Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

MODELING AND SIMULATION-BASED ANALYSIS OF EFFECTIVENESS OF TACTICAL LEVEL CHEMICAL DEFENSE OPERATIONS

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ABSTRACT

The objective of tactical level chemical defense operations is to protect forces from chemical attack and restore combat power. To accomplish the objective of chemical defense, combat units, higher level command, chemical protective weapons and support units must perform their respective roles and also cooperate with each other. The aim of this study is to the evaluate the effect of factors affecting chemical operations. This study presents a chemical defense operations model using a DEVS formalism and its virtual experiments. The virtual experiments evaluated protection effectiveness by varying chemical operation factors such as 1) detection range, 2) MOPP transition time, 3) NBC report make-up time, 4) report transmission time, and 5) chemical reconnaissance patrol time. The results of the experiments showed that chemical reconnaissance patrol time and communication time are as important as detection range in terms of strength preservation.

1 INTRODUCTION

Chemical weapons were banned by the Chemical Warfare Convention (CWC) and the Organization for the Prohibition of Chemical Warfare (OPCW) in the late 20th century for reasons of cruelty and inhumanity (Ellision 2007; Huang 2002; Haber 1986). However, some nations have not joined the OPCW and retain chemical weapons (Squassoni 2006) and have even reinforced its chemical attack capabilities and increased the threat of attacks with various chemical warfare agents and weapons. Accordingly, it has become important to be prepared with chemical and high-yield explosive response capability (ROKMND 2014). To respond to the chemical threat, the military must also strengthen its chemical defense weapon systems and chemical defense operations procedures.

Chemical defense operations are comprised of detection, protection and decontamination tasks. Since the purpose of chemical operations is to minimize damage to friendly forces, each combat unit, higher level of command, and chemical protective weapons and support units need to perform their independent tasks and cooperate with each other via seamless communication (ROK Army 2008; U.S. Army 2003).

To maximize the effectiveness of chemical defense operations, we have studied how chemical defense operations are affected by each factor, such as the performance of chemical protective weapons, the training level of soldiers and officers, and communication ability. Using the knowledge of each factor`s contribution level, we sought to determine weak points and choose areas of concentration for improving overall capability against a chemical threat. Thus, the aim of the present study is to examine the effectiveness of chemical defense operations in accordance with several operational factors.

Many studies on chemical warfare have mainly focused on the physicochemical properties of the chemical agents themselves, such as the lethal effects of chemical agents (Smith et al. 1995) and the numerical model of diffusion (McRae 1982), etc. Other research areas include chemical agent protection, detoxification and the protective performance of equipment such as gas masks and chemical protective overgarments, and medical treatment training (Lemieux et al. 2010) etc. Little research has focused on the effectiveness of chemical defense operations. Seok and Kim analysed Company level chemical defense effectiveness in accordance with a detector`s sensitivity, MOPP transition time, and evasion direction (Seok and Kim 2014).

This study evaluates the effectiveness of chemical defense operations on a tactical level considering various factors based on existing doctrine and organization. We constructed a simulation model of chemical operation using the DEVS formalism, based on Battalion defensive operations scenario. Using the simulation model and scenarios, we performed virtual experiments to evaluate the protection effectiveness of varying chemical operation factors such as 1) detection range, 2) MOPP transition time, 3) NBC report make-up time, 4) report transmission time, and 5) chemical reconnaissance patrol time. With the simulation results, we carried out various statistical analyses to assess the effectiveness of factors on chemical defense operations.

The findings from the virtual experiments and statistical analysis show that the chemical reconnaissance patrol time is the most significant factor for performance measure. We also found that heat stress is not a negligible factor for combat unit strength reduction. In some simulation cases, even though there were no casualties due to a chemical agent, strength decline occurred because of heat strain due to the long time spent in MOPP4. We expect that this study could be a basic reference for strengthening the ROK military response capability against chemical warfare.

2 PROBLEM DEFINITION

2.1 Procedure for Chemical Defense Operation

The chemical defense operational procedure at the tactical level mainly consists of standoff detection, warning, protection, chemical reconnaissance, and decontamination. These tasks are related through the NBC (Nuclear, Biology, Chemistry) warning and reporting systems. Standoff detection offers a warning of a forthcoming cloud (not a specific chemical agent) in sufficient time to apply the protective measures before exposure to agent contamination occurs (U.S. Army 2003). For attacks upwind, detection must occur at sufficient upwind distances to provide reasonable time for detection, processing, and information transmission.

Immediately after a warning is released, a standoff detector such as a chemical reconnaissance vehicle provides an NBC-1 report to a higher level of command. The NBC-1 report is an initial observation report which contains the position of the observer, the time the attack started, the location of attack, and means of delivery, etc. The higher level of command, synthesizing NBC-1 reports from various observers, issues a NBC-2,3 report to combat units and reconnaissance units that could be affected by the hazard. The NBC-2,3 report includes evaluated data, immediate warning of predicted contamination areas and plans for chemical reconnaissance (ROK Army 2008; U.S. Army 2003).

When receiving an NBC-2, 3 report from the higher level of command, The Chemical Reconnaissance Vehicle (CRV) or chemical reconnaissance unit performs chemical reconnaissance. The chemical reconnaissance missions identify and quantify the chemical agent, figure out required resources for decontamination, mark the boundaries of a contaminated area and carry out sampling of materials and/or environmental items to support intelligence collection and operational requirements (ROK Army 2008). Chemical reconnaissance units or chemical reconnaissance vehicles report the results of their reconnaissance to a higher level of command using an NBC-4 report. The higher level of command then moves decontamination units to contaminated areas (U.S. Army 2006). Figure 1 depicts the sequence for the chemical defense operations procedure.

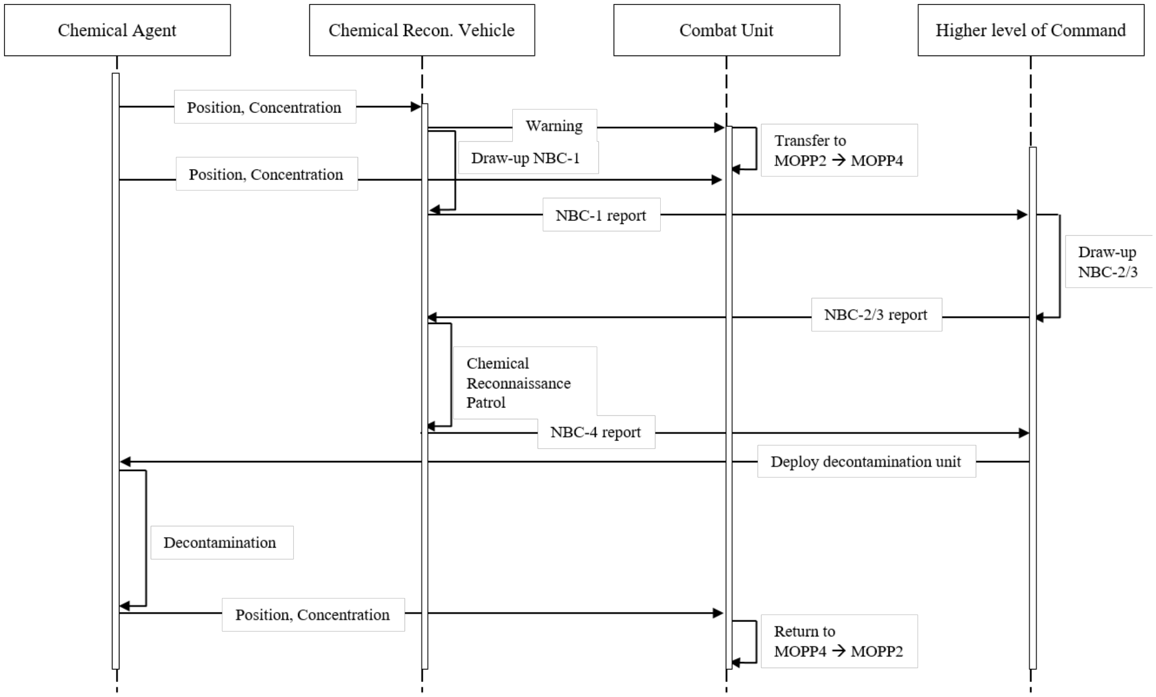

Figure 1: Sequence diagram for chemical defense operational entities.

2.2 Experimental Scenario

We established a scenario for a chemical defense operation at the tactical level according to the chemical operations doctrine. A combat unit holds a defensive position, and the chemical agent cloud (blister gas) is moving towards the combat unit. The Chemical Reconnaissance Vehicle (CRV) which has a standoff detector, as a detachment from Division, directs support from the high level of command. The CRV and the higher level of command are located to the rear of the combat unit.

The following air conditions are assumed: velocity of wind = 2.5m/s, wind direction = constant and air temperature = 30˚C. Chemical-agent concentration is 1400 m/g-min/m^3 (LCt50: concentration and time necessary to cause death in 50% of the population for percutaneous exposure) (Curling et al. 2010). These are the most appropriate conditions for chemical-agent deployment, and they represent the most severe threat possible to the defensive combat unit. Figure 2 illustrates the graphical scenario for chemical defense operation.

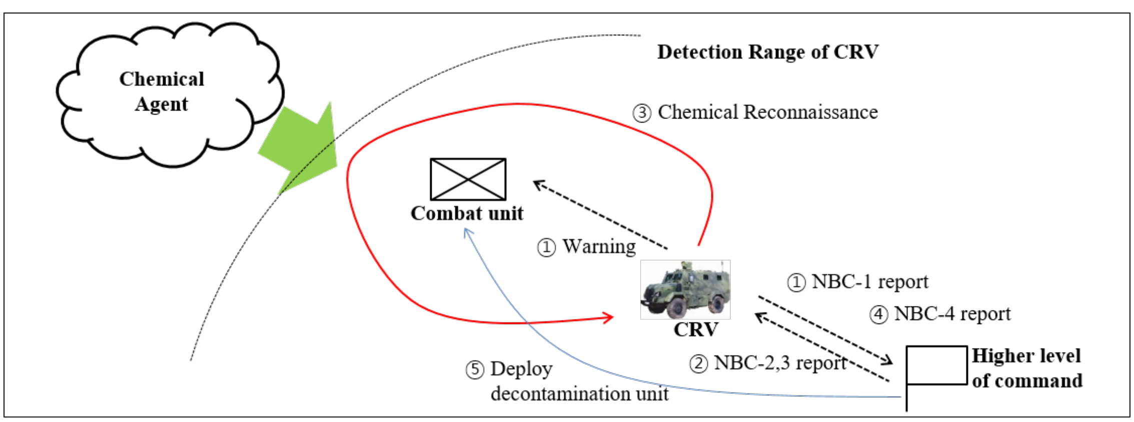

Figure 2: Experimental scenario for the chemical defense operation graphically depicted.

The objectives of this work are to 1) simulate the chemical defense operations through virtual experiments, 2) evaluate the chemical defense operations based on varying chemical operational factors, 3) analyze the results from the virtual experiment to examine the effect of the factors. To accomplish this, we constructed a chemical defense operation model at the tactical level including the combat unit, chemical reconnaissance vehicle and higher level of command entities. Then we carried out virtual experiments to examine how protective effectiveness was affected by each control factor.

3 METHODOLOGY

We used the discrete event system specification (DEVS) formalism and DEVS diagrams to represent the chemical defense operation (Zeigler, Kim, and Praehofer 2000). The DEVS formalism is module-based and can easily be used to construct hierarchical models, such as the DEVS atomic model and the DEVS coupled model (Jung et al. 2015; Bae and Kim 2010; Wainer 2008; T. G. Kim 2007). The atomic models describe the individual entities or components simulated in the coupled model, and the coupled model presents the relationship between the atomic models (Seo et al. 2011; D. S. Kim, Kim, and Sung 2012; Song and Kim 2010).

3.1 Overall Model Structure

The overall structure of the model is illustrated in Figure 3. The model comprises two coupled models: a chemical defense operations model and an experimental frame model. The chemical defense operations model consists of three atomic models and one coupled model. The chemical agent model, chemical reconnaissance vehicle model and higher level of command model are presented as atomic models, and the combat unit model is a coupled model, which includes the behavior model and damage assessment model. The coupling between atomic and coupled models represents the relationships and communication between the combat entities. The chemical agent model is abstracted to a discrete model. The chemical agent model moves toward the combat unit model based on the direction and velocity of wind. On reaching the defensive position of the combat unit, it remains at this location and inflicts chemical damage on the unit. When the chemical agent model gets a 'Decontamination' message from the higher level of command model, the concentration of chemical agent then decreases. The values for the decrease rate are drawn from empirical data (ROK Army 2008). The experimental frame model comprises two atomic models: a generator and a data collector.

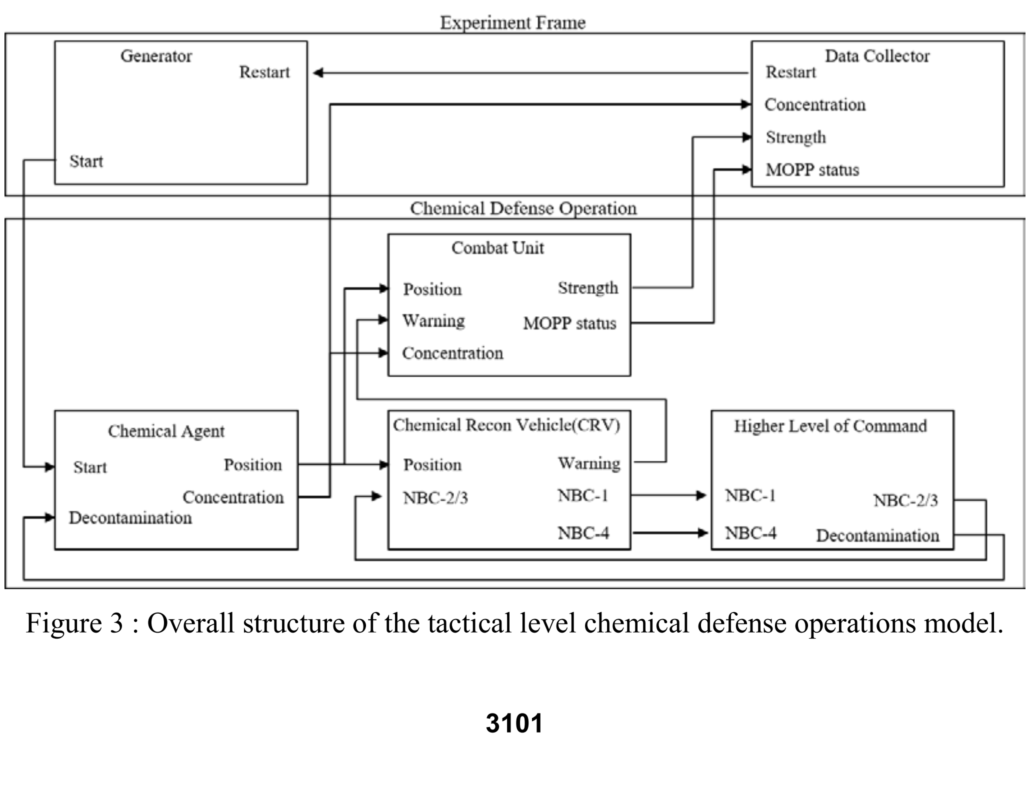

Figure 3 : Overall structure of the tactical level chemical defense operations model.

3.2 The Combat Unit Model

The combat unit model consists of two atomic models: 'Behavior' and 'Damage Assessment'. The behavior model implements the chemical protective measures, namely Mission Oriented Protective Posture (MOPP), and the initial state of the behavior model is MOPP 2. The behavior model receives the 'Warning' message and reports a 'MOPP status' message after changing the MOPP status from level 2 to level 4. At the MOPP 4 level soldiers are protected against a chemical agent, however a long time spent in MOPP 4 causes heat stress to soldiers due to the individual protective equipment, which includes a chemical overgarment, protective boots, protective mask, and protective gloves. Hence, after a recommended threshold time to prevent heat strain, the combat unit model transfers to the 'HEAT STRESS' state. Table 1 explains MOPP levels and their description (U.S. Army 2003).

Table 1: MOPP levels for chemical protection.

MOPP levels	**Description**
MOPP 0	Carry mask; Individual protective equipment available
MOPP 1	Don overgarment
MOPP 2	Don protective boots
MOPP 3	Don protective mask
MOPP 4	Don protective gloves

The damage assessment model gets a messages from the behavior model and chemical agent model, and determines whether the combat unit is damaged, then subtracts strength from the combat unit. We modelled two types of damage assessment in accordance with the causes of damage. The first type of damage is from the chemical agent and the second type is damage is from the heat stress. When the combat unit is exposed to chemical contamination, before implementing the MOPP 4 level, damage is inflicted by the chemical agent. When the state of behavior model is 'HEAT STRESS', strength decline occurs due to heat stress. A number of documents present guidelines for work/rest time to prevent heat strain damage in MOPP 4 level (U.S. Army and AF 2003). However, to the best of our knowledge, the damage rate during the time period after the time limit, is not presented. Instead, we assume that strength starts to decline right after the work time limit (60 minutes), and all soldiers in the combat unit are neutralized when the time limit is doubled (120 minutes).

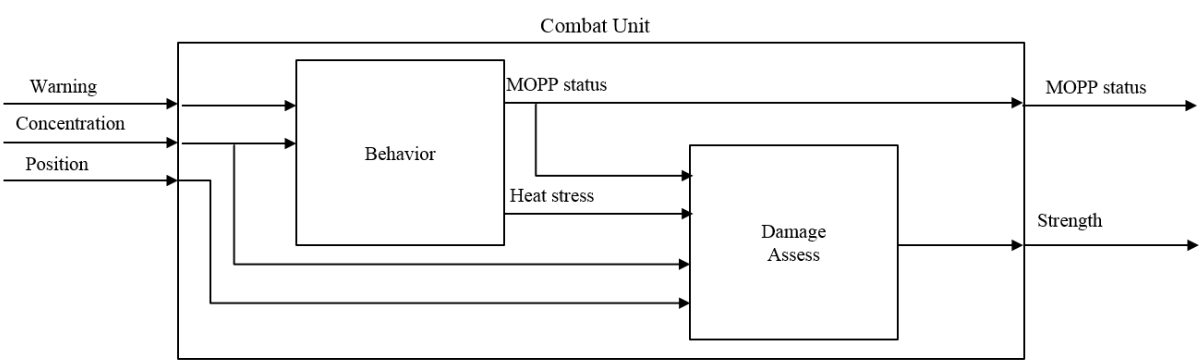

Figure 4 : Coupled DEVS model of combat unit.

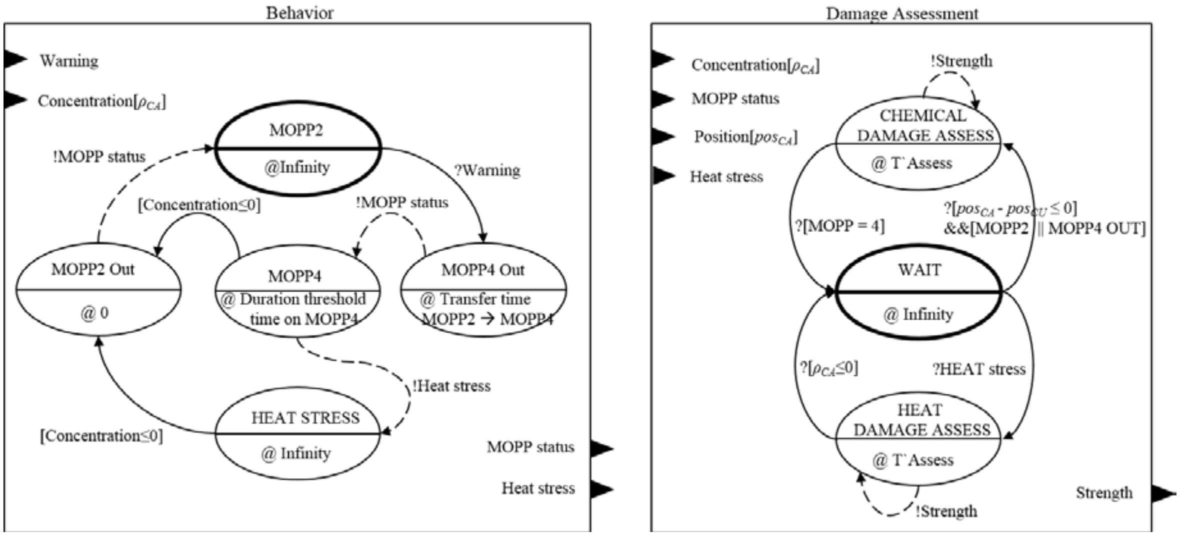

Figure 5 : Atomic DEVS models of combat unit.

3.3 The CRV Model and Higher Level of Command Model

The chemical reconnaissance vehicle is both a standoff detector and reconnaissance unit. Having detected the chemical agent within the detection range of the chemical reconnaissance vehicle (CRV), the CRV model immediately sends a 'Warning' message to the combat unit facing the threat, and reports an 'NBC-1' report message to a higher level of command. Next, the higher level of command issues 'NBC-2, 3' reports that designate the CRV to reconnoiter the contaminated area. After completing the chemical reconnaissance patrol, the CRV creates NBC-4 reports that depict the contaminated area and identify the chemical agent detected. Based on the information in these reports, the higher level of command sends a decontamination unit to the contaminated area. Figure 6 depicts the CRV model and the higher level of command model (ROK Army 2008; U.S. Army 2003).

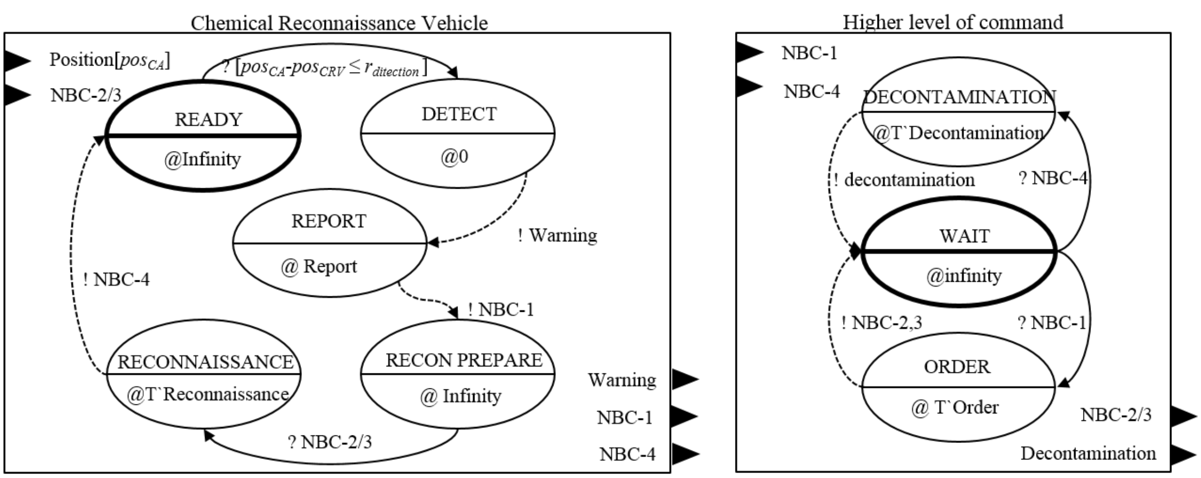

Figure 6: DEVS atomic models of chemical reconnaissance vehicle and higher level of command.

3.4 Simulation Parameters and Performance Measures

Simulation parameters consist of scenario parameters and operational parameters. Scenario parameters, as a constant parameter, create virtual experimental conditions which are assumed according to field manuals and doctrine. Since the movement of a chemical agent model is affected by air conditions, we used velocity, air temperature and chemical agent concentration as scenario parameters.

Operational parameters are an input parameter (control factor) which are selected to examine the effectiveness of chemical defense operations against various factors. As chemical defense operations are a combined arms cooperative operations (U.S. Army 2001), we established five control factors to represent the characteristics of each unit entity: 1) Detection range represents the standoff detection performance of the chemical reconnaissance vehicle, 2) MOPP transition time reflects the training level of the combat unit, 3) the NBC report draw-up time and 4) the report transmission time imply the training level of the NBC staffs and personnel and 5) the chemical reconnaissance patrol time stands for the training level of the NBC personnel and the operational capability of the chemical reconnaissance vehicle. We measured the strength of the combat unit at the end of the simulation, and evaluated the protective effectiveness of each factor of the chemical defense operation. Table 2 shows details of the simulation parameters.

Table 2: List of parameters and the performance measure.

Type	Name	Description
Scenario parameters	Air condition	Velocity of wind : 2.5 m/s
		Air temperature : 30 (Celsius degree)
	Concentration of combat unit	Initial 1400 m/g-min/m^3 (LCt50 for percutaneous dosage)
Operational parameters	Detection range	Detection range of chemical reconnaissance vehicle (ahead of combat unit)
	MOPP transition time	Time for transition from MOPP2 to MOPP4
	NBC report draw-up time	Time for make-up NBC report of each level of unit
	Report transmission time	Average reporting time for NBC report from communication start to completion
	Reconnaissance patrol time	Chemical reconnaissance patrol time of chemical reconnaissance vehicle
Performance measure	Strength of combat unit	Strength of combat unit at the end of simulation (unit: percentage)

4 EXPERIMENTAL DESIGN

We constructed the simulation model by means of DEVsim ++ v3.0© (T. G. Kim 2009) and performed a virtual experiment using the simulation engine of DEVsim++ v3.0© to analyze how the performance and operational capability of CRV, and training level factors, affected the strength of the combat unit. We introduced the following independent variables as the chemical defense operations factors: detection range (DRANGE), MOPP transition time (MOPPT), NBC report draw-up time (NBCDT), report transmission time (RTT), and reconnaissance patrol time (RPT). Table 3 shows the experimental design for the virtual experiments. We built 243 cases for the simulation, and the experiment was replicated 30 times for each case. The simulation was terminated when the concentration of chemical agent reached 0 percent.

Table 3: Experimental design of the chemical defense operations model.

Variables	Value
Detection range (DRANGE)	100, 500, 1000m
MOPP transition time (MOPPT)	30, 45, 60 sec
NBC report draw-up time (NBCDT)	60, 180, 300 sec
Report transmission time (RTT)	0.5sec (Auto transmission), 60, 180 sec
Reconnaissance patrol time (RPT)	1200, 1800, 2400 sec
Total number of cells	3x3x3x3x3 = 243cases (30 replications for each case)

5 SIMULATION RESULTS

We analyzed the performance measure, the strength of the combat unit, in relation to five control factors: 1) DRANGE, 2) MOPPT, 3) NBCDT, 4) RTT and 5) RPT. Figure 7 shows the strength value for different levels of each control factor. The graphical results demonstrate that the levels of the control factors significantly affect the mean value of strength. A long DRANGE increases protective effectiveness, which is consistent with the intuition that long standoff detection range is beneficial. However, the DRANGE values of 500 meters and 1000 meters produce the same strength, implying that it is an unnecessarily excessive detection range. Considering the control factors related to time such as MOPPT, NBCDT, RTT and RPT, short values increase strength. The graphical results shows that RPT is the most sensitive factor, while MOPPT is the least sensitive factor, and MOPPT values of 30 seconds and 45 seconds produce statistically equivalent results.

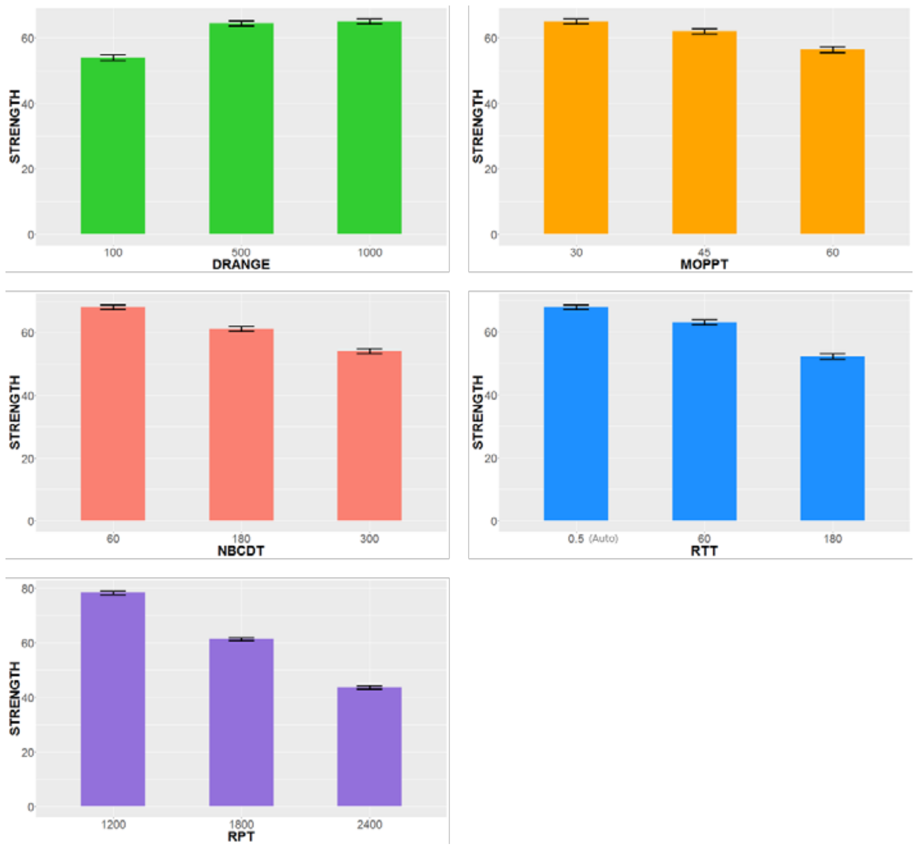

Figure 7: STRENGTH for different levels of DRANGE, MOPPT, NBCDT, RTT and RPT.

To confirm the statistical rigor of the virtual experiments, we also meta-modeled the simulation results. We applied linear regression analysis to verify the relative influence of the control factors on protective effectiveness. Table 4 shows the meta-model analysis. The table elements indicate the standardized coefficient values of the corresponding experimental variables and show how much impact the variables have on the performance measure. Generally, the results of the meta-model support the graphical results. The results also indicate that RPT is the most sensitive factor. The negative coefficient of RPT suggests that rapid and fluid chemical reconnaissance is the most important factor at the tactical level of the chemical defense operation. RTT is the second most sensitive factor during the tactical level chemical defense operations, and its negative coefficient indicates that seamless communication enhances combined arms operational capability.

Table 4: Results of the meta model analysis on the combat unit`s strength. Standardized coefficient for sensitivity of factors and *p*-value for robustness of factors (**: $p < 0.001$).

Variables	Standardized coefficient
Detection range (DRANGE)	-0.5101**
MOPP transition time (MOPPT)	-0.4670**
NBC report draw-up time (NBCDT)	-0.2044**
Report transmission time (RTT)	-0.3151**
Reconnaissance patrol time (RPT)	-0.6841**
DRANGE:MOPPT	0.8186**
DRANGE:NBCDT	-0.0138
DRANGE:RTT	0.0047
DRANGE:RPT	-0.0097
MOPPT:NBCDT	-0.0338
MOPPT:RTT	0.0151
MOPPT:RPT	0.0237
NBCDT:RTT	-0.0120
NBCDT:RPT	-0.0353
RTT:RPT	-0.0122
Adj. R-square	0.7682

Table 5 gives the ANOVA of the meta-modeling results. The reconnaissance patrol time, RPT (F=8975.9902) is the most important and report transmission time, RTT (F=1914.8853) is the second most important factor. Another finding from the results is the interaction effects of DRANGE and MOPPT. When these factors are improved simultaneously, there is a synergetic effect in improving strength.

Table 5: ANOVA for significance analysis of experiments factors and interaction effects (**: $p < 0.001$).

Source	DF	SS	MS	F	Pr > F
Detection range (DRANGE)	2	187957	93987	1158.3673	<0.001**
MOPP transition time (MOPPT)	2	91435	45717	563.4555	<0.001**
NBC report draw-up time (NBCDT)	2	236167	118084	1455.3476	<0.001**
Report transmission time (RTT)	2	310739	155369	1914.8853	<0.001**
Reconnaissance patrol time (RPT)	2	1456583	728291	8975.9902	<0.001**
DRANGE:MOPPT	4	188463	47116	580.6891	<0.001**
DRANGE:NBCDT	4	125	31	0.3839	0.82028
DRANGE:RTT	4	28	7	0.0853	0.98699
DRANGE:RPT	4	115	29	0.3538	0.84153
MOPPT:NBCDT	4	655	164	2.0180	0.08910
MOPPT:RTT	4	75	19	0.2320	0.92050
MOPPT:RPT	4	340	5	1.0466	0.38147
NBCDT:RTT	4	276	69	0.8490	0.49394
NBCDT:RPT	4	672	168	2.0717	0.08174
RTT:RPT	4	189	47	0.5817	0.67589
Error	7239	587356	81		
Total	7289	3061175	1189184		

Figure 8 demonstrates the proportion of damage due to the chemical agent and heat stress. The graphical results indicate that DRANGE values of 500 meters and 1000 meters, and MOPPT value of 30 seconds produce no chemical agent casualties, while Figure 7 shows that the strength declines to about 35 percent. In addition, the proportion of reduced strength due to heat stress is larger than damage by chemical agent. This implies that sufficient standoff detection range and rapid MOPP status transition will prevent chemical agent casualties, whereas heat strain, due to delays of the following operations, reduce the strength of the combat unit.

Thus, to reinforce the response capability against chemical threat, we need to consider not only improvements in chemical defensive weapon performance, such as detection range and protection capability, but also methods to reduce the operational delay time.

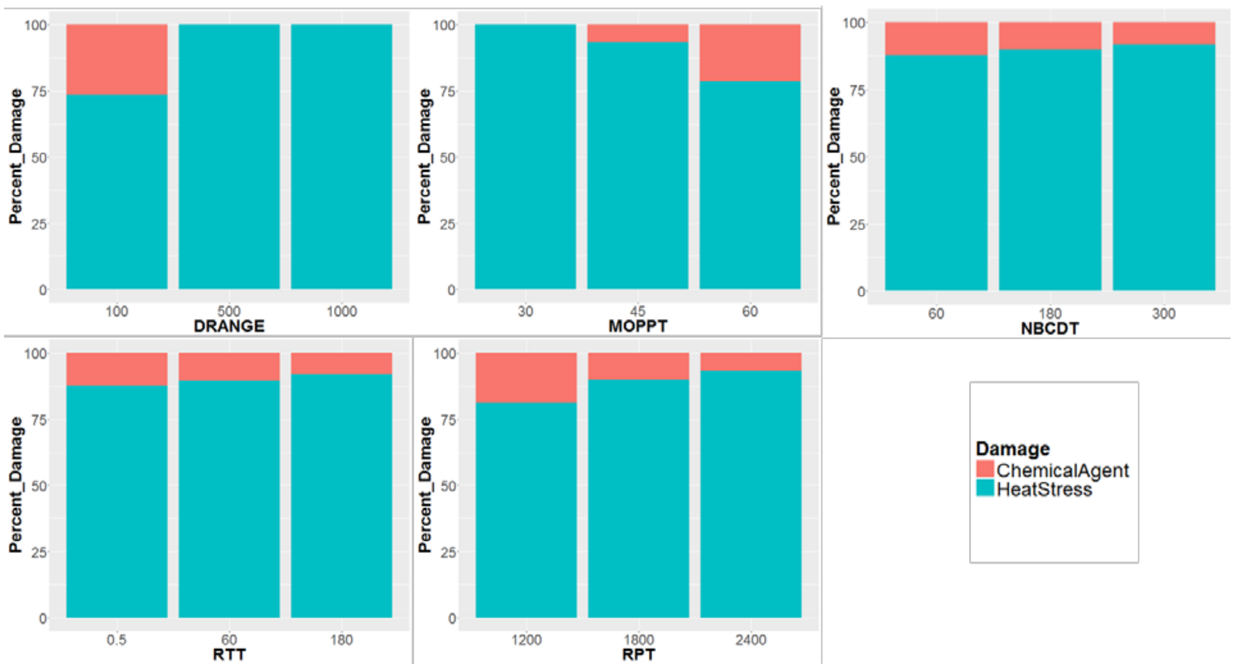

Figure 8: Proportional stacked bar plot for the damage due to chemical agent and heat stress.

6 DISCUSSIONS

To build the simulation model, we adopted the data from the various sources such as field manuals and technical reports, etc. There are limitations with this method because a number of data are empirical data which depend on the experimental environments and conditions. Thus our modeling and simulation includes a number of assumptions. And the survey of modeling features and operational procedures are limited to unclassified materials, which are very typical, and it is therefore not always possible to include up-to-date features in detail.

The simulation engine used to implement our simulation model provides a log data of simulation progress, enabling us to carry out verification and face validation. Face validation is a practical method used when a lack of datasets makes numerical validation difficult (Naylor and Finger 1967). The first step of the face validation is observing the simulation progress. Domain experts can validate the simulation log data against operational procedures and doctrines, and we had two army officers confirming the validity of the simulations.

7 CONCLUSION

To maximize the effectiveness of chemical defense operations, we need to figure out how the chemical defense operations are affected by various factors. In this study, we constructed a simulation model of chemical operations using DEVS formalism, and performed virtual experiments based on existing doctrine and tactical level defensive operation scenarios.

Statistical analysis results from the virtual experiments provided two insights for chemical defense operations. First, a rapid and fluid chemical reconnaissance is the most important factor to preserve the strength of the combat unit, and seamless communication ability enhances the combined arms operational capability. Second, as a large portion of reduced strength resulted from heat stress, to improve the response capability against chemical threat, we considered not only improving the chemical defensive weapon performance itself but also methods to reduce the following operational delay time, for example chemical reconnaissance techniques and methods, standard operational procedures, and C4I infrastructure, etc.

In our future work, we plan to study methods to reduce operational time and then simulate the methods in various scenarios. Moreover, we plan to extend the study scope to operational and strategic levels to investigate the effectiveness of chemical defense operations at various levels.

ACKNOWLEDGEMENTS

This research was supported by the Defence Acquisition Program Administration and the Agency for Defence Development, under contract UD140022PD, Korea.

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