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A Methodology for Modeling the Network-Centric Operations Value Chain

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Abstract-The tenets of network-centric operations state that a robustly networked force will ultimately result in improved mission effectiveness, where the intervening steps can be viewed as the value chain. This paper proposes a four-step methodology for modeling the network-centric operation value chain. The first identifies the key operational concepts and their linkages from the operation process. The second analyzes the factors influencing the causality of each linked pair of key concepts. The third measures each key operational concept and intervening factor. The last formulates the value transfer functions, which are determined by the intervening factors and transform the attributes of the key concepts. This is the first research toward quantitatively exploring what elements, which attributes of the elements, and how the attributes of the elements plays roles in the benefits accumulation process within the network-centric operations.

Keywords: network-centric operations, value chain, transfer function, modeling, metrics

1. Introduction

Network-centric operation (NCO) is a term developed to date to describe the way we will organize and fight in the information age [1]. As a new theory of war, NCO essentially translates information superiority into combat power by effectively linking knowledgeable entities in the battlespace, and can be summarized by a hierarchy of hypotheses. Central among these hypotheses are that improved networked force capability will improve the quality of information and shared sense-making, support more dynamic decision-making and agile force synchronization, and will ultimately increase force effectiveness and the likelihood of a successful operational outcome. The basis of the hypothesis is that improved networked force capability will add value and ultimately result in improved mission effectiveness, where the intervening steps can be viewed as the NCO value chain (NCO-VC).

A systematic and quantitative research on the NCO-VC could articulate the process of benefits accruing and transferring within the NCO and the exogenous elements influencing the processes. However, it is a major challenge in that establishing a quantifiable link between the improved networked force capabilities and combat outcomes is extremely elusive. The research reported in this paper is founded on the existing related work, and further proposes a four-step methodology for the modeling of NCO-VC, attempting to relieve the difficulty in quantitatively analyzing the NCO-VC.

2. Related Work

Derived from a new mental model, D.S. Alberts briefly portrayed the key elements of NCO-VC and their causality in [1]. US DoD's OFT and ASD NII jointly developed a NCO Conceptual Framework (NCO-CF) that is considered as an elaborated NCO-VC [2]. The NCO-CF identifies the key concepts and linkages in all the physical, information, cognitive and social domains, and contains a large number of measures related to the NCO concepts. In the research on the information superiority, RAND Corporation explored part of the NCO-CF in more detail [3], where the scope is confined to the information and awareness components, and assessed the effects of information collection, fusion and dissemination on individual and shared situational awareness. Besides, RAND Corporation also applied and validated the NCO-CF using an air-to-air combat case study [4], where the advantage NCO capability (Link 16) was examined whether to provide the air forces in the air superiority mission, and expected results were gained. With the support of quantitative evidence, Georgia Court made some testing and modifications to the existing network enabled capability (NEC) benefits chain [5], which was created by mapping the benefits map proposed in the NCO-CF onto the UK command and battle-space management building blocks.

Besides the key concepts, the multiple factors influencing the value transfer among the key concepts are also indispensable for the NCO-VC. However, most existing research has only focused on the former [1][2][4]. Although the research on the information superiority has studied the latter in [3], only one intervening factor was taken into account and which attributes play roles is not clearly recognized. To systemically analyze the NCO-VC, it is vital and intricate to recognize what exogenous factors, which attributes of the factors, and how the attributes of the intervening factors play roles in the process of value transfer. To deal with above problems, this paper proposes a methodology for the modeling of NCO-VC.

3. NCO-VC modeling process

The proposed methodology for modeling the NCO-VC in this paper encompasses four steps, summarized as follows:

a） Identifying the key operational concepts and their linkages according to the combat process;

b） Analyzing the exogenous factors that intervene the causality between each linked pair of the key concepts;

c） Defining the vector of attributes and metrics for the key concept and intervening factor respectively;

d） Formulating the value transfer functions with the consideration of the related intervening factors.

To be clear, we show the NCO-VC modeling process in Figure 1 and discuss it in detail in the latter paragraphs.

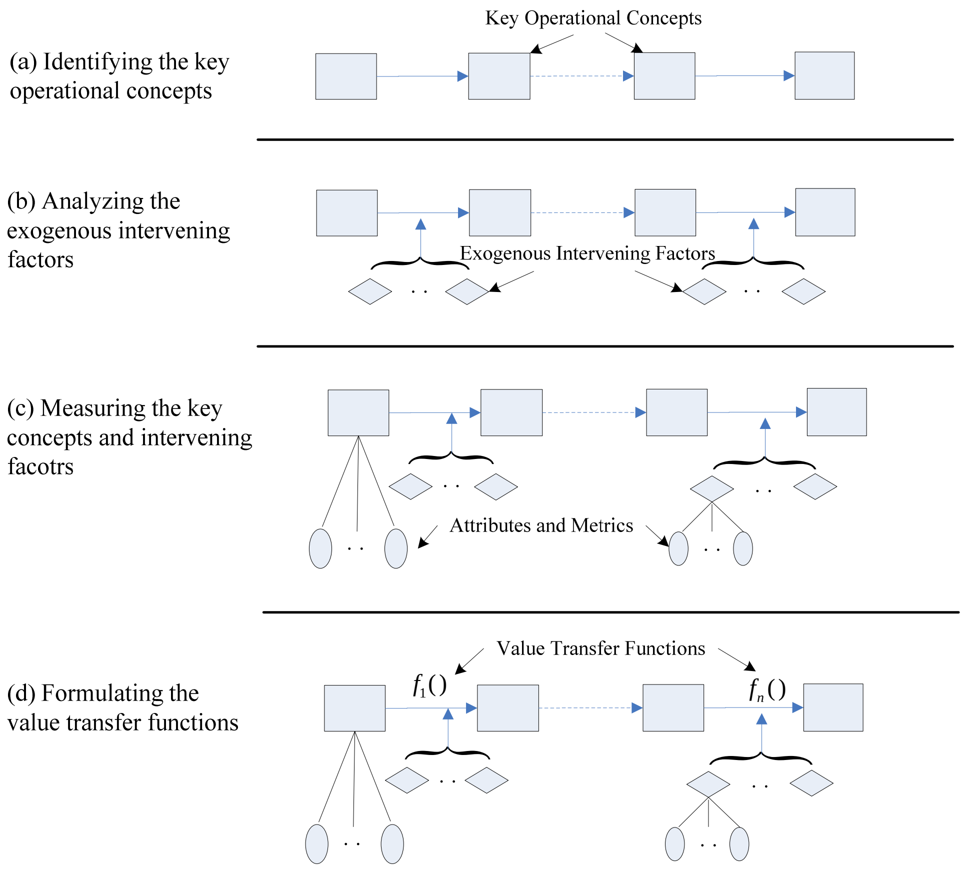

Figure 1 Four steps to model the NCO-VC

3.1 Identifying the key operational concepts

The first step of modeling the NCO-VC is to identify the key operational concepts by analyzing the operation process and construct the linkages among them. For the sake of comprehensibility, we suppose a simple and linear air-defense case with the following process:

a） A set of sensors are used to collect the information of the threat objects penetrating into a specific spatial region;

b） The sensors transmit their collected information to a central processing facility by the network connections to generate a single integrated air picture (SIAP);

c） The central processing facility transmits various versions of the fused SIAP to the decision-makers by the communication networks;

d） The decision-makers collaboratively interpret the received SIAP by communication networks to achieve some level of common battle-space realization;

e） The decision-makers collaboratively arrive at an agreed decision, devise the air-defense plans and send them to the operational units;

f） The operational units carry out the devised plans to intercept the incoming threat objects.

From above operation process, we can sequentially identify the following key operational concepts: ground truth, quality of sensor information, quality of fused SIAP, quality of received SIAP, quality of shared sense-making, quality of collaborative planning, quality of action and mission effectiveness. Figure 2 shows these key concepts and the relationships between them.

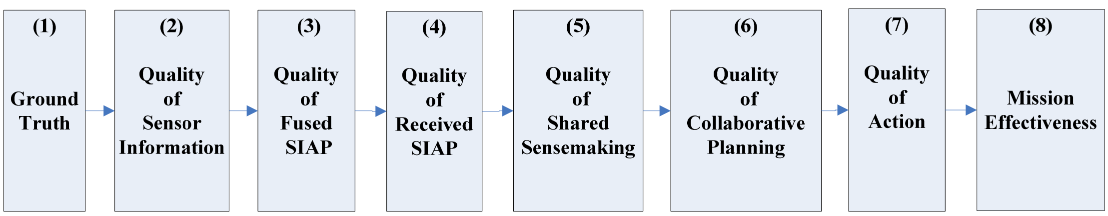

Figure 2 Key operational concepts of the NCO-VC

3.2 Analyzing the exogenous intervening factors

The second step of modeling the NCO-VC is to list the exogenous factors affecting the causality of the key concepts. Usually, there are multiple factors influencing the causality between each linked pair of key concepts. However, to make a tradeoff between the integrity and simplicity, not all but the most important intervening factors could be taken into account.

Take two examples for explanation. Firstly, the sensor information is derived from the signal characteristic of the objects (ground truth), and its quality is also affected by the factors of sensor performance, environment conditions, etc. Secondly, although high quality of sensor information is prone to lead to high quality of fused SIAP, the SIAP is also affected by the degree of integration in the sensor suite, the connectivity of the communications network, the communication rules of the network, the level of fusion available at the fusion centers, and so on. Other related factors affecting the value transfer are shown in Figure 3.

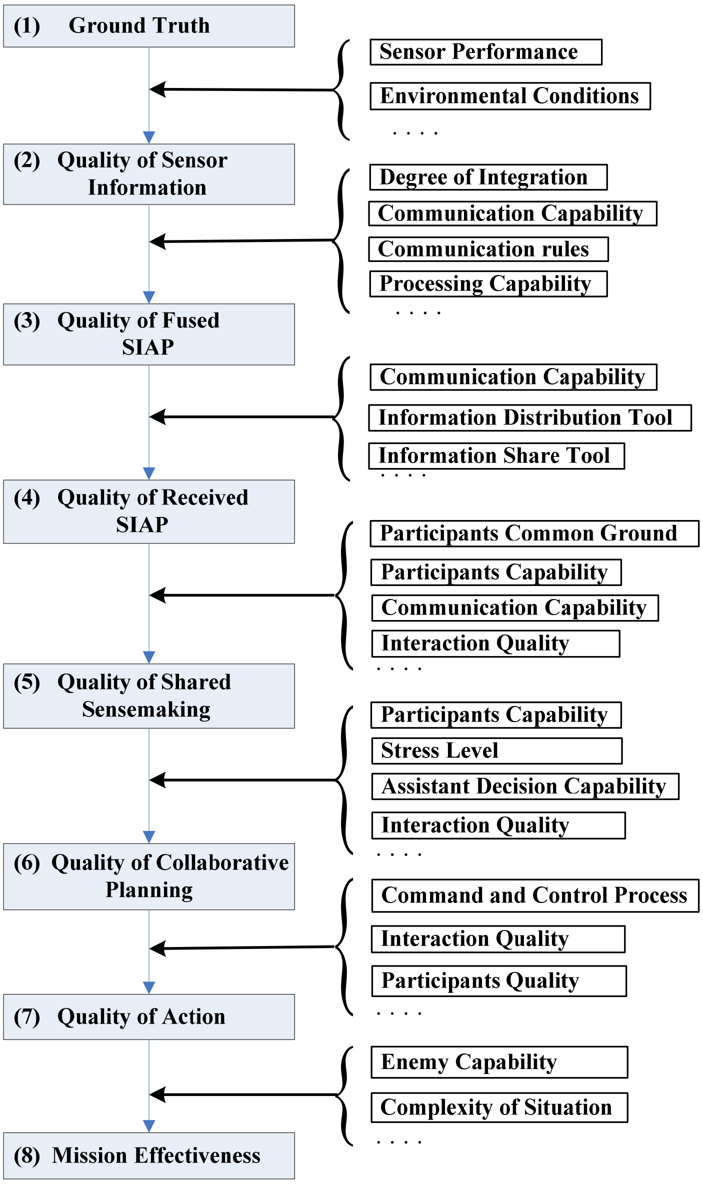

Figure 3 Exogenous intervening factors of the NCO-VC

3.3 Measuring the key concepts and intervening factors

The third step of modeling the NCO-VC is to build a set of attributes and metrics to measure each key operational concept and exogenous intervening factor. The attributes measure different characteristics of the key concept and intervening factor in terms of quantity and quality. Each attribute is actually measured by a metric or set of metrics that specifies in detail what data would be needed to measure the attribute.

Take the fused SIAP and communication capability for examples to describe the measures of key concept and intervening factor respectively. As illustrated in Table 1, the fused SIAP can be assessed by the attributes of completeness, currency, clarity, continuity, kinematic accuracy, ID completeness, correctness, and so on. For the detailed definition of the attributes and metrics, we can refer to references [6][7]. As illustrated in Table 2, the communication capability can be assessed by the attributes of reach, quality of service (QoS), assurance, availability, redundancy, reliability, and so on. A relatively full-scale presentation on the attributes and metrics of the related key concepts and exogenous factors is provided in references [2][8].

Table 1 Measures for the key concept of fused SIAP

Attribute	**Metric**
Completeness	The SIAP is complete when all objects in certain region are detected, tracked and reported.
Currency	The total time required to obtain a SIAP from the target detection.
Clarity	The SIAP is clear when it does not include ambiguous or spurious tracks.
Continuity	The SIAP is continuous when the track number assigned to an object does not change.
Kinematic Accuracy	The SIAP is kinematically accurate when the position and velocity of each assigned track agree with that of the associated object.
Correctness	The ID is correct when all tracked objects are in the correct ID state.
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Table 2 Measures for the intervening factor of communication capability

Attribute	**Metric**
QoS	Vector of performance metrics, including average bandwidth provided, packet delay, delay jitter and data loss.
Reach	Degree to which force entities can connect and communicate in desired access modes, information formats and applications.
Assurance	Extent to which network provides services that facilitate the assurance of information in the areas of privacy, availability, integrity, authenticity and nonrepudiation.
Availability	The percentage of time all authorized users have access to the network.
Redundancy	Multiple ways to get at the same information or to get from point A to point B in a network.
Reliability	An attribute of any network that consistently produces the same results, preferably meeting or exceeding its specifications.
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3.4 Formulating the value transfer functions

The last step of modeling the NCO-VC is to formulate the value transfer functions in the form of illustrative mathematical representations. The transfer functions are determined by the intervening factors and transform the attributes of the key concepts, i.e. map the attributes of a key concept to the attributes of its successive key concept in the NCO-VC. By the form of mathematical formula, the transfer functions clearly define what exogenous factors, which attributes of the factors, and how the attributes of the intervening factors play roles in the attribute transform.

Take the formulating of value transfer function between quality of sensor information and quality of fused SIAP as an example. The structure of the networked sensors and fusion center is shown in Figure 4, where the sensor coverage area is assumed not to overlap. The sensors transmit their readings to a central fusion facility by the underlying network, and the central fusion facility combines the sensor inputs into a SIAP. Currency and completeness are selected as the attributes to assess the quality of sensor information and fused SIAP. Communication capability of the network and processing capability of the fusion facility are selected as the factors affecting the value transfer. Transmission delay and probability of packet loss are selected to assess the communication capability, and processing delay and capacity are selected to assess the processing capability.

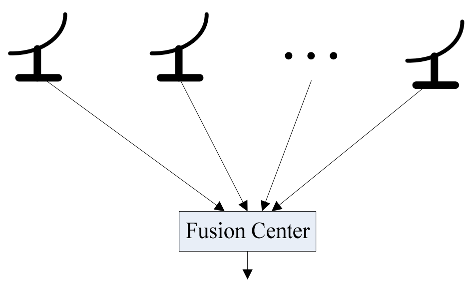

Figure 4 Structure of networked sensors and fusion center

Currency and completeness of the sensor information can be defined respectively as

$$T_{Sen} = TimeSensorSendingReports - TimeSensorDetectingTarget \qquad (1)$$

$$C_{Sen} = \frac{NumberOfDetectedTargets}{NumberOfLiveTargetsInCoverageArea} \cdot 100\% \qquad (2)$$

Currency and completeness of the fused SIAP can be similarly defined. Transmission delay and packet loss probability of the network can be defined respectively as

$$T_{Net} = TimeFusionFacilityReceivingSensorReports - TimeSensorSendingReports \quad (3)$$

$$P_{Net} = \frac{NumberOfLostSensorReports}{NumberOfSentSensorReports} \cdot 100\% \quad (4)$$

Processing time delay and capacity of the fusion facility can be defined respectively as

$$T_{Fus} = TimeSIAPProduced - TimeSensorReportsArriving \quad (5)$$

$$M_{Fus} = MaximumNumberOfTargetNumberFusionCenterCanProcess \quad (6)$$

With above definitions, the currency of the SIAP, which is determined by the currency of the sensor information T_{Sen}, transmission delay of the network T_{Net} and processing delay of the fusion facility T_{Fus}, can be expressed by the following transfer function

$$\begin{aligned} T_{F-SIAP} &= f_1\left(T_{Sen_i}, T_{Net_i}, T_{Fus} \mid i = 1,\dots,K \right) \\ &= \max_{i=1,2,\dots,K} T_{Sen_i} + \max_{i=1,2,\dots,K} T_{Net_i} + T_{Fus} \end{aligned} \quad (7)$$

where K denotes the total number of the sensors.

The completeness of the fused SIAP, which is derived from the completeness of sensor information C_{Sen} and affected by the packet loss probability of the network P_{Net} and processing capacity of the fusion facility M_{Fus}, can be approximately expressed by the following transfer function

$$\begin{aligned} C_{F-SIAP} &= f_2\left(C_{Sen_i}, P_{Net_i}, M_{Fus} \mid i = 1,\dots,K \right) \\ &= \frac{\bigcup_{i=1}^{K} A_{Sen_i}}{A_0} \cdot \sum_{i=1}^{K} W_i C_{Sen_i} \cdot \sum_{i=1}^{K} W_i \left(1 - P_{Net_i}\right) \cdot h\left(M_{Fus}, N\right) \end{aligned} \quad (8)$$

where A_{Sen_i} means the coverage area of sensor *i*, A_0 means the entire concerned area, W_i denotes a weight accounting for the relative size of the sensor coverage, and *N* denotes the number of the targets all the sensor report,

$$\sum_{i=1}^{K} W_i = 1 \quad (9)$$

$$h\left(M_{Fus}, N\right) = \begin{cases} \dfrac{M_{Fus}}{N} & M_{Fus} \le N \\ 1 & M_{Fus} > N \end{cases} \quad (10)$$

Value transfer function formulation is the most important and intricate step in the modeling of NCO-VC. Above mentioned example is simple and ideal. As taking the personnel behavior into account, it is often extremely difficult, even impossible to formulate a reasonable transfer function using the analytics, and then we can turn to the virtual simulation.

4. Conclusion

This paper has outlined a methodology for modeling the NCO-VC. A systematic NCO-VC model will be the focus of experimentation and analysis, not only help us to understand the benefits accumulation process within NCO, but also recognize the factors having the greatest payoff and the conditions under which the benefits will accrue. However, it should be noted that this research just gets under way and many details remain to be explored. As more evidence regarding NCO is collected from studies, simulations, experiments and actual operations, the NCO-VC model could be further tested, enriched and improved.

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