T) and the system functions (F) they generate.
4) *S-F Mapping Definition*: It appears as a BDSM which describes the dependencies between the systems (S) and the system functions (F) they possess.
5) *C-F Mapping Definition:* It appears as a BDSM which

describes the dependencies between the capabilities (C) and the functions (F) in systems-level.

6) S-C *Mapping Definition*: It appears as a BDSM which describes the dependencies between the systems (S) and their emergent capabilities (C).
7) P-S *Mapping Definition*: It appears as a BDSM which describes the dependencies between the portfolios (P) and the systems (C) they contain.
8) S-S *Mapping Definition*: It appears as a binary DMM which describes the integration relationship among all the systems (S).
9) C-P *Mapping Definition*: It appears as a BDSM which describes the dependencies between the portfolios (P) and the capabilities (C) they can supply.

Thus, in Figure 2, we build a simple DSM/DMM hypercube model. There are 5 systems which include 4 functions in all. And there are 5 technologies to support these functions. These systems forms 5 portfolios and can supply 5 capabilities.

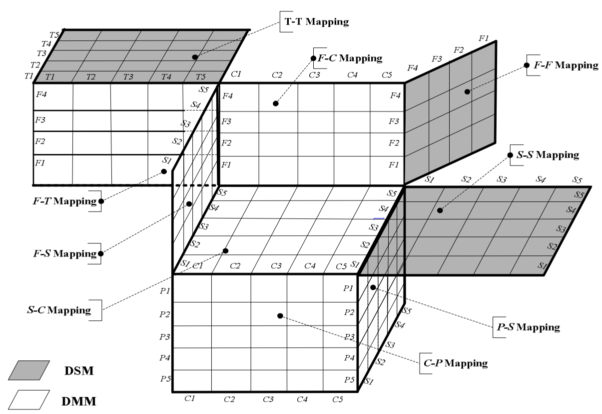

FIGURE 2: Sample of DSM/DMM hypercube model

3.2 Dependency Flow and Value Flow in the Hypercube Model

As the interdependencies and interactions defined as 9 mapping, the dependency and the value (technologies and capabilities) are aggregate from the basic elements to the whole ASoS. And the hypercube model can show this kind of aggregation flow.

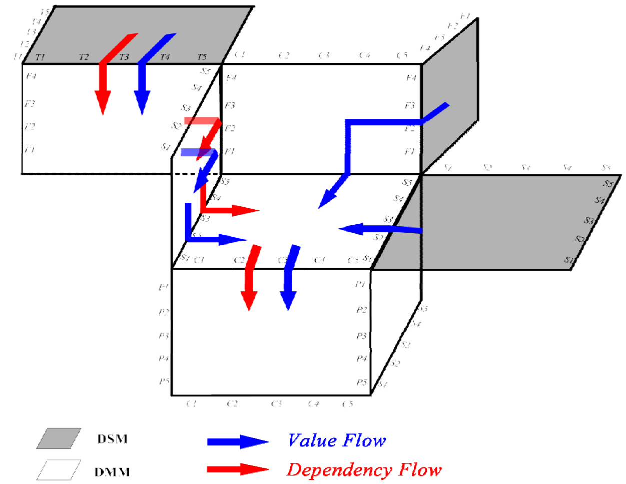

FIGURE 3: Dependencies flow and Value flow

Dependency Flow

The dependency flow are existed in F-T mapping, S-F mapping, C-F mapping, S-C mapping, P-S mapping and C-P mapping. And with the considering of the mission and capabilities that ASoS has, the dependency flow can be drawn-out simply in two lines with P-C mapping, P-S mapping, C-F mapping, S-F mapping and F-T mapping.
One flow is transferred in the sequence of the P-S mapping, S-F mapping and F-T mapping, which can be treated as the structure dependency of ASoS. The other is transferred in the sequence of the P-C mapping, C-F mapping and F-T mapping, which can be treated as capabilities dependency of ASoS. The dependency flow are shown in the red lines of Figure 3

Value Flow

The value flow are existed in all the mappings, and also can be simplified with the thought of its reality meaning. The value are generated from T-T mapping, changed in F-F mapping, S-S mapping and Transferred through the dependency flows. In this paper, the value of the flow mainly referring to the technologies and capabilities impacts, and the aggregation value of the whole ASoS can be shown in TM_p, TI_p, CS_p. The value flow are shown in the blue lines of Figure 3 and the computation methods are discussed in chapter 3.3.

3.3 Evaluation Indicators based on Hypercube Model

Based on the analysis of the dependency flow and value flow above, we set a step father to discuss the indicators of the evaluation. In the paper, we proposed three indicators, Technology Maturity (TM), Technology Integration (TI), and capabilities supply (CS).

Technology Maturity

Technology Maturity of the ASoS (TM_p) is generated from basic element's technology maturity, and it can be computed in the following functions.

Assuming the each basic technology maturity is tm_i, then all the basic technologies can be noted as TM .

$TM = (tm_1, tm_2, ..., tm_n)$

And the F-T mapping can be noted as BDSM matrix.

$$BDSM_{F-T} = \begin{bmatrix} f_1t_1 & ... & f_1t_n \\ \vdots & \ddots & \vdots \\ f_mt_1 & ... & f_mt_n \end{bmatrix},$$

$$f_it_j = \begin{cases} 0, t_j \text{ is not the technology formed } f_i \\ 1, t_j \text{ is the technology formed } f_i \end{cases}$$

Then with the dependency flow in the F-T mapping, we can get the technology maturity of each function TM_F.

$$TM_F = \left(TM_{f_1}, TM_{f_2}, ..., TM_{f_n}\right) = BDSM_{F-T} \wedge TM^{\mathrm{T}} \quad ...(1)$$
$$\left(\text{the} \wedge \text{here is the logic and}\right)$$

Also the S-F mapping can be noted as the BDSM matrix.

$$BDSM_{S-F} = \begin{bmatrix} s_1f_1 & ... & s_1f_n \\ \vdots & \ddots & \vdots \\ s_mf_1 & ... & s_mf_n \end{bmatrix},$$

$$s_if_j = \begin{cases} 0, s_i \text{ can not supply function } f_j \\ 1, s_i \text{ can supply function } f_j \end{cases}$$

Then with the dependency flow in the S-F mapping, we can get the technology maturity of each system TM_S.

$$TM_S = \left(TM_{s_1}, TM_{s_2}, ..., TM_{s_n}\right) = BDSM_{S-F} \vee TM_F^{\mathrm{T}}$$
$$\left(\text{the} \vee \text{here is the logic or}\right) \quad ...(2)$$

Also the P-S mapping can be noted as the NDSM matrix.

$$NDSM_{P-S} = \begin{bmatrix} p_1s_1 & ... & p_1s_n \\ \vdots & \ddots & \vdots \\ p_ms_1 & ... & p_ms_n \end{bmatrix},$$

p_is_j *is the number of* s_j *contains in* p_i

Finally with the dependency flow in the P-S mapping, we can get the technology maturity of the whole ASoS (Portfolio) TM_P.

$$TM_P = \left(TM_{p_1}, TM_{p_2}, ..., TM_{p_n}\right) = NDSM_{P-S} \bullet TM_S^{\mathrm{T}} / n, \quad n \text{ is the sum of systems} \quad (3)$$

Technology Integration

Technology integration of the ASoS (TI_p) is generated from basic element's technology integration, and it can be computed in the following functions.

Assuming that t_it_j means the integration of technology i and technology j from the T-T mapping, which can be noted as NDSM matrix.

$$NDSM_{T-T} = \begin{bmatrix} 1 & ... & t_1t_n \\ \vdots & \ddots & \vdots \\ t_mt_1 & ... & 1 \end{bmatrix},$$

$t_it_j \in (0,1)$ *is the integration of technology i and technology j*

And considering with the F-T mapping, we can get the technology integration of each function. In order to described it clearly, we imported the matrix $BDSM_{T-T}(f_i)$ for each function.

$$BDSM_{T-T}(f_i) = \begin{bmatrix} t_1t_1 & \cdots & t_1t_n \\ \vdots & \ddots & \vdots \\ t_nt_1 & \cdots & t_nt_n \end{bmatrix},$$

$$t_it_j = \begin{cases} 1, \text{where the } BDSM_{F-T}(f_i, i) = 1 \text{ and } BDSM_{F-T}(f_i, j) = 1 \\ 0, \text{else} \end{cases}$$

$$TI_F = \left(TI_{f_1}, TI_{f_2}, ..., TI_{f_n}\right)$$
$$= BDSM_{F-T} \wedge NDSM_{T-T}^{\mathrm{T}} .* BDSM_{T-T}(f_i) \wedge [1,1,...,1]^{\mathrm{T}} \quad (4)$$
$$\begin{pmatrix} .* \text{ means matrix corresponding multiply.} \\ \text{And there are n 1 in the vector} \end{pmatrix}$$

Then with the S-F mapping, we can get the TI_S.

$$TI_S = \left(TI_{s_1}, TI_{s_2}, ..., TI_{s_n}\right) = BDSM_{S-F} \vee TI_F^{\mathrm{T}} \quad (5)$$

Finally with the P-S mapping, we can get the TI_P

$$TI_P = \left(TI_{p_1}, TI_{p_2}, ..., TI_{p_n}\right) = NDSM_{P-S} \bullet TI_S^{\mathrm{T}} / n, \quad n \text{ is the sum of systems} \quad (6)$$

Capability Supply

Capability supply of the ASoS (CS_p) is generated from C-F mapping and S-F mapping, which can be computed in the following functions.

Assuming that c_if_j means the level that function j can supply for the capability i from C-F mapping, which can be noted as NDSM matrix.

$$NDSM_{C-F} = \begin{bmatrix} c_1f_1 & ... & c_1f_n \\ \vdots & \ddots & \vdots \\ c_mf_1 & ... & c_mf_n \end{bmatrix}, c_if_j \in (0,1) \text{ is the level}$$

that function j can supply for the capability i

Then we can get CS_S.

$$CS_S^{\mathrm{T}} = \left(CS_{s_1}, CS_{s_2}, ..., CS_{s_n}\right)^{\mathrm{T}} = BDSM_{S-F} \vee NDSM_{C-F}^{\mathrm{T}} \vee [1,1,...,1]^{\mathrm{T}}$$
$$\left(\text{there are n 1 in the vector}\right) \quad (7)$$

Finally we can get CS_P.

$$CS_P = \left(CS_{p_1}, CS_{p_2}, ..., CS_{p_n}\right) = NDSM_{P-S} \bullet CS_S^{\mathrm{T}} / n, \quad n \text{ is the sum of systems} \quad (8)$$

4 CASE STUDY

The model proposed in this paper can evaluate the ASoS's efficiency. Here is a sample to illustrate it.

4.1 Case Description

To illustrate the modeling and evaluation of the DSM/DMM hypercube model, we presented a numerical experiment on Air-Defense weapon system of systems as shown in figure 4, 10 candidate systems, 15 functions based on 10 technologies, and 5 capabilities are considered in this Air-Defense weapon system of systems. The basic technologies and capabilities are referenced form the office of the ASN (RD&A). Table 1 shows the maturity of each technology; table 2 shows the integrations of all the technologies; table 5 shows the functions' support probability of capabilities; and the component of each elements all shown in other tables.

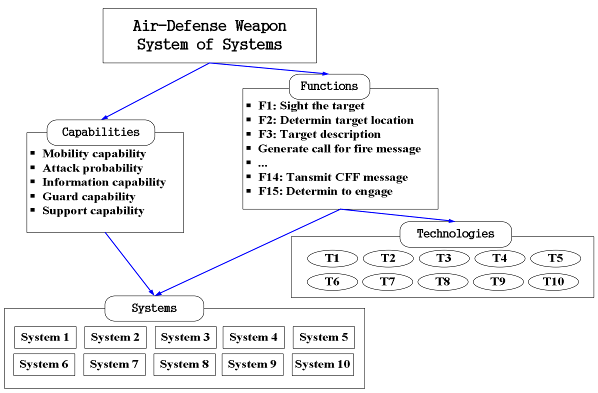

FIGURE 4: Air-Defense weapon system of systems

Table 1 Technology Maturity

T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
1.0	1.0	1.0	0.9	0.9	0.8	0.8	0.8	0.6	0.6

Table 2 Technology Integration

T	Integrations of each technology (T1~T10)
T1	[1.0, 0.8, 0.8, 0.9, 0.9, 0.7, 0.7, 0.6, 0.6, 0.5]
T2	[0.8, 1.0, 0.8, 0.9, 0.9, 0.7, 0.7, 0.6, 0.6, 0.5]
T3	[0.8, 0.8, 1.0, 0.9, 0.9, 0.7, 0.7, 0.6, 0.6, 0.5]
T4	[0.9, 0.9, 0.9, 1.0, 0.8, 0.7, 0.7, 0.8, 0.8, 0.7]
T5	[0.9, 0.9, 0.9, 0.8, 1.0, 0.7, 0.7, 0.8, 0.8, 0.7]
T6	[0.7, 0.7, 0.7, 0.7, 0.7, 1.0, 0.8, 0.8, 0.8, 0.7]
T7	[0.7, 0.7, 0.7, 0.7, 0.7, 0.8, 1.0, 0.8, 0.8, 0.7]
T8	[0.6, 0.6, 0.6, 0.8, 0.8, 0.8, 0.8, 1.0, 0.9, 0.8]
T9	[0.6, 0.6, 0.6, 0.8, 0.8, 0.8, 0.8, 0.9, 1.0, 0.8]
T10	[0.5, 0.5, 0.5, 0.7, 0.7, 0.7, 0.7, 0.8, 0.8, 1.0]

Table 3 Technologies of functions

Functions	Technologies of the function
F1	T1, T4, T5, T6, T7, T9
F2	T1, T4, T5, T6, T8, T10
F3	T1, T4, T5, T7, T9, T10
F4	T1, T4, T5, T6, T7, T8
F5	T1, T4, T5, T6, T9, T10
F6	T1, T2, T4, T5, T7, T8, T10
F7	T1, T2, T4, T5, T6, T7, T9, T10
F8	T1, T2, T4, T5, T6, T8
F9	T1, T2, T4, T5, T7, T9, T10
F10	T1, T2, T4, T5, T6, T7, T8
F11	T1, T2, T3, T4, T5, T6, T9, T10
F12	T1, T2, T3, T4, T5, T7, T8, T10
F13	T1, T2, T3, T4, T5, T6, T7, T9
F14	T1, T2, T3, T4, T5, T6, T8, T10
F15	T1, T2, T3, T4, T5, T7, T9

Table 4 Functions of systems

System	Functions of the system
S1	F6, F9, F11, F12, F14, F15
S2	F3, F5, F7, F8, F12, F13
S3	F2, F5, F8, F10, F12, F13, F14
S4	F2, F3, F6, F7, F9, F10, F11, F14, F15
S5	F2, F3, F4, F5, F6, F7, F12, F14, F15
S6	F1, F3, F6, F9, F14, F15
S7	F1, F3, F5, F8, F9, F11, F12, F15
S8	F1, F2, F6, F9, F10, F11, F12
S9	F1, F2, F5, F7, F13, F14
S10	F1, F2, F5, F6, F7, F12, F14

Table 5 Functions support probability of capabilities

	F1~F15 support probability of each capability
C1	[0.1,0.1,0.1,0.3,0.3,0.5,0.5,0.6,0.6,0.6,0.7,0.7,0.9,0.7,0.9]
C2	[0.4,0.4,0.4,0.6,0.3,0.8,0.6,0.4,0.5,0.6,0.6,0.2,0.7,0.7,0.7]
C3	[0.6,0.6,0.6,0.3,0.6,0.8,0.5,0.6,0.5,0.6,0.4,0.2,0.2,0.4,0.6]
C4	[0.8,0.8,0.8,0.4,0.6,0.6,0.5,0.8,0.6,0.4,0.3,0.1,0.1,0.3,0.2]

Table 6 Portfolio components

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
P1	8	10	15	4	5	6	6	6	5	4

4.2 Modeling and Result

Based on the theories described in chapter 3.3, we can evaluate this portfolio in Technology Maturity (TM), Technology Integration (TI), and capabilities supply (CS).Here are the results.

Table 7 Functions Maturity and Integration

Functions	TM_F	TI_F
F1	0.6	0.6
F2	0.6	0.5
F3	0.6	0.5
F4	0.8	0.5
F5	0.6	0.5
F6	0.6	0.5
F7	0.6	0.5
F8	0.8	0.5
F9	0.6	0.5
F10	0.8	0.5

F11	0.6	0.5
F12	0.6	0.5
F13	0.6	0.5
F14	0.6	0.5
F15	0.6	0.5

Table 8 Systems Maturity Integration and Capabilities

System	TM_S	TI_S	CS_S
S1	0.6	0.5	0.9
S2	0.8	0.5	0.9
S3	0.8	0.5	0.9
S4	0.8	0.5	0.9
S5	0.8	0.5	0.9
S6	0.6	0.6	0.9
S7	0.8	0.6	0.8
S8	0.6	0.6	0.8
S9	0.6	0.6	0.9
S10	0.8	0.6	0.8

Table 9 Portfolio Evaluation Result

Portfolio	TM_P	TI_P	CS_P
P1	0.7449	0.5391	0.8855

5 Conclusion

The hypercube model based on DSM/DMM focused on the independence and interaction of those elements in ASoS. The dependency and relations of the ASoS can be shown in different mapping views. And the hypercube model can also evaluate and analysis the system portfolios in technology maturity, technology integration, and capabilities supply.

The advantages of this model are that the hypercube model can show the elements and its relations with its different dimension clearly, and it analyzed the dependency flow and value flow of the ASoS. And the evaluate method was simple and clearly. Besides the shortage of this model is that the evaluate method cannot reflect all the feature of the dependency flow and value flow. But considering of the current situation, this paper is worth considering

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