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MANUSCRIPT

Improving counterfire operations with enhanced command and control structure

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Abstract
The success of military operations depends on soldiers' execution of the operation as well as resources used for the operation. However, this does not mean that more men and firepower will ensure victory. Military units, just like any other organization, are collections of distributed elements, and improving the organization or command and control (C2) structure of such elements will ultimately show the true power of more men and resources. This paper presents a case study comparing two C2 structures in a counterfire operation, which is a very realistic scenario in some parts of the world. We modeled each structure with meta-networks and agent-based simulations, and then determined why one structure has a better outcome in the simulation. In particular, we jointly analyze the virtual experiment and network metrics, i.e., centralities, to identify the important resources and human factors. This research provides critical insight and suggestions to reform the C2 structure based on quantitative findings. In terms of the C2 structure, assigning detection units to the decentralized echelon brings about the reduction of the time for the targeting process, while the strengthened gun power for multiple targets is proved to have strong influence from the operational perspective.

Keywords Agent-based model · Meta-network · Counterfire operation · Battle experiment

1 Introduction

Counterfire operations are an essential part of combined arms operations, since other arms depend on the survival of artillery with the ability to suppress the hostile forces Bailey (2003). Although the artillery is very traditional weaponry, the efficient response to an artillery attack is a complex operation. In particular, concerning

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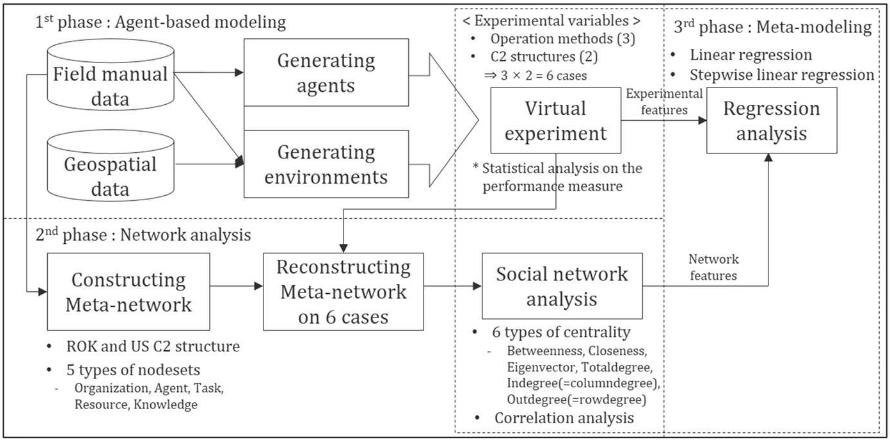


Fig. 1 The overview of research process: agent-based modeling (first phase), network analysis (second phase), and meta-modeling (third phase)

an equivalent response, many advanced weapons cannot be used and counterfire operations become the only possible political option. The objective of counterfire operations is to defeat the enemy's indirect fire elements, including their artillery, target acquisition system, and command and control (C2) components Army (2008). From this perspective, a better organizational structure of the responding unit can be a better countermeasure compared to cutting-edge weapons.

If we limit our problem to the design of a complex organization performing counterfire operations, the organizational design should include enhanced structure of the units as well as optimized processes of organizational operations. In part, these operational advances can be achieved by improved communications, personnel training, etc. However, to make a quantum leap in our operations, we need to redesign the C2 structure within units, and the operational procedures corresponding to the C2 structure.

This paper compares the C2 structures of two alternatives in counterfire operations. One alternative organizational structure was adopted from a newly-designed brigade combat team (BCT) with increased fire power and information-gathering capabilities. The other alternative is a traditional counterfire operational structure inherited from the division structure dating back to the Korean War and World War II. This comparison will show which structure is the better alternative, and what lessons can be learned to optimize the organizational structure in counterfire operations.

Figure 1 shows the overview of our research flow to answer our research question. We developed an agent-based model for a counterfire operation and simulated the model by varying operation methods and C2 structures. We also constructed meta-networks Carley et al. (2002) for the two alternative C2 structures, and modified the meta-networks by considering the experimental variables in the first phase. Lastly, we built a meta-model that correlates the simulation results from the experiments and network features from the configured meta-networks. We applied the

Discrete Event System (DEVS) formalism Zeigler et al. (2000) to develop a multi-agent model based on a hypothetical island skirmish scenario. Using the developed model, we performed virtual experiments where fire operation methods were varied by the two alternative C2 structures. For instance, the different experimental cells have (1) different sizes of units to fire, i.e., battalion-level and battery-level; (2) different modes of artillery fire, i.e., Fire For Effect (FFE) and Time On Target (TOT); and (3) different number of guns in a single battery. We also developed two meta-networks corresponding to C2 organizations to compare their structural properties. We discovered the important nodes in the meta-networks by applying various centrality measures. These different structural properties are expected to result in different operational performances in the real world as well as in our simulation models. Finally, we explain why the operational performance in simulation experiments was increased or decreased by the structural properties. In order to link the simulation results to the organizational design, we performed regression analysis to explain the operational performance with network centralities. In addition, further organizational characteristics were captured to improve operational performance through this meta-modeling.

Our contributions are summarized as follows:

– We provide a new case study with subject-matter knowledge on artillery counterfire, which compares every possible combination of the proposed operation methods and C2 structures.
– Our experimental results give insight on how to identify significant factors and strengthen the organizational structure and operations to efficiently respond to threats. We revealed the importance of the observation battery, and the recent C2 structure shows higher performances by placing the observation battery in the organizational structure differently compared to the traditional C2 design. Furthermore, the proposed alternative structures show greater efficiency than the baseline C2 structure in the counterfire operation.

2 Problem definition

This section identifies two problems in counterfire operations, namely operation methods and C2 structures, each of which is discussed in turn.

2.1 Methods of counterfire operations

The current C2 structure of the artillery battalion consists of three batteries, and each battery has six howitzers or self-propelled guns, for a total of 18 guns (3×6). The current field manual recommends that battalion-based counterfire is more efficient than battery-based counterfire Army (2008). For example, let us assume that an officer directing fire in the battalion decides that 18 rounds of high-explosive projectiles need to be fired. Following the field manual, the officer will choose a battalion to fire one round of ammunition (i.e., FFE). This

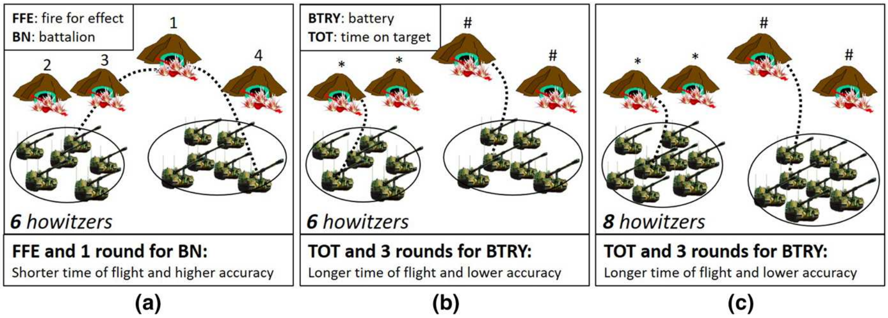


Fig. 2 Alternatives in the counterfire operation: **a** battalion mission (units to fire: battalion, fire method: FFE), **b** battery mission (units to fire: battery, fire method: TOT), **c** strengthened battery mission (units to fire: battery, fire method: TOT)

battalion-wide mission execution is centralized with short-time usage of broad resources. This short round of firing enables a surprise attack and reduces the risk of exposure to enemy target acquisition assets.

However, the field manual also raises concerns that the battalion mission might have difficulty handling multiple targets. Artillery forces are supposed to shoot and evade immediately after shooting, which limits the number of engagements with diverse targets given a small window of time. Instead, this challenge should be met by operating the battery-based counterfire, i.e., three units to fire against three different targets instead of one. Although battery-based counterfire can engage more units, this method also has a higher risk of exposure to enemy target acquisition assets. In order to have the same effect as battalion counterfire, the battery needs to fire three times, which increases exposure risk. In addition, the battery counterfire uses TOT firing, which is the military tactic of using artillery fire so that several munitions reach the target at precisely the same time. This provides a surprise attack element but still increases the exposure risk. The howitzer or self-propelled gun fires three times during the TOT mission. In order for the three shots to reach the target at the same time, the three shots should have different trajectories: intentional high-angle fire, normal-angle fire, and intentional low-angle fire. The high-angle fire has a longer flight time and lower accuracy because of its intentionally-designed longer trajectory. The three shots reach the target at the same time at the arrival time of the longer trajectory. Therefore, the flight time of the rounds fired increases and the shots become inaccurate in the TOT mission compared to the battalion fire.

Finally, the third solution is strengthening the battery to have more guns than the ordinary. This is called a strengthened battery and is an alternative C2 structure. Specifically, we modeled the strengthened battery as having eight howitzers, like the US Army Paladin battery. This method still has a longer exposure than battalion counterfire, but will inflict more damage than battery counterfire. It should be noted that this counterfire method will require additional deployments of artillery. Figure 2 illustrates the operational concepts of three different counterfire methods, and Table 1 summarizes the key points of the three alternatives.

Table 1 Comparisons of advantages and disadvantages of the counterfire methods

Category	Battalion mission	Battery mission	Strengthened battery mission
Unit to fire	Battalion	Battery	Strengthened battery
Method of fire	Fire for effect	Time on target	Time on target
Number of guns	18 howitzers	18 howitzers	24 howitzers
Fire order	Sequential	Simultaneous	Simultaneous
Flight time	Shorter time of flight	Longer time of flight	Longer time of flight
Accuracy	Higher accuracy	Lower accuracy	Lower accuracy

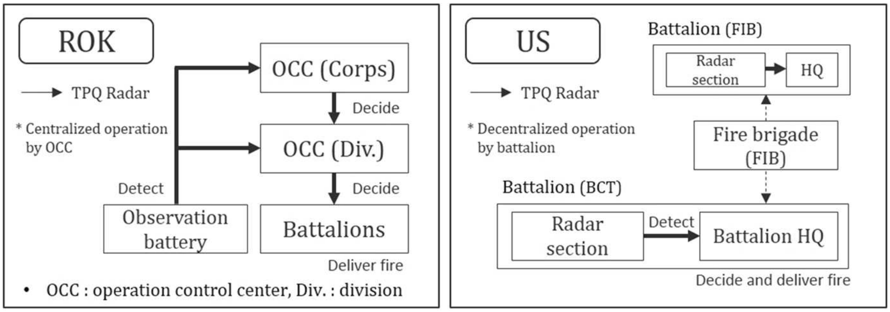


Fig. 3 The targeting process in the counterfire operation between the baseline and alternative artilleries. The baseline artillery units dealing with targeting process are operated separately. On the other hand, the alternative artillery units perform it at the battalion level

This paper compares and contrasts the operational procedure and organizational structure of the three different alternatives in counterfire operation: battalion counterfire, battery counterfire with TOT (newly proposed in this paper), and strengthened battery counterfire with TOT (alternative structure).

2.2 Command and control structure

The operational procedures require the optimization of the organizational structure to follow the procedures. Therefore, the baseline and alternative counterfire operations were carried out with two different organizational structures. Figure 3 shows the actual targeting process in the counterfire operation between the baseline and alternative artilleries. While the baseline artillery is centralized by the Operation Control Center (OCC) in a hierarchical structure, the alternative artillery is decentralized by the fire battalion in a networked structure. In the baseline artillery, the observation battery operates the target acquisition radar and delivers the target information to the OCC when it acquires the artillery target. The OCC executes the targeting process and determines which battalion will attack. In contrast, the fire battalion of the alternative artillery, which primarily plans and executes fires for the brigade combat team (BCT), has three components in the fire support system: target acquisition, C2, and attack resources. Therefore, the fire battalion of the alternative artillery provides not only field artillery attack resources to the BCT but also target acquisition capability because the target acquisition platoon is organized into the fire battalion. Furthermore, the fire battalion of the alternative artillery has increased number of assistant officers in the intelligence, operation, and radar sections where the counterfire operation is conducted, to perform targeting processes at the battalion level. This enables the fire battalion of the alternative artillery to carry out the fire mission independently without any support from higher headquarters, e.g., fire brigade (FIB). The centralized structure of the baseline artillery requires more processes than the decentralized structure of the alternative artillery. In other words, the centralized structure lengthens the time required for the targeting process, which leads to an inefficient decision-making process.

The field manual at the baseline illustrates that the C2 structure is hierarchically arranged; the target detecting units, C2 units, and gun units are hierarchically connected. If the current C2 structure is adopted for the battery mission, the level of C2 hierarchy will increase such that the efficiency of the battery mission will eventually decrease.

On the other hand, the alternative C2 structure requires that detection and fire be carried out at the battalion level, and not at the higher level like in the baseline. This enables the fire cycle in the alternative artillery to be shorter than that of the baseline artillery. However, the alternative C2 structure also has a negative aspect, which is the increased operating costs in terms of resources, owing to the overarching scope of the mission from detection to firing.

3 Previous research

This paper focuses on analyzing the effectiveness of alternative firing methods during counterfire operations using modeling and simulation (M&S). We also analyzed the difference in C2 structures between the baseline and alternative artillery organizations using the meta-network to determine the influence of structural differences on combat effectiveness. We applied the two main approaches, i.e., M&S and network analysis, to analyze the organizational structures, i.e., the C2 structures. Thus, we reviewed previous studies in three parts: the defense M&S for counterfire operations, network analysis for C2 analyses, and the joint analysis of M&S and network analysis of organizations.

3.1 Defense M&S for counterfire operation

M&S has been widely used as a tool for training Zavarelli (2006), acquisition Air force (2009), and analysis Cramer (2008) in the defense field. One of the most important aspects of defense M&S is increasing the fidelity to real-world situations Roza (2005), which requires modeling approaches to describe a specific circumstance as accurately as possible. However, it is difficult to describe all the details of operations. In some parts, this difficulty stems from the requirements of domain knowledge Sung et al. (2010). Therefore, cooperation between subject matter experts who supply the domain knowledge and M&S experts who model the domain knowledge as a simulation model is essential in defense M&S Kim et al. (2010). The modeling and subject matter experts together produced the models and scenarios applied in this counterfire study. The models were based upon mainly military doctrines that describe the principles of counterfire operations. After constructing the entire model, the virtual experiments were designed and executed using common procedures in simulation-based experiments.

In particular, we used DEVS formalism to represent our models. DEVS formalism (Kim and Zeigler 1987; Zeigler et al. 2000) is the formal specification of a discrete event system, and specializes in describing the rule-based system. This formalism enables a large discrete event system to be specified by hierarchically decomposing the system into modules. Also, DEVS formalism allows us to clearly describe the behavior of individual modules and the interaction among the modules within the complex large system, rather than simple programs or pseudocodes. Therefore, DEVS formalism is frequently used to describe defense systems, i.e., C2 structures and military operations Kim and Moon (2012). Chung et al. (2008) used DEVS formalism to study the operation of a mine artillery, from opening the mine until the strike on targets. Here, the mine artillery needed to be defined further. The mine artillery is an artillery unit that occupies hardened points, such as caves or mines under mountains, and maneuvers through roads and rails between the hardened locations to the fire locations. These mine artillery are naturally very time-sensitive targets because they are invisible and impossible to target at the hardened locations. Hence, our reactions under the C2 systems should be tested against these mine artillery maneuvers.

Despite the fact that DEVS formalism is an alternative to modeling the counterfire operation, there is no dominant formalism. In defense M&S, other approaches have been utilized to describe the behavior of military entities. For instance, Map Aware Nonuniform Automata (MANA) Lauren and Stephen (2002) and Finite State Machine (FSM) Arbib (1972) can also specify the details of the behavioral rules in a defense system Lee et al. (2010). Additionally, some studies have built simulations without any formal representation, and the main modeling artifact in these cases is the source code.

As there are multiple alternatives in developing simulation models, there are also previous works that modeled counterfire operations. For example, Kim and Lee (2008) proposed a new target reference table of hit probability while executing counterfire operations, and simulated this using MANA to verify the method. Lee (2011) identified the operation of a target acquisition radar and self-propelled howitzer's strike plan by considering the North artillery's weakest time. Lim (2012) ascertained the best combination of combat factors by case studies with several variables. Table 2 summarizes some previous research on the counterfire situation with M&S.

Table 2 Summary of the previous counterfire operation models categorized by modeling objectives and methods

Literature	Objective	Method (software)	Characteristics
Chung et al. (2008)	Analyzing the counterfire operations varying time variables	DEVS, Zeigler et al. (2000)	Performing the virtual experiment to analyze the survival rate
Kim and Lee (2008)	An improvement of hit-probability and efficient counterfire execution	MANA, Lauren and Stephen (2002)	Proposing new target reference table and simulating using MANA to verify
Lee (2011)	Analyzing tactical operations of attacking mine artillery	Any logic, Borshchev and Filippov (2004)	Identifying the operation of anti-artillery radar and self-propelled howitzer
Lim (2012)	Analyzing tactical operations and acquisition	FSM, Arbib (1972)	Assessing the best combination of tactical operation

3.2 Network analysis for command and control

We use network analysis based on the results of the virtual experiment, for example, by centralities, to identify the important resources and human factors. The network analysis is one of the major methodologies in investigating organizational structure and C2 systems Baber et al. (2012). Controlled individuals in the military C2 structure follow no more than one or two higher-ranking individuals, which naturally makes the C2 structure a hierarchy Brown (1978). Researchers have proposed potential organizational structures other than a hierarchy. Guetzkow and Simon (1955) hypothesized using alternative structures, such as all-channel, wheel, circle, and so on. He quantitatively investigated the path lengths from one individual to another as a proxy measure of information-sharing between agents. Carley and Lin (1995, 1997) studied the design of organizations for high performance under stressful conditions. They examined organizational performance with various designs in different task environments and under various types of information distortion.

These previous studies differ by domains but commonly utilized social network analysis (SNA) Wasserman (1994). Clustering algorithms (i.e., Newman clustering) Newman (2001) and property measures (i.e., degree centrality) Friedkin (1991), are the algorithms and measures that belong under SNA. These algorithms and metrics can determine organizational characteristics, such as cohesive groups, relative positions, importance of individuals, etc.

Traditional SNA is often limited to the networks between entities, but the C2 of military units is more than the collection of individuals. The C2 should include pieces of information passed on by individuals, assigned tasks, required resources, and more. The meta-network enables this expansion of node semantics in SNA Carley et al. (2002). The meta-network is a network that assumes multiple entity sets and multiple link types. By utilizing this meta-network concept, the organizational structure of the C2 is analyzed in a more informed way compared to using only agent interactions. Hence, we applied network analysis to the meta-networks of C2 structures of interest.

3.3 Joint analysis of M&S and network analysis on organizations

As discussed in Sects. 3.1 and 3.2, we conducted organizational analysis with C2 systems by taking into account both M&S and network analysis. Some works have considered a variety of organization types with joint approaches of M&S and network analysis, which are clearly in line with our work. For example, Lanham et al. designed headquarters, which are the actors when a crisis occurs, as agents and constructed meta-networks for identifying the main actors. This work was aimed at the supporting crisis de-escalation by building the model and responding to the crisis as quickly as possible Lanham et al. (2014). Li et al. (2015) observed the organizational dynamics of terrorist networks utilizing cellular network modeling and agent-based simulation analysis. Mizgier et al. (2012) considered the production dynamics of a supply chain network. To impart a sense of reality into the simulation environment, they reflected the concepts of price dispersion, price dynamics, production costs, and so on. Costa et al. (2015) modeled banks as agents and addressed the impact of bank failure, the failure factors, and the spreading complexion caused by the failure. Table 3 lists some of these joint analyses of M&S and network analysis by comparing them to our work. Besides research on counterfire operation models, Gutiérrez et al. (2014) studied on the control of complex systems such a peer-to-peer (p2p) network by modeling based on multi-agent models and analyzing the modularity of the architecture.

4 Counterfire operation model

We surveyed the C2 structure and counterfire operation procedures of two different artilleries. Then, we transformed the survey results, mostly field manuals, into an agent-based model for the counterfire operations. In particular, our counterfire operation model describes detailed damage assessments by artillery type and provides detailed operational processes of the two artilleries. Before setting out our model details, we briefly describe how the counterfire operation progresses.

4.1 Procedure of counterfire operation

Counterfire is aimed at destroying or neutralizing enemy artillery, including fire systems and support systems Army (2012). Figure 4 shows the overall procedure of counterfire operations. A counterfire operation is mainly composed of three phases: detection, command, and delivery of fire. First, target acquisition radars of friendly forces emit beams to the sectors where targets are likely to be found. When the enemy artillery in these sectors fire, the radars acquire the enemy artillery's coordinates by tracking the projectiles. The acquired coordinates are sent to the control center, which selects the battalion that should fire against the acquired coordinates. Lastly, the artillery battalion that receives the fire request from the control center fires at the enemy's artillery.

4.2 Hierarchical structure of counterfire operation model

Our counterfire operation model replicates the bombardment during a small island skirmish where multiple battalion units are engaged. The battalion units are also hierarchically structured with subordinate units. Considering these characteristics, we applied the large-scale, dynamic, extensible, and flexible (LDEF) formalism Bae et al. (2012) to develop the counterfire operation model. The LDEF formalism is an extension of DEVS formalism Zeigler et al. (2000), and specializes in developing agent-based models by hierarchical compositions of diverse models.

Figure 5 illustrates the hierarchical structure of our counterfire operation model, and Fig. 6 shows their overall coupling structure. The counterfire operation model comprises two models: the multi-agents model and multi-environment model. The multi-agents model illustrates engagement units in the counterfire operation; hence,

Table 3 Research involving joint analysis M&S and network analysis on organizations

Literature	Domain	Agents in agent-based modeling	Network model in network analysis
Lanham et al. (2014)	Organization—Crisis De-escalation	Headquarters	Meta network, Carley et al. (2001)
Li et al. (2015)	Society—Terrorism	Terrorists	Cellular network
Mizgier et al. (2012)	Business—Supply chains	Raw materials providers, suppliers, manufacturers, retailers	Supply chain network, Melo et al. (2009)
Costa et al. (2015)	Economics—Financial markets	Banks	Functional dependency network, Garvey and Pinto (2009)
Ours	Military—Command and control	Battalion, battery, gun, operation center, red C2, radar	Meta network, Carley et al. (2001)

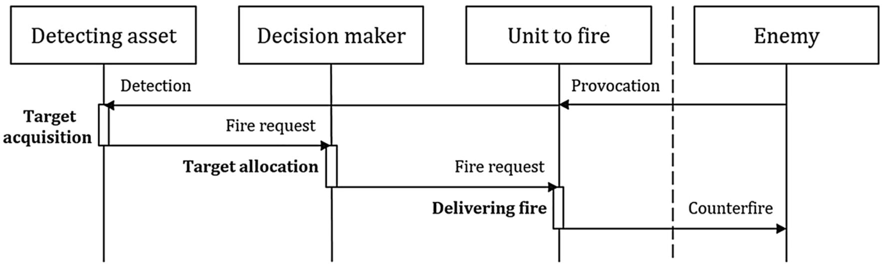


Fig. 4 Sequence diagram of targeting process in the counterfire operation

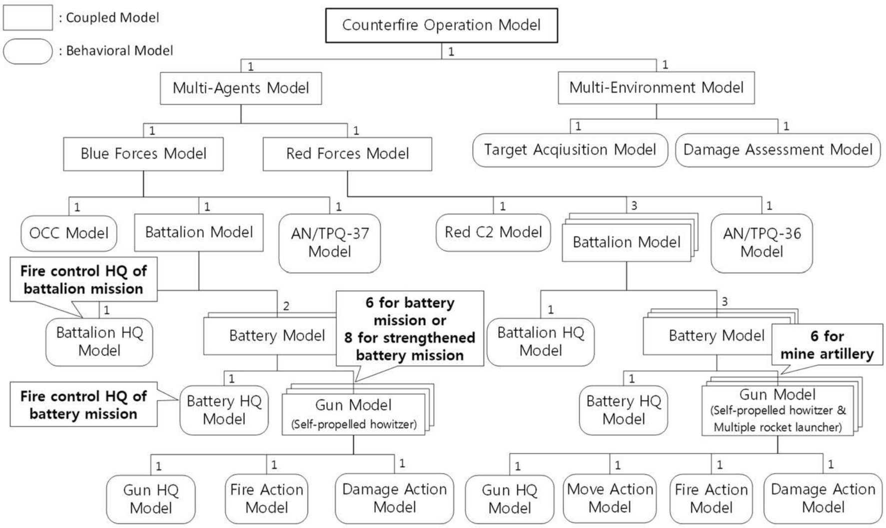


Fig. 5 Hierarchical structure of the counterfire operation model

it consists of blue and red forces. Each force has models for detection, such as anti-artillery radar, decision making, and delivering fire. The battalion model has headquarter (HQ) models for mission allocation and multiple battery models for firing at targets with guns. The multi-environment model consists of the target acquisition model and damage assessment model. The target acquisition model acquires the location of the firing battery for the counterfire operation, while the damage assessment model evaluates the damage caused by gunfire.

There are some details that should be noted because these reflect key properties of blue and red forces. Considering the red artillery deployed near the island, we described the red forces' gun models as mine artilleries, i.e., they move along the hardened artillery sites and are not damaged in the hardened area. Therefore, the red gun models have a movement action model but the blue ones do not. For the blue forces, we varied the structure of the battalion model with respect to the operation methods. Firstly, the HQ model in the battalion may or may not control the

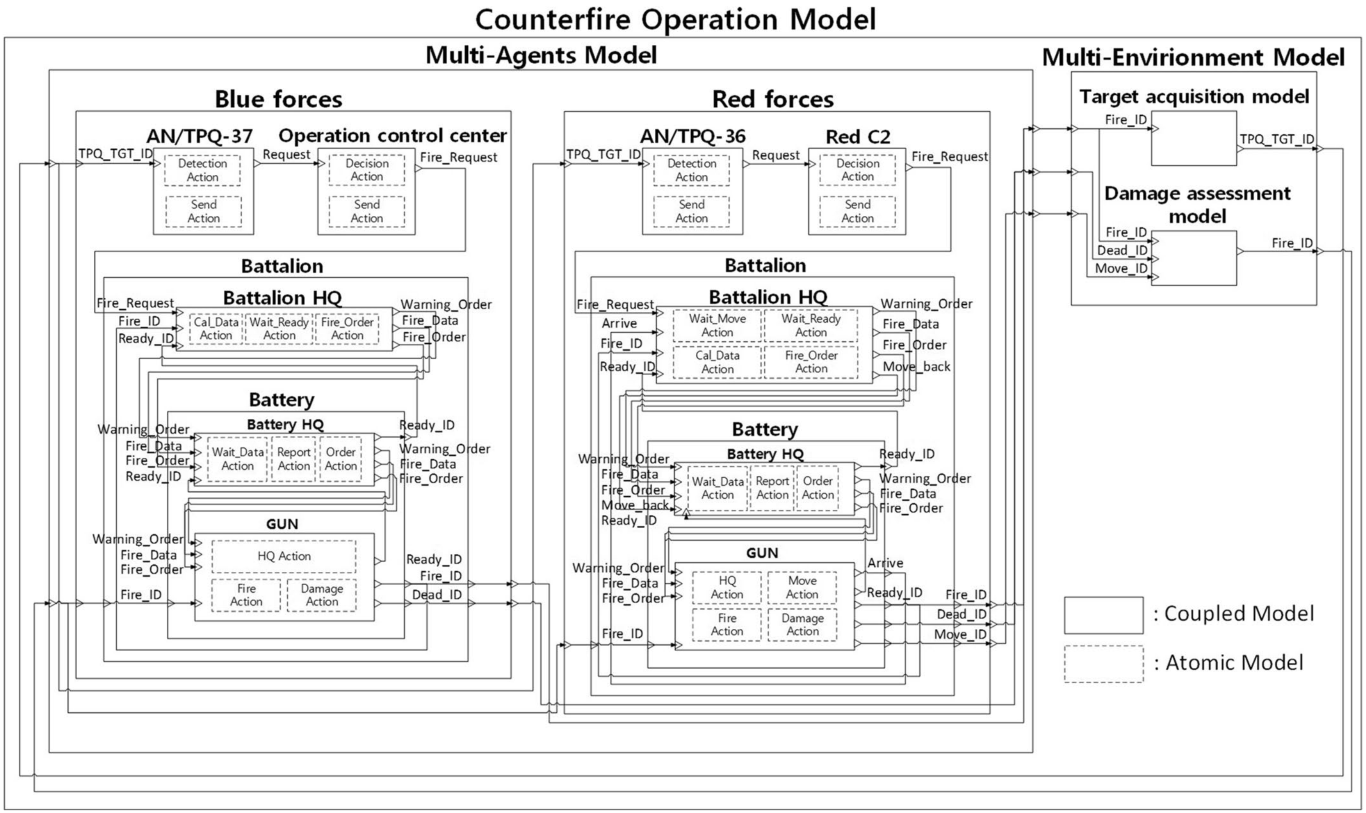


Fig. 6 Coupling structure of the counterfire operation model. This diagram follows the notations of the DEVS coupled model. AN/TPQ-# refers to the one of mobile radar systems, whose serial number is #

Table 4 List of behavioral models in the counterfire operations model

Category	Behavioral model name		Functions
Agent	Battalion	Battalion HQ	Target allocation, Fire order
	Battery	Battery HQ	Target allocation, Fire order
	Gun	Gun HQ	Fire order
		Fire action	Delivering projectile
		Move action	Reporting gun's current location
		Damage action	Dividing the damage by full or part damage
	Operation center, red C2		Target allocation, Fire request
	Anti-artillery radar		Target acquisition, Fire request
Environment	Damage assessment		Evaluating damaged howitzers
	Target acquisition		Calculating the center point of battery

fire mission by the operation methods. Secondly, the number of gun models varies depending on whether the battery is strengthened or not. These variations enable the simulation experiments on unit configurations.

4.3 Behavioral models in counterfire operation model

This section illustrates the behavior of the counterfire operation model. Note that although the counterfire operation model was developed by LDEF formalism Bae et al. (2012), it can also be depicted by DEVS diagrams because LDEF formalism is an extension of DEVS formalism. Table 4 shows a list of behavioral models in the counterfire operation model. The behavioral models are categorized into agent-behavior models and environment-behavior models. Among them, the HQ models include the battalion and battery HQs, operation centers, and Red C2 models; the detection models of radars and the damage assessment model, which have relatively complex behaviors, are introduced in the subsequent sections.

4.3.1 Headquarter models

In field manuals, all echelons from the operation center to guns have their own headquarters, and the headquarters determine various decisions in the battlefield. However, battalion and battery HQ models in the counterfire operation model focus on target allocation and fire order using reports received from subordinate units. Figure 7 shows model diagrams of battalion and battery HQ models.

The battalion HQs (see Fig. 7a) receives a *Fire_Request_in message* and issues *Warning_Order_out messages* to the battery HQs. As time passes in the Cal_Data state, the battalion HQs sends the *Fire_Data_out message* containing target information to the battery HQs. Once the subordinate batteries are ready for the fire mission, the battalion HQs issues the *Fire_Order_out message*. After fire mission completion, the battalion HQs repeats the internal transition from the Cal_Data to the Next state when there are remaining fire missions.

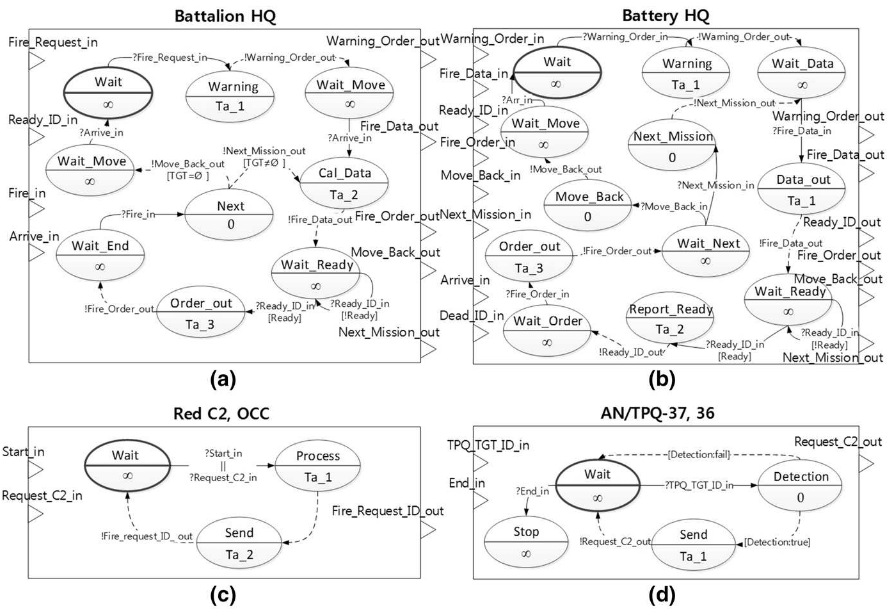


Fig. 7 State transition diagram of four behavioral models: **a** Battalion HQ, **b** Battery HQ, **c** Red C2, operations center, and **d** anti-artillery radar. The diagram follows the notations of the DEVS atomic model

The battery HQs (see Fig. 7b), as the middle echelon between the battalion HQs and gun HQs, controls the gun HQs and reports the current status to the battalion HQs. For example, the battery HQ model delivers *the Warning_Order_out*, *Fire_Data_out*, and *Fire_Order_out messages* to the gun HQ model and reports the *Ready_ID_out message* to the battalion HQ model.

Unlike the blue battalion and battery HQs, the red battalion and battery HQs have additional states associated with movement because we described the red forces' gun models as mine artillery. After the fire mission, the red battalion and battery HQs issue instructions to gun HQs returning to the hardened artillery sites where it waits for the howitzers to arrive. On the other hand, the blue battalion and battery HQs immediately return to initial state, e.g., *Wait*, after the fire mission when there are no missions left.

In the case of the battery mission of blue forces, the blue forces' battalion HQs allocates the targets between two batteries by considering its mission execution status, which is the same transition function as that of the operation center model. Instead, the battery HQ model serves as the battalion HQ model, e.g., calculating fire data and issuing fire orders. In other words, HQ models that control fire mission vary according to the operation methods between the battalion and battery for blue forces.

The operation center and Red C2 models (see Fig. 7c) are the second-highest command in the scenario. These models receive the *Request_C2_in messages* from the radar model and perform target allocation. While the blue forces' operation

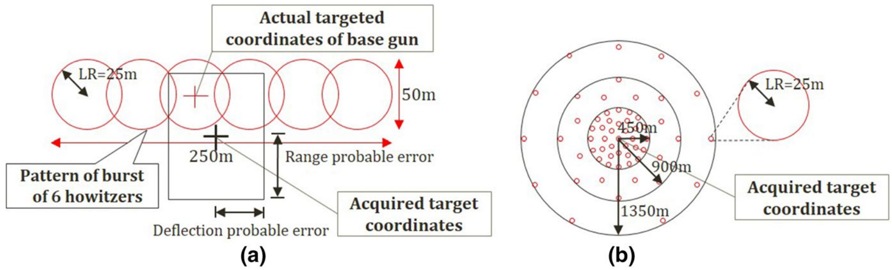


Fig. 8 Two types of damage assessment based on the acquired target coordinates: **a** lateral spread distribution for six howitzers in a battery, **b** circular error probability for multiple rocket launchers

center sends the *Fire_Request_ID_out message* directly to the one battalion without target allocation, the Red C2 models determine which battalion is available by considering its execution of the fire mission and allocates the targets among the three battalions.

4.3.2 Detection models

The anti-artillery radar models (see Fig. 7d) receive the *TPQ_TGT_ID_in messages*[1] from the environment model (target acquisition model) and acquires the target information in accordance with the detection probability. The radar model sends the *Request_C2_out message* to the OCC or Red C2 model when it succeeds in detecting based on the probability of detection. Otherwise, the radar model changes the state transition back to *Wait* and stands by until the next target information. In the case of the alternative artillery C2 structure, the blue forces' radar model sends the *Request_C2_out messages* to the battalion HQ model without sending the messages to the operation center.

4.3.3 Damage assessment model

The counterfire operation model describes two types of guns, the howitzer and rocket launcher, by changing the parameters of the fire action model. The damages caused by the two guns are evaluated by the damage assessment model. In the case of howitzer damage, the damage assessment model applies lateral spread distribution (see Fig. 8a) with two different probable errors—range and deflection—to describe the limited explosive area Army (1976). For example, when the battery acquires target coordinates from the radar, (1) it chooses one point, which is the actual targeted coordinates of the base gun, randomly and within probable errors; and then (2) it chooses other points, which are the actual targeted coordinates of other guns, based on the base gun, in order to spread the burst of fire in the weapon-specified strike area.

[1] TPQ means Transportable Multipurpose Radar, and TGT is an abbreviation of target.

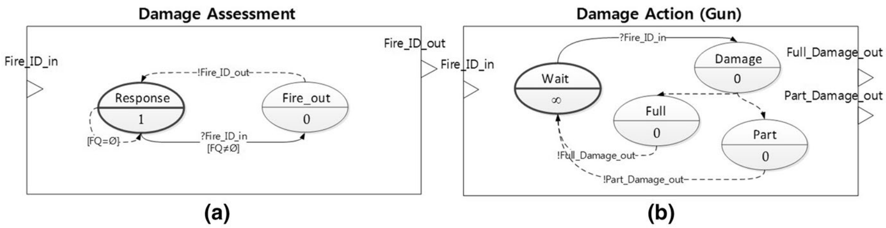


Fig. 9 State transition diagram of two models in damage assessment process: **a** damage assessment model in the multi-environment model, **b** damage action model in gun model. The diagram follows the notations of the DEVS atomic model

In the case of rocket launcher damage, the damage assessment model applies circular error probability (CEP) (see Fig. 8b). CEP is defined as the radius of a circle, centered about the mean, whose boundary is expected to include the landing points of 50% of the rounds. In Fig. 8b, 50% of the rockets land within a 1CEP radius of the weapon specification, and 99% of rockets land within a 3CEP radius randomly. In contrast to the howitzer, the rocket launcher is aimed at multiple unspecified areas and targets; hence, we described the behavioral properties of the rocket launcher by applying the concept of CEP.

We also applied a damage assessment method from the *baseline army fire operation analysis model* Army (2006b). Following the guidance of the baseline army fire operation analysis model, which said that the cookie-cutter algorithm is suitable for the counterfire operation Army (2006b), the algorithm was applied for evaluating damages from the above indirect fires. The cookie-cutter algorithm assumes that all targets within a lethality radius (LR) sustain fire damage.

Figure 9 shows the state transition diagram of (a) damage assessment model in the multi-environment model and (b) damage action model in the gun model. During the counterfire operation, a fire action model of each gun sends a *Fire_ID_out message* to the damage assessment model with its target point and gun type. Based on the received message, the damage assessment model calculates the explosive area with respect to the gun type and identifies enemy units in the area. Then, the damage assessment model sends *Fire_ID_out messages* to the enemy units within the LR, and the damage action models in the enemy units evaluate the damages they sustained according to the *Fire_ID_out message*.

The damage action model subdivides its damage into *full damage* (i.e., all functions are disabled) and *part damage* (i.e., either maneuver or fire function is disabled) with equal probability. If the damage is defined as total damage, then the damage action model sends a *Full_Damage_out message* to gun HQs, and the gun HQs becomes disabled; otherwise, the damage action model sends a *Part_Damage_out message* to move the action model or fire action model, and the received one loses its function.

5 Virtual experiments

This section discusses the design of a virtual experiment with the counterfire operation model and the analyses of the experimental results. Before introducing the details, model parameters and a performance measure are presented. Our implementation based on LDEF formalism Bae et al. (2012) was built using Java platform. In addition, the virtual experiments are performed in a machine with the following specifications:

* CPU: Intel Core i7-2600 K 3.4 Ghz;
* RAM: 8 GB;
* OS: Windows 7 64-bit.

5.1 Model parameters and performance measure

Model parameters in the counterfire operation model (see Table 5) consist of specifications and probabilistic measures of the detection devices and firing weapons used in the counterfire operation. Among the parameters, the probable error, LR, and time of flight are referred to as the results of operation tests and evaluation of the field manual of the blue force. Meanwhile, the CEP for rocket launchers in the red forces was estimated from research on an actual incident McDonald (2010). The engagement is a countefire operation in that the red force begins with a preemptive attack on the blue force and corresponds to the attack on the blue force. The interactions between two forces during the engagements are maneuvering and striking. Specifically, the interaction is limited only to the perception of the attack by the trajectory of the other party's fire by each radar.

To illustrate the numerical inferiority of the blue force compared to the red force, the blue artillery consists of two batteries, while the red artillery consists of two self-propelled battalions and one rocket launcher battalion in the scenario (Fig. 10). We arranged the blue and the red assets based on the expert's suggestions. We measured the number of red guns alive after simulation as a performance measure. Then, we compared the damage effectiveness in experimental cases by counting the number of red guns who survived; the less survivors, the greater damage inflicted on them.

5.2 Experimental design

We conducted experiments to analyze the effectiveness of the counterfire operation by considering operation methods and C2 structures. In particular, the experiments compared the counterfire operations between the baseline and alternative artillery structures. The operation method was tested by varying the unit structures by changing the number of resources and their distributions. Specifically, the operation methods can be either battalion-driven (baseline C2 structure, centralized operation against a single target) or battery-driven (alternative C2 structure, decentralized operation against multiple targets). Additionally, we considered the strengthened

Table 5 Input, output, and parameters of the counterfire operation model

Type	Name	Value	Implication
Input	Operation method	Varied in experiments	Units to fire and methods to fire mission in blue forces
	C2 structure	Varied in experiments	Headquarter operating target acquisition radar in blue forces
Output	The number of survived red guns	Measured from simulations	The number of alive red guns after simulation to compare the effect of damage
Parameter	The number of guns in blue	12, 16	12 howitzers and for battalion and battery mission (6 howitzers each battery), 16 for strengthened battery mission (8 howitzers each battery)
	The number of guns in red	48	36 howitzers and 12 rocket launchers in 3 battalions
	Lethality radius (LR)	25	The distance from the mean point of impact to assess the damage (unit: meter)
	Probability of damage	p (damage) = 1	Units in LR are always damaged (from the cookie-cutter algorithm)
	Lateral spread distribution	250 × 50	The pattern of burst in or around the target area (unit: meter)
	Circular error probability (CEP)	1 CEP = 450	The radius of a circle whose boundary includes the landing points of 50% of the rounds (unit: meter)
	Probable error	Range = 50 (L), 90 (H)/ deflection = 7 (L), 14 (H)	The error which a weapon may be expected to exceed as often as not (unit: meter). L represents low-angle fire and H represents high-angle fire
	Time of flight	20 (L), 80 (H)	Time for a round to travel from the muzzle to the target point (unit: second). L represents low-angle fire and H represents high-angle fire
	Probability of detection	0.75 (blue), 0.65 (red)	The detection rate of radar while a round travels to the target point (unit: percentage)

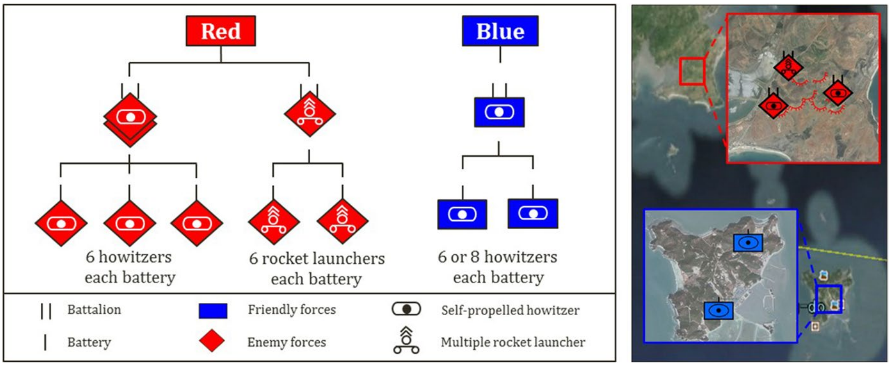


Fig. 10 Combat entities of red and blue forces in the counterfire operation model (left) and their initial artillery positions (right)

Table 6 Experimental design for the counterfire operation model

Variable	Value	Implication
Operation method	Battalion mission, battery mission, and strengthened battery mission	12 howitzers and fire for effect for Battalion mission; 12 howitzers and TOT for battery mission; 16 howitzers and TOT for strengthened battery mission
C2 structure	Baseline C2 and alternative C2	Headquarters operating anti-artillery radar: operation center (baseline C2) and battalion (alternative C2)
Total experiment cells	Total 3 × 2 = 6 cells	30 Replications for each cell (total 180 simulation runs)

battery mission (alternative C2 structure, decentralized operation with strengthened elements against multiple targets) as another operation method. To analyze the targeting process, including detection, decision making, and delivering fire, the experiments defined the C2 structure as another variable. Specifically, the C2 structures became different by placing the detection radar at a different C2 echelon. The baseline C2 structure places the radar above the battalion, making the structure centralized. The alternative C2 structure places the radar at the battalion making the battery more autonomous. Table 6 shows the experimental design. We established six cases from two experimental variables, and each case was replicated 30 times. The experiment was finished when the survivability of blue artillery forces was below 20%.

5.3 Result analyses

Figure 11 shows several captured pictures during simulation execution of the counterfire operation model. The screenshots show the red force's artillery position in the red deployed area (see Fig. 11a) and the blue force's artillery position in the blue deployed area (see Fig. 11b). Blue and red circles in the figure

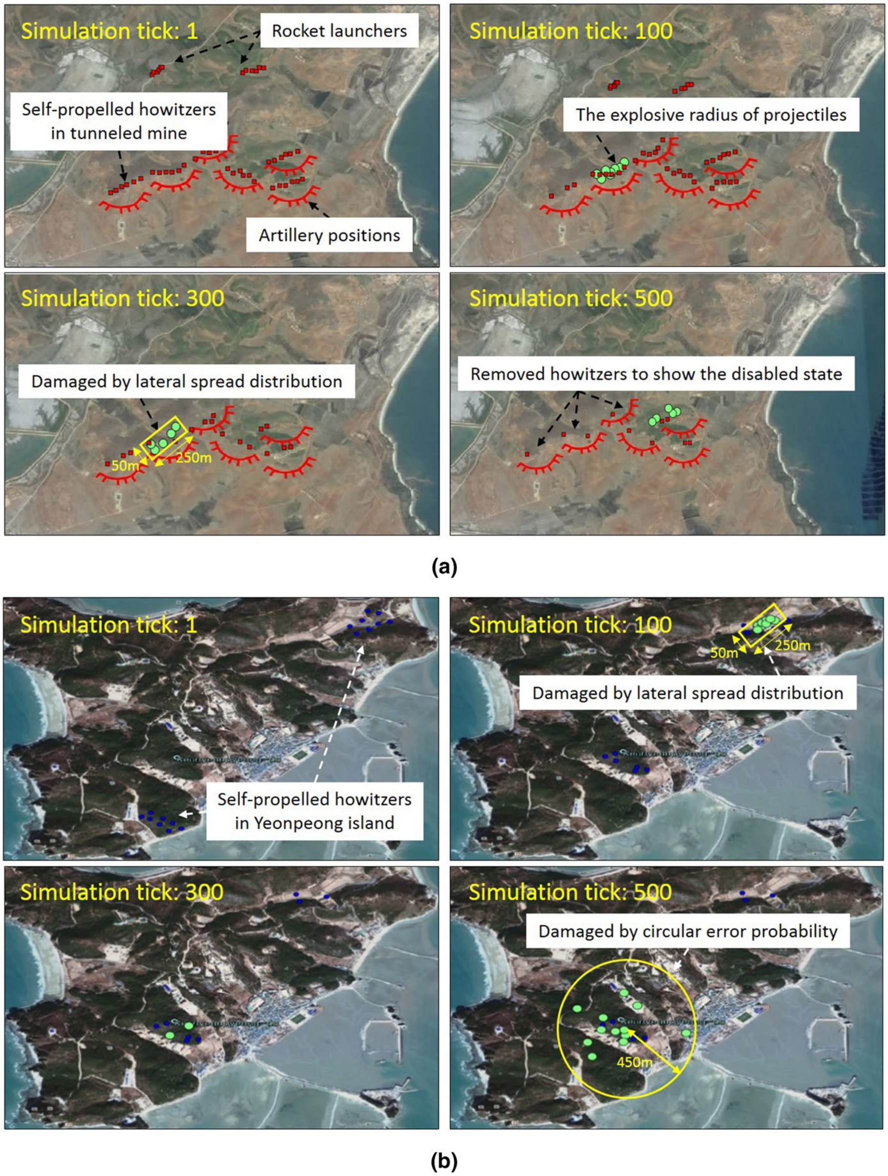


Fig. 11 Screenshots of the virtual experiment in the **a** red force area and **b** blue force area: red and blue circles represent howitzers, and green circles represent the lethality radius of projectiles (the simulation video clip is posted on https://youtu.be/920eR1jA08U)

represent guns, and the green circles represent the explosive radius of projectiles. When guns are located within the LR and receive the full damage that the guns can sustain, they are removed to represent the disabled state.

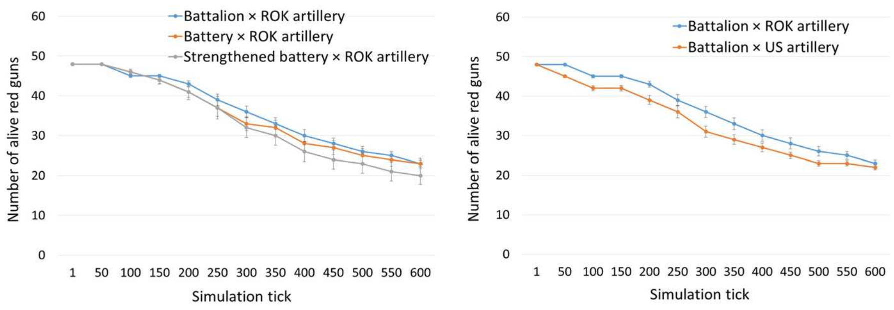


Fig. 12 The number of red guns alive at every 50 simulation tick with varying operation methods (left) and C2 structure (right). (the error bars represent 95% confidence intervals)

Table 7 Standardized coefficient from regression analysis by the number of red guns alive after simulation against experimental variables (††$p < 0.01$, †$p < 0.05$)

Experimental variables	Standardized coefficient
Battery mission	− 0.0046
Strengthened battery mission	− 0.5603††
US artillery (C2)	− 0.1565†
Adj. R^2	0.3246

Figure 12 shows the number of red guns alive at every 50 simulation tick by operation methods (left) and C2 structure (right). We did not show the blue force attrition because this scenario was designed for blue force to be defeated. The mission objective is to inflict maximum damage on the red forces. At the start of simulation, the effectiveness of the battalion mission was better than that of the battery mission. However, as the simulation progressed, the battery mission outperformed the battalion mission. The battery mission executed two missions simultaneously since the blue battalion consists of two batteries. This concurrent mission execution shows better performance when multiple targets are detected, even though the battery mission has lower accuracy than the battalion mission. This is because execution time from detection to delivering fire is critical to the counterfire operation. Though the number of alive guns at the end of the simulation is almost same, the important thing is the rate of decrease in the number of killed guns during the war. Furthermore, the strengthened battery mission showed better results than the battery mission. This result is obvious because the strengthened battery not only enabled simultaneous firing as the battery mission but augmented the fire by increasing the number of guns.

To identify which factors had more influence on the performance measure, we applied linear regression analysis to create a meta-model. We configured the baseline C2 structure and the battalion-based mission as the baseline settings. Table 7 shows the results of the linear regression analysis. The result shows that the strengthened battery mission (standardized coefficient − 0.5603 with p value under 0.01) and the alternative C2 structure (standardized coefficient − 0.1565 with p-value under 0.05) significantly reduced the red forces. Specifically, the prediction on the number of alive red guns is likely to have a 95 probability of being influenced by

Table 8 ANOVA for significance analysis of experimental variables and their interaction effects ($^{\dagger\dagger}p < 0.01$, $^{\dagger}p < 0.05$)

Source	DF	SS	MS	F	Pr > F
Battery mission	1	158.67	158.67	19.9965	< 0.01††
Strengthened battery mission	1	492.08	492.08	62.0143	< 0.01††
US artillery (C2)	1	51.20	51.20	6.4525	0.0119†
Battery mission × US artillery (C2)	1	0.02	0.02	0.0032	0.9553
Strengthened battery mission × US artillery (C2)	1	7.01	7.01	0.8832	0.3486
Error	174	1380.67	7.93		
Total	179	2089.65			

Table 9 Description of five nodesets in the meta-network

Nodeset	Description
Organization	Units associated targeting process in division-level
Agent	Military officers who belong to the units, especially intelligence, operation, and fire support staff
Task	Assigned tasks in targeting process including the counterfire operation
Knowledge	Necessary information in the counterfire operation
Resource	Artillery equipment assigned to the units for counterfire operation

a strengthened battery mission, and a 90 probability by US artillery (C2). It should be noted that the Strengthened battery mission shows the higher absolute coefficient than US artillery(C2), which is because that it is obvious that the hardware advantages are more powerful factors rather than software advantages of C2 structures. However, the reason for including the gun power factor within the analysis is that we tried to figure out the relative enhancement level of hardware advantages.

We performed analysis of variance (ANOVA) and the results shown in Table 8 confirm the linear regression results. Specifically, the type of ANOVA we conducted was the two-way ANOVA, which can find the interaction effects as well. The results indicate that the mean of the performance measure significantly differed when we take the battery-based missions and the alternative C2 structure as treatments. In addition, the interaction effects among experimental variables were not found. In addition to Tables 7 and 8 shows that there is likely have no dependency between the C2 system and the software advantages such as the gun power. That is, the gun power exercise the advantage regardless of the C2 system.

6 Meta-network results

The meta-model showed that the alternative C2 structure is more efficient than the baseline C2 structure. To identify the factors contributing to this result, we analyzed the two C2 structures using network analysis. Specifically, we developed two

Table 10 Meta-network of the baseline C2 structure (total nodeset size: 84, density = 0.211)

	Organizations	Agents	Tasks	Resources	Knowledge
Organizations (*O*; 5 organizations)	Organizational structure (*OO*; density = 0.400)	Permanent station (*OA*; density = 0.200)	Assigned task(*OT*; density = 0.226)	Artillery equipment (*OR*; density = 0.164)	Not used
Agents (*A*; 14 agents)	–	Interrelated staff (*AA*; density = 0.306)	Assigned task(*AT*; density = 0.070)	Artillery equipment (*AR*; density = 0.078)	Necessary information(*AK*; density = 0.521)
Tasks (*T*; 46 tasks)	–	–	Not used	Not used	Necessary information(*TK*; density = 0.367)
Resources (*R*; 9 resources)	–	–	–	Not used	Not used
Knowledge (*K*; 10 knowledge)	–	–	–	–	Not used

Table 11 Meta-network of the alternative C2 structure (total nodeset size: 86, density = 0.218)

	Organizations	Agents	Tasks	Resources	Knowledge
Organizations (*O*; 5 organizations)	Organizational structure (*OO*; density = 0.533)	Permanent station (*OA*; density = 0.200)	Assigned task(*OT*; density = 0.200)	Artillery equipment (*OR*; density = 0.236)	Not used
Agents (*A*; 14 agents)	–	Interrelated staff (*AA*; density = 0.296)	Assigned task(*AT*; density = 0.090)	Artillery equipment (*AR*; density = 0.117)	Necessary information (*AK*; density = 0.521)
Tasks (*T*; 46 tasks)	–	–	Not used	Not used	Necessary information(*TK*; density = 0.367)
Resources (*R*; 11 resources)	–	–	–	Not used	Not used
Knowledge (*K*; 10 knowledge)	–	–	–	–	Not used

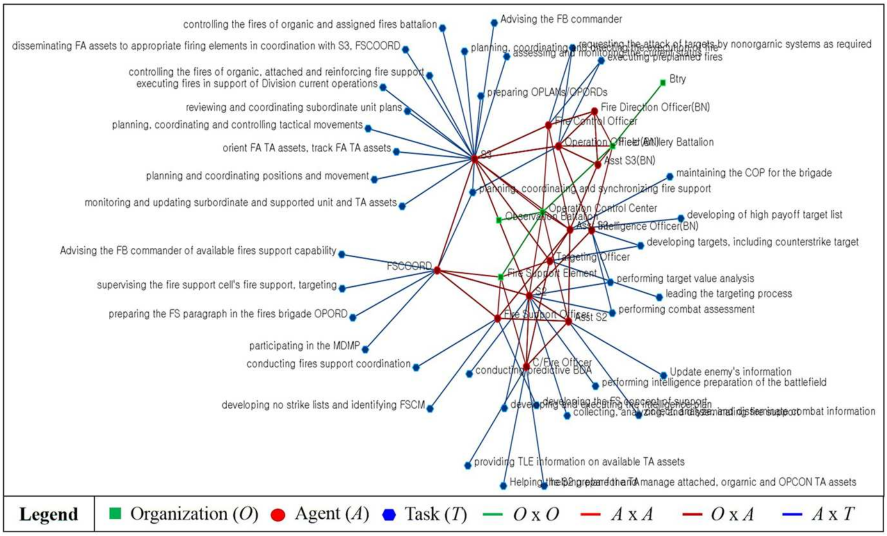


Fig. 13 Partial visualization of the meta-network: organizations, agents, and tasks of the baseline artillery

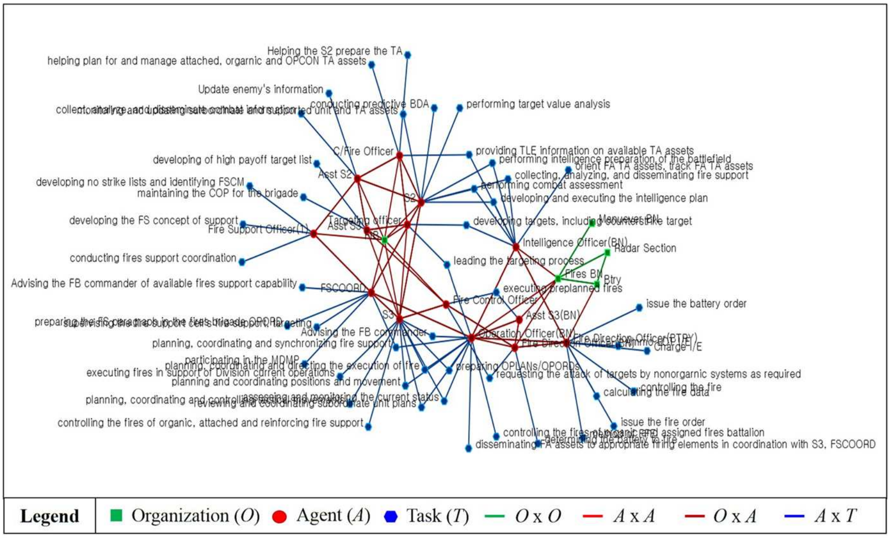


Fig. 14 Partial visualization of the meta-network: organizations, agents, and tasks of the alternative artillery

meta-networks Carley et al. (2002) that represent the organizational structures of the baseline and alternative artillery with five node types: organizations, agents, tasks, knowledge, and resources, based on their field manuals (Army 2001, 2004, 2006a, 2008, 2012) (see Table 9).

The meta-networks are composed by assuming a situation where division artillery organizations conduct the targeting process in the counterfire operation. Tables 10 and 11 include details of the meta-network factors of the baseline and alternative artillery, and Figures 13 and 14 illustrate the partial visualized results of their meta-networks. In Fig. 13 describing the baseline artillery, we found that the two organizations *Observation Battalion* and *Btry* are far from each other on the network. On the other hand, Fig. 14 shows that in the alternative artillery, the two organizations *Fires BN* and *Btry* are very near to each other on the network, which implies that those organizations have a very close relationship. Through the network analysis, we could observe the structural difference, which leads to the network difference shown in Fig. 15. The specific data can be found at (http://seslab.kaist.ac.kr/xe2/board_projects/10726).

With two meta-networks, we restructured the meta-networks according to six experimental cases to analyze the virtual simulation and meta-network results simultaneously. For example, while the battalion node is only linked to the operation center node in the case of the baseline C2's battalion mission, both battalion and battery nodes are linked to the operation center node in the case of the baseline C2's battery mission. In the case of the alternative C2's strengthened battery mission, both battalion and battery nodes are directly linked to the radar section node, and the battery node has eight howitzer nodes instead of six.

Then, using the ORA-NetScenes tool Carley et al. (2013), we received the detailed network measures of node centrality. We confirmed eight types of network measures for three node types—organizations, agents, and resources—to compare the structural properties between the baseline and alternative C2. Table 12 shows the description of network measures used in the meta-network analysis, and Table 13 lists the top five critical nodes for organizations and agents with regard to the four types of network measures between the two C2 structures.

As shown in Table 12, nodesets have different network measures according to their connection status, and a total of 258 network measures were calculated. Then, to find the critical network measures, we calculated the correlation coefficients between 258 network measures. When a correlation coefficient is larger than 0.9, we removed one of the network measures associated with the correlation coefficient. By removing these network measures, the 258 network measures was reduced to 16 representative network measures. Figure 15 shows the visualized correlation results before (left) and after (right) the reduction. The depth of color means a correlation value: the more positive the correlation, the darker and bluer the color; the more negative correlation, the darker and redder color.

Then, we performed regression analysis with the features from the C2 network (i.e., 16 network measures) as well as the features from the simulation experimental parameters. Here, the dependent variable is the performance, or the red damage, from the simulations. The regression shows which independent variable can further explain performance with the information contained in the variable. We also performed stepwise linear regression to explain the performance measure with the minimum number of significant features. Table 14 lists their standardized coefficient values and the † marked values represent the significant ones. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) (see bottom left of

Table 12 The descriptive statistics of network measures used in the meta-network analysis

Nodeset	Network measure		Number
	Centrality	Network	
Organization	Betweenness	Organization × organization	10
	Closeness	Organization × organization	10
	Columndegree	Organization × organization	5
		Organization × agent	5
		Organization × task	5
	Rowdegree	Organization × organization	5
		Organization × resource	5
	Eigenvector	Organization × organization	5
	Indegree	Organization × organization	5
		Organization × agent	5
		Organization × task	5
	Outdegree	Organization × organization	5
		Organization × resource	5
	Totaldegree	Organization × organization	5
Agent	Betweenness	Agent × agent	14
	Closeness	Agent × agent	14
	Eigenvector	Agent × agent	14
	Indegree	Agent × agent	14
		Agent × resource	14
		Agent × task	14
	Outdegree	Agent × agent	14
		Agent × organization	14
		Agent × resource	14
		Agent × task	14
	Totaldegree	Agent × agent	14
Resource	Columndegree	Resource × organization	4
		Resource × agent	4
	Rowdegree	Resource × agent	8
	Indegree	Resource × organization	4
	Outdegree	Resource × agent	4
Total number			258

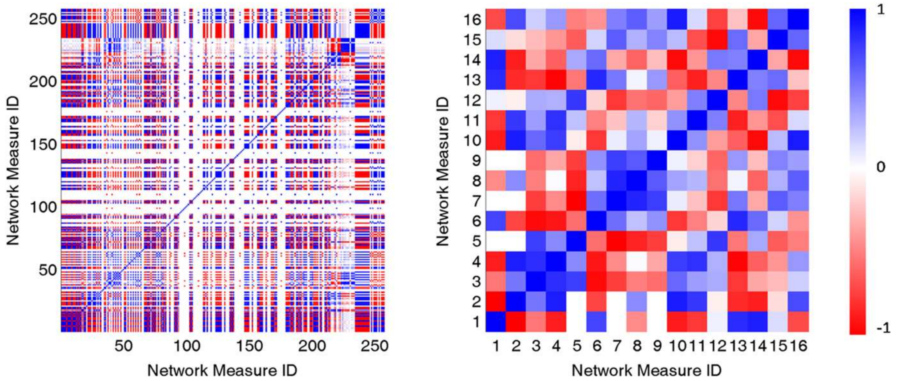
Table 14) are the criteria for choosing between competing statistical models, and the preferred model is the one with the minimum AIC value. Considering the adjusted *R*-square, AIC, and BIC, the stepwise linear regression results show the best linear relationship between the performance measure and the features.

In the case of linear regression with C2 network features, only the strengthened battery mission factor significantly contributed to the performance measure. Unlike the results in Table 7, the alternative C2 artillery was not a significant factor when we analyzed the C2 structures by network analysis and performed

Table 13 The top five critical nodes for organizations and agents in the network: Comparison of organization (up) and agent (down) between the ROK and US artillery

Rank	Totaldegree centrality	Betweenness centrality	Closeness centrality	Eigenvector centrality
Organization × organization network (ROK artillery echelon)				
1	OCC (0.75)	OCC (0.83)	OCC (0.8)	OCC (0.92)
2	Battalion (0.5)	Battalion (0.5)	Battalion (0.67)	Battalion (0.71)
3	Battery (0.25)	Battery (0)	Observation battery (0.5)	Observation battery (0.5)
4	Observation battery (0.25)	Observation battery (0)	Fire support element (0.5)	Fire support element (0.5)
5	Fire support element (0.25)	Fire support element (0)	Battery (0.44)	Battery (0.38)
Organization × organization network (US artillery echelon)				
1	Battalion (0.8)	Battalion (0.33)	Battalion (0.5)	Battalion (0.69)
2	Battery (0.6)	Battery (0)	Battery (0.44)	Battery (0.59)
3	Radar section (0.6)	Radar section (0)	Radar section (0.44)	Radar section (0.59)
4	Fires brigade (0.2)	Fires brigade (0)	Maneuver battalion (0.4)	Maneuver battalion (0.32)
5	Maneuver battalion (0.2)	Maneuver battalion (0)	Fires brigade (0.2)	Fires brigade (0)
Agent × agent network (ROK artillery officer)				
1	S3(OCC) (0.44)	S3(OCC) (0.26)	S3(OCC) (0.59)	S3(OCC) (0.61)
2	S2(OCC) (0.41)	Asst S3(OCC) (0.21)	S2(OCC) (0.52)	Asst S3(OCC) (0.58)
3	Asst S3(OCC) (0.41)	FDO(Battalion) (0.17)	S3(Battalion) (0.52)	S2(OCC) (0.46)
4	Asst S2(OCC) (0.33)	S3(Battalion) (0.15)	FDO(OCC) (0.52)	Asst S2(OCC) (0.42)
5	S3(Battalion) (0.33)	S2(OCC) (0.14)	Asst S3(Battalion) (0.5)	Targeting officer(OCC) (0.37)
Agent × agent network (US artillery officer)				
1	S3(Battalion) (0.37)	FSCOORD(FIB) (0.35)	FSCOORD(FIB) (0.54)	S3(FIB) (0.59)
2	FSCOORD(FIB) (0.33)	S3(Battalion) (0.3)	S3(FIB) (0.52)	S2(FIB) (0.49)
3	S3(FIB) (0.33)	S3(FIB) (0.21)	FDO(FIB) (0.5)	Asst S3(FIB) (0.48)
4	S2(FIB) (0.33)	S2(FIB) (0.15)	S2(FIB) (0.5)	FSCOORD(FIB) (0.45)
5	Asst S2(FIB) (0.33)	FDO(FIB) (0.14)	S3(Battalion) (0.46)	Asst S2(FIB) (0.42)

OCC operation control center, *FIB* fires brigade, *FSCOORD* fire support coordinator, *S2* intelligence staff, *S3* operation staff, *FDO* fire direction officer, *Asst* assistant



List of Reduced Network Measures

Network Measure ID	Network Measure	Network Measure ID	Network Measure
1	OCC and FIB's betweenness	9	Battery's outdegree
2	OCC and FIB's columndegree	10	Observation battery's eigenvector
3	Battalion's betweenness	11	S2(OCC and FIB)'s eigenvector
4	Battalion's columndegree	12	S3(OCC and FIB)'s eigenvector
5	Battalion's outdegree	13	S2(Battalion)'s eigenvector
6	Battery's closeness	14	S3(Battalion)'s closeness
7	Battery's columndegree	15	S3(Battalion)'s eigenvector
8	Battery's eigenvector	16	S3(Battalion)'s indegree

Fig. 15 The visualized correlation results of before (left) and after (right) the reduction of similar network measures

regression with network measures. However, in the case of stepwise linear regression, two factors—strengthened battery mission (standardized coefficient − 40.5521 with p value under 0.01) and observation battery's eigenvector centrality (standardized coefficient − 0.1632 with p value under 0.01)—are the significant factors.

Based on the above regression results, we took a deeper look into the influence of network features on the performance measure, particularly, the observation battery's eigenvector centrality. The eigenvector centrality of a vertex in a graph was calculated as the sum of the degree centrality of its neighborhood vertices in the graph. The negative coefficient of the observation battery's eigenvector centrality in the regression results indicate that the performance measure is inversely proportional to the coefficient value; in other words, this could mean that the number of red guns alive will decrease when the observation battery is connected to the unit that has most connections in a C2 structure.

Following the field manuals of the two artilleries, in the baseline C2 structure, the observation battery is linked to the associated operation center, which is the higher level of the battalion. However, in the alternative C2 structure, the observation battery, which is equivalent to the radar section, is linked to the

Table 14 Standardized coefficients for the regression analysis by the performance measure against experimental features and network features ($^{\dagger\dagger}p < 0.01$, $^{\dagger}p < 0.05$)

Variable factors	Baseline (linear regression)	Baseline + network analysis (linear regression)	Baseline + network analysis(stepwise linear regression)
Experimental features			
Battery mission	– 0.0046	– 0.1083	–
Strengthened battery mission	– 0.5603††	– 0.6641††	– 0.5521††
US artillery (C2)	– 0.1565†	– 0.0831	–
Network features (centrality)			
OCC and FIB's betweenness	–	– 0.2751	–
OCC and FIB's columndegree	–	– 0.0328	–
Battalion's betweenness	–	– 0.2928	–
Battalion's columndegree	–	– 0.0223	–
Battalion's outdegree	–	– 0.0282	–
Battery's closeness	–	– 0.0255	–
Battery's columndegree	–	– 0.0866	–
Battery's eigenvector	–	– 0.0204	–
Battery's outdegree	–	– 0.0748	–
Observation battery's eigenvector	–	– 0.0338	– 0.1632††
S2 (OCC and FIB)'s eigenvector	–	– 0.0283	–
S3 (OCC and FIB)'s eigenvector	–	– 0.0019	–
S2 (Battalion)'s eigenvector	–	– 0.0409	–
S3 (Battalion)'s closeness	–	– 0.0057	–
S3 (Battalion)'s eigenvector	–	– 0.0582	–
S3 (Battalion)'s indegree	–	– 0.0056	–
Adj. R^2	0.3246	0.3203	0.3305
AIC	888.9818	892.4705	884.4723
BIC	904.8342	908.5154	897.1769

battalion (see Fig. 3). This structural difference provides one reason for the performance difference between the two C2 structures (refer to the regression results on the baseline in Table 14). For instance, the radar section in the alternative C2 (0.6853) has a higher eigenvector centrality value than that of the baseline C2 (0.4225). Considering the concept of eigenvector centrality and the regression results, we can say that the combat efficiency of the counterfire operation will increase when the observation battery is linked to the units connected to more organizations, agents, and resources in the C2 structure.

7 Discussion

The experimental results indicate that the alternative C2 structure is more efficient than the baseline C2 structure in the counterfire operation. To see the details of the C2 structures, we developed meta-networks from field manuals and discovered central vertices in the meta-networks. Through regression analysis with the central vertices and experimental variables, we confirmed that it is efficient to operate the observation battery by connecting it to the echelon that has more connections with others.

To investigate the reason for the above result, we analyzed the organizational differences between the baseline and alternative C2 structures. In the baseline artillery organization, the three phases of the counterfire operation (i.e., detection, command, and delivering fire) were performed by the collaboration of different echelons (i.e., observation battery, operation center, and battalion). On the other hand, in the alternative artillery organization, the counterfire operation was conducted by a battalion with three components associated with the three phases. Hence, the alternative observation battery for detection is linked to a battalion, and the battalion has more connections with other units than the operation center in the baseline organization.

The main difference between the two C2 structures is that the alternative battalion conducts initiative actions in the counterfire operation. The above analyses show that such decentralized operations Alberts and Hayes (2003) enhance performance in terms of combat efficiency against the baseline artillery. This would make sense because the decentralized operations shortens the overall time for the targeting process, and several research on the OODA loop (Brehmer 2005; Grant and Kooter 2005) illustrate that faster decision-making leads to better performance in engagements.

8 Conclusion

In the information era, the modern army has undergone reforms that substitute military personnel with strengthened arsenals. While the details of reformation differ by armies, it should be guaranteed that the reformed army can efficiently respond to threats. In that sense, this paper examined how to strengthen the organizational structure and operations, and suggested alternatives from the perspective of operational methods and C2 structures based on the counterfire operation.

To this end, this paper proposed a method to identify significant factors in current artillery operations. Specifically, we applied agent-based modeling and network analyses, and drew comprehensive conclusions by applying statistical analyses to the results. From the operational perspective, the augmented fire and flexibility for multiple targets showed better performance. From the C2 structure perspective, by assigning detection units to the decentralized echelon, the time for the targeting process was reduced so that combat efficiency improved. Having said that, the results presented illustrate ways to apply these combined analytical methodologies in realistic threat scenarios; hence, the results can change by adding modeling components and extending the scope of scenarios.

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