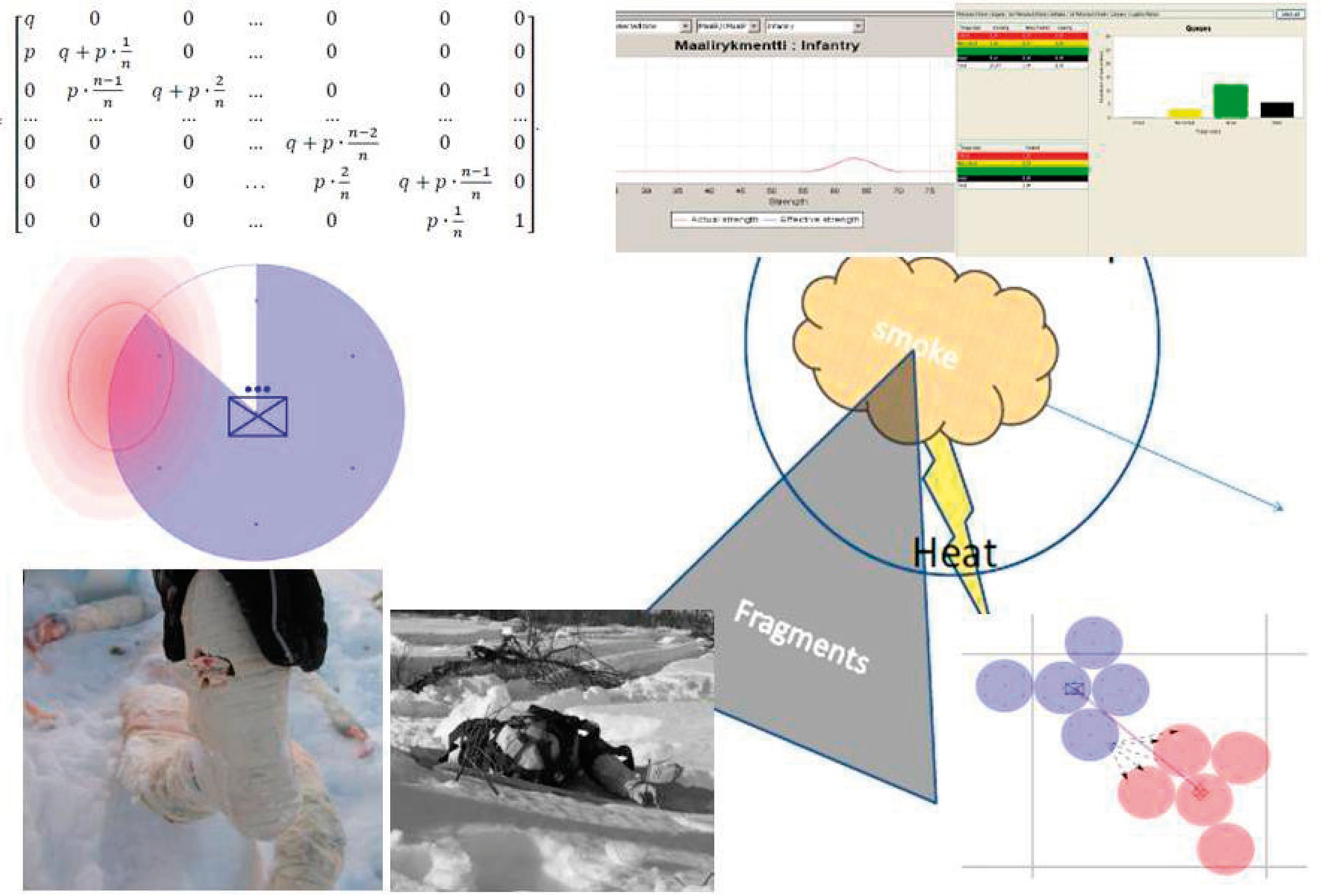
COMPUTATIONAL METHODS FOR TACTICAL SIMULATIONS



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Julkaisusarja 1 Nro 1/2012

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1 LYHENNELMÄ

Tämä taktiikan tutkimus keskittyy tietokoneavusteisen simuloinnin laskennallisiin menetelmiin, joita voidaan käyttää taktisen tason sotapeleissä. Työn tärkeimmät tuotokset ovat laskennalliset mallit todennäköisyyspohjaisen analyysin mahdollistaviin taktisen tason taistelusimulaattoreihin, joita voidaan käyttää vertailevaan analyysiin joukkue-prikaatitason tarkastelutilanteissa. Laskentamallit keskittyvät vaikuttamiseen. Mallit liittyvät vahingoittavan osuman todennäköisyyteen, jonka perusteella vaikutus joukossa on mallinnettu tilakoneina ja Markovin ketjuina. Edelleen näiden tulokset siirretään tapahtumapuuanalyysiin operaation onnistumisen todennäköisyyden osalta.

Pienimmän laskentayksikön mallinnustaso on joukkue- tai ryhmätasolla, jotta laskenta-aika prikaatitason sotapelitarkasteluissa pysyisi riittävän lyhyenä samalla, kun tulokset ovat riittävän tarkkoja suomalaiseen maastoon. Joukkueiden mies- ja asejärjestelmävahvuudet ovat jakaumamuodossa, eivätkä yksittäisiä lukuja. Simuloinnin integroinnissa voidaan käyttää asejärjestelmäkohtaisia predictor-corrector –parametreja, mikä mahdollistaa aika-askelta lyhytaikaisempien taistelukentän ilmiöiden mallintamisen. Asemallien pohjana ovat aiemmat tutkimukset ja kenttäkokeet, joista osa kuuluu tähän väitöstutkimukseen.

Laskentamallien ohjelmoitavuus ja käytettävyys osana simulointityökalua on osoitettu tekijän johtaman tutkijaryhmän ohjelmoiman ”Sandis”- taistelusimulointiohjelmiston avulla, jota on kehitetty ja käytetty Puolustusvoimien Teknillisessä Tutkimuslaitoksessa. Sandikseen on ohjelmoitu karttakäyttöliittymä ja taistelun kulkua simuloivia laskennallisia malleja. Käyttäjä tai käyttäjäryhmä tekee taktiset päätökset ja syöttää nämä karttakäyttöliittymän avulla simulointiin, jonka tuloksena saadaan kunkin joukkuetason peliyksikön tappioiden jakauma, keskimääräisten tappioiden osalta kunkin asejärjestelmän aiheuttamat tappiot kuhunkin maaliin, ammuskulutus ja radioyhteydet ja niiden tila sekä haavoittuneiden evakuointi-tilanne joukkuetasolta evakuointisairaalaan asti.

Tutkimuksen keskeisiä tuloksia (kontribuutio) ovat 1) uusi prikaatitason sotapelitilanteiden laskentamalli, jonka pienin yksikkö on joukkue tai ryhmä; 2) joukon murtumispisteen määritys tappioiden ja haavoittuneiden evakuointiin sitoutuvien taistelijoiden avulla; 3) todennäköisyyspohjaisen riskianalyysin käyttömahdollisuus vertailevassa tutkimuksessa sekä 4) kokeellisesti testatut tulen vaikutusmallit ja 5) toimivat integrointiratkaisut.

Työ rajataan maavoimien taistelun joukkuetason todennäköisyysjakaumat luovaan laskentamalliin, kenttälääkinnän malliin ja epäsuoran tulen malliin integrointimenetelmineen sekä niiden antamien tulosten sovellettavuuteen. Ilmasta ja mereltä maahan -asevaikutusta voidaan tarkastella, mutta ei ilma- ja meritaistelua. Menetelmiä soveltavan Sandis -ohjelmiston malleja, käyttötapaa ja ohjelmistotekniikkaa kehitetään edelleen. Merkittäviä jatkotutkimuskohteita mallinnukseen osalta ovat muun muassa kaupunkitaistelu, vaunujen kaksintaistelu ja maaston vaikutus tykistön tuleen sekä materiaalikulutuksen arviointi.

2 ABSTRACT

Tactical level war gaming using computational simulation is used in military analysis. In this study, computational methods have been developed in order to simulate brigade level scenarios for comparative studies. The brigade level does not allow analysis of all individual soldiers, because of increased number of entities and small time stepping (one second or less). Thus minute-level time stepping was selected, with a platoon or squad as the smallest entity or agent.

The computational models of a platoon level unit use Markov chains and state machines. The platoon level unit is considered as a distribution of unit strengths in order to model the stochastic nature of war. Probabilistic risk analysis is possible as fault tree analysis combines platoon level success probabilities with overall operation success probability. Weapon system effects in the simulation are based on earlier studies adjusted for platoon level targets. Adaptive integration is used in the artillery model and the weapon selective predictor-corrector method to model phenomena within the selected longer time step. Field tests were also used to study the goodness of models and parameters.

The computational models were tested and their usability as part of the simulation tool was proved by programming them in the Sandis software. The coding team was led by the author at the Finnish Defence Forces Technical Research Center (PVTT). The Sandis tool is used for comparative combat analysis from platoon to brigade level. The input comprises weapon and communication characteristics, units and their weapons, fault logic for units and operation success, map and user actions for units at the platoon level. The output is the operation success probability, probability of each unit being defeated, unit strength distributions, average combat losses and the killer-victim scoreboard, ammunition consumption, radio network availability and medical evacuation logistics and treatment capacity analysis. During the game, the man in the loop is responsible for tactical decisions.

The contribution of this dissertation is a novel war gaming model including a success probability tree for brigade level scenarios and the computational models needed for platoon level units. The integration methods for the artillery model and predictor-corrector method are improvements to previous methods used in Finland. Infantry loss models have been created and a field test conducted. The state machines model the action of soldiers under fire and the secondary effects of combat casualties are studied using the resources needed during the evacuation of casualties. These are used in break point analysis instead of a (constant) break point loss percentage.

The study is limited to computational models for creating the probabilistic values for platoon level units and their probabilistic use. Air and naval warfare are not part of the study. As another limitation, only open sources are used. Future studies could examine urban warfare, vehicle duel models and analysis of logistics.

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LIST OF PUBLICATIONS

This thesis consists of a summary and the following articles.

[P1] Esa Lappi. Sandis Military Operation Analysis Tool. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

[P2] Risto Bruun and Esa Lappi. A Weapon Selective Predictor-Corrector Method for Combat Simulations. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008

[P3] Esa Lappi. A Markov chain-based method to evaluate combat value of a platoon after battle casualties. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

[P4] Esa Lappi, Bernt Åkesson, Sami Mäki, Santtu Pajukanta and Kari Stenius. A Model for Simulating Medical Treatment and Evacuation of Battle Casualties. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

[P5] Esa Lappi, Olli Pottonen, Sami Mäki, Kosti Jokinen, Olli-Pentti Saira, Bernt Åkesson and Marko Vulli. Simulating Indirect Fire – A Numerical Model and Validation through Field Tests. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

[P6] Esa Lappi and Olli Pottonen. Combat parameter estimation in Sandis OA software. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

[P7] Esa Lappi and Marko Vulli. Field Test for Parameter Estimation of Small Arms Fire. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

[P8] Esa Lappi, Kari Stenius and Marko Vulli. Field Tests for Finding the Injury Profile from Mortar Fire. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

[P9] Lauri Kangas and Esa Lappi. Probabilistic Risk Analysis in Combat Modeling. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

[P10] Esa Lappi. Network Warfare and Probabilistic Risk Analysis. In Lehtinen, Matti (ed.) Calculating Combat. MPKK STEKNL Series 1: Military technology research n:o27 ISBN987-951-25-1777-0.

[P11] Esa Lappi, Risto Bruun and Kosti Jokinen. Direct Fire Target Selection in Sandis Combat Simulation. . IFAC Workshop on Control Applications of Optimization (2009)
Control Applications of Optimization, Volume# 7 | Part# 1, May 6-8, Jyväskylä ISBN: 978-3-902661-42-5

The author of this thesis is the only author of [P1], [P3] and [P10], and the main author of [P2], [P4], [P7], [P8], [P9], and took part in writing [P5], [P6] and [P11]. The author wrote [P7] and [P8] alone and in [P5], [P7], [P8] and [P9] was responsible for planning and conducting the field tests. The author created the algorithms and wrote the first versions of [P2], [P4] and [P9] and was responsible for the method in [P5] and [P11].

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Figure 4.3.4 Starting situation of the war game

Figure 5.1 Time needed for Sandis analysis. The value of 1 for a battalion indicates that a one-day battle will take one day to be simulated by Sandis. The variations (recalculation of the same basic scenario with some differences) for comparative analysis take half of the time. (Figure by Dr. Bernt Åkesson.)

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PREFACE

The main contribution of this study is a set of computational combat models for tactical simulations. The realization of the new models in software has shown that they are applicable in combat simulations. Also, they have proved to be useful for the needs of the Finnish Defence Forces Technical Research Centre (PVTT). The software engineering and use of the simulation tool have been carried out as teamwork, in which the contribution of all members has been important. All the coauthors deserve my gratitude for their work.

I am also grateful to representatives of many organizations for their contributions. The organizations that provided major assistance in parameter estimation were the Center for Military Medicine (SOTLK, Lahti), Jaeger brigade (JPR, Sodankylä) and Army Academy (MAASK, Lappeenranta). Werner Hacklingin säätiö (Werner Hackling Foundation) has supported this work economically. The practical work and leadership by Marko Vulli from the Army Academy (MAASK) was essential in ensuring successful field measurements. The work of Kari Stenius from the Center of Military Medicine (SOTLK) on medical parameters was likewise vital. Major Jari Sormunen from the Army Academy (MAASK) gave me the opportunity to participate in his company attack study. I was also able to benefit from the mortar studies performed by Lt. Col. Antti Pyykönen.

The National Defence University (MPKK) has given me support and guidance, and professor Pasi Kesseli, Dr. Matti Lehtinen, and Dr. Colonel Mika Hyytiäinen always had time for me when I needed it. The pre-examiners Dr. Ydrim Ziya and professor Juha Honkonen gave some useful advice, which also improved the thesis.

All my colleagues and superiors at PVTT have encouraged my work, and here I would especially like to mention Dr. Juhani Hämäläinen, Dr. Bernt Åkesson, Major (eng) Timo Pulkkinen and M.Sc Seppo Härkönen. Cooperation with the Norwegian Forsvarets Forskninginstitut (FFI) was also important and my discussions the discussion with Bård Eggeraide and Walther Åsen provided an important contribution to the starting phase of the work.

The author especially wishes to thank all the conscript scientists of the Sandis team: Dr. Teemu Murtola for his excellent work as the coder of the first Matlab version of the software, Lauri Kangas and Santtu Pajukanta for their contribution in creating the first version of the Java code and Sandis tool, Yrjö Peussa and Dr. Olli Pottonen for continuing the coding and model development and also for their contribution during the military exercises, Sami Mäki for his work in field tests and Java coding, Olli-Pentti Saira for his contribution in coding and especially the adaptive integration of the indirect fire model, Jussi Sainio for his work in combining the Norwegian Calcradio and Finnish Sandis tools, Risto Bruun and Kosti Jokinen for their effort in creating models and finally Timo Viitanen, Jari Kolehmainen, Mika Kangas and Juha Arpiainen for the improved models and user-friendlier version of the Sandis software.

Few have a family like mine, who not only has given its moral support but has contributed in a concrete way to my research during a time period of decades. I have to thank my brothers Riku and Jyrki for the wargaming and elementary software engineering in the early 80’s, which actually laid the ground for my work in this field. My parents Seppo and Marja Lappi have helped me get essential material from the library of late General Yrjö Keinonen, who taught me the basics of single fighter tactics. That specific library and its long time keeper, my late grandmother Irma Keinonen, have been an invaluable source of information.

Children are a source of joy and happiness but sometimes they even support their parents' research in a practical way. My daughter Linnea has coauthored an oral presentation in EISTA and my son Teo has introduced me to most popular user interfaces in the commercial field of wargaming. Little Aurora has been a great little traveller on conference trips, making many things easier than they should be. My parents in law Anja- Liisa and Timo Alanko have been a source of encouraging and insightful discussions. Finally I thank my wife Merikki for her continuous support and encouragemen to the work. Furthermore, without her work in her own field most of the people behind Sandis would never have been brought together.

1 INTRODUCTION

During the last 50 years, computer-aided simulation, simulators and computational methods have become part of military studies and industrial planning. With constantly increasing computing speed and the concurrent improvement of algorithms, new methods and models have become available for computational simulations in both industry and the military community.

In the study, computational models are created for combat simulations. Thus the subfield of military tactical studies considered in the study is computer-aided simulations as a tool for the optimization of the use of combat resources. The aim of the study is to create methods for combat simulation tools for brigade level land warfare scenarios. In an agent-based simulation, the used entity (agent) is a platoon or group level unit. As the smallest entity is usually a platoon or squad, battalion or brigade level gaming becomes possible as the number of simulated entities is reasonable.

The work combines methods of mathematical modeling, stochastic processes and probabilistic risk analysis, all applied to battle simulation models suitable in the Finnish combat environment. The results are needed for military planning, acquisition processes and cost-effectiveness calculations.

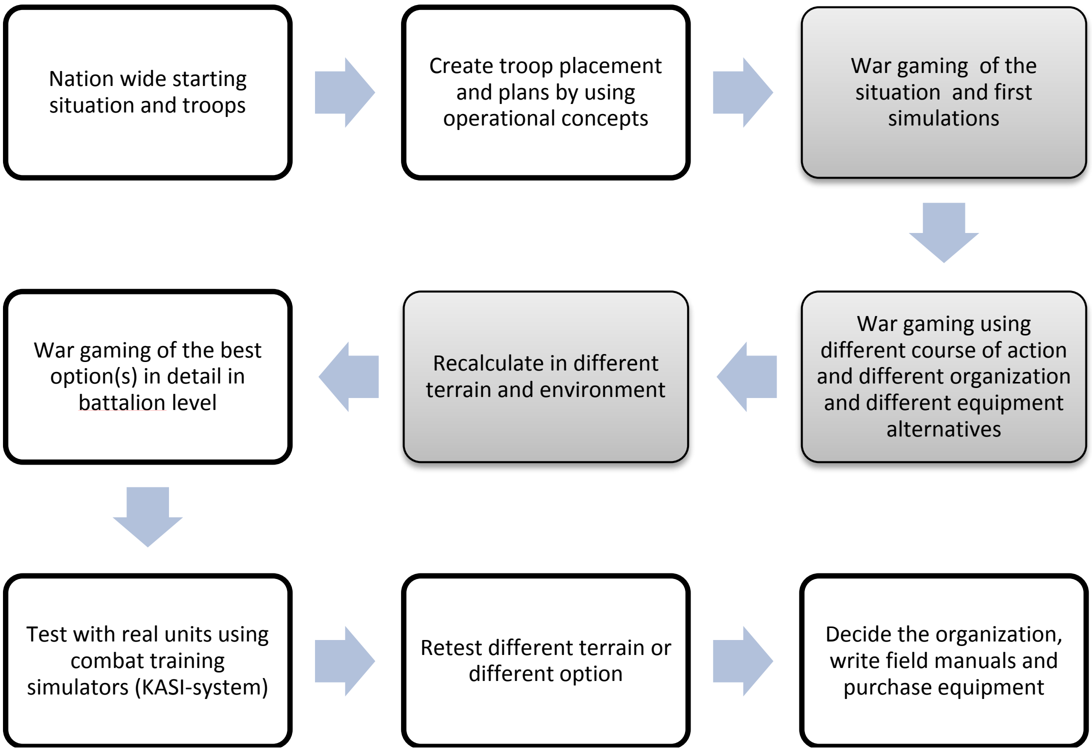
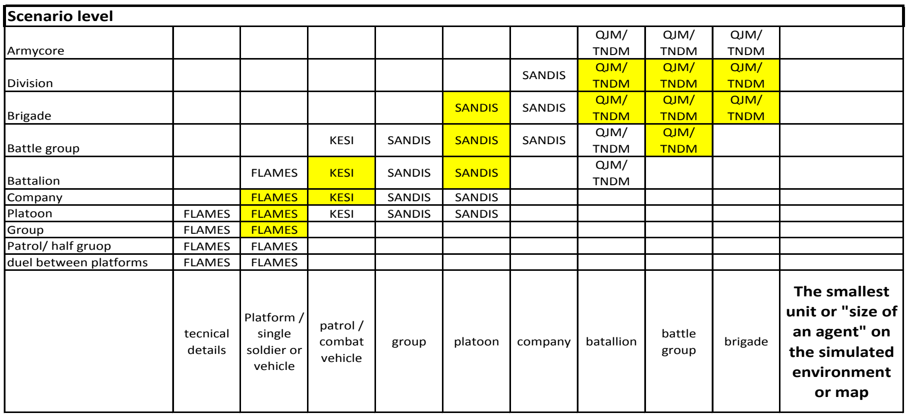


Figure 1.1 Army tactics, organization and equipment development process by Major General Räty used in war gaming and simulations. (Räty, 2009) *The computational models and a simulation tool like Sandis can be used in the highlighted steps.*

The fact that there is a need for this kind of a tactical simulation tool in the army development process has clearly been recognized in the Finnish Defence Forces, as evidenced by the diagram shown in Figure 1.1, which was presented by a high-ranking author (Räty, 2009).

The work on a brigade level operational analysis tool and computational models started at the Finnish Defence Forces Technical Research Centre in 2002. During the first years, different alternatives were studied, and the need for novel simulation models was discovered. Figure 1.2 shows the situation in the Finnish combat simulation environment. Neither computational models nor software were available : for the gaps left by score point methods like QJM/TNDM and entity-level constructive simulations like FLAMES or the KESI officer training simulator.



Scenario level										
Armycore							QJM/ TNDM	QJM/ TNDM	QJM/ TNDM	
Division						SANDIS	QJM/ TNDM	QJM/ TNDM	QJM/ TNDM	
Brigade					SANDIS	SANDIS	QJM/ TNDM	QJM/ TNDM	QJM/ TNDM	
Battle group			KESI	SANDIS	SANDIS	SANDIS	QJM/ TNDM	QJM/ TNDM		
Battalion		FLAMES	KESI	SANDIS	SANDIS		QJM/ TNDM			
Company		FLAMES	KESI	SANDIS	SANDIS					
Platoon	FLAMES	FLAMES	KESI	SANDIS	SANDIS					
Group	FLAMES	FLAMES								
Patrol/ half gruop	FLAMES	FLAMES								
duel between platforms	FLAMES	FLAMES								
	tecnical details	Platform / single soldier or vehicle	patrol / combat vehicle	group	platoon	company	batallion	battle group	brigade	**The smallest unit or "size of an agent" on the simulated environment or map**

Figure 1.2 Combat simulation models in the Finnish environment. The highlighted cells show the area for which the proposed simulation software is the most suitable. The FLAMES, KESI and score point method QJM/TNDM leave a gap. The computational methods of this study are used to fill the gap.

This study concentrates on platoon or group level models suitable for battalion to brigade simulations. The platoon was modeled to be the operational entity for brigade level analysis instead of a single vehicle or soldier. This level was selected, because it was considered to be the largest unit, which can use practically all its weapon systems against other same size units in Finnish terrain. In guerilla type warfare, the smallest unit must be a small squad or an individual soldier.

The computational models developed in this study enabled the creation of the Sandis tool, which can be used to evaluate alternatives in acquisition or tactical optimization problems.
As the models have been implemented in the Sandis tool, they can be used in evaluating the outcome of a battle and the probability of success of an operation or a specific task performed by forces up to a brigade in strength (or an equivalent unit) as well as Red and Blue combat losses in different tactical alternatives [P1]. Sandis also has a user interface for entering and editing the military scenarios and combat model [P1].

The computational models and sub-models for the tactical combat environment were treated as mathematical modeling tasks. Consequently, the most important research methods used were standard mathematical modeling procedures.

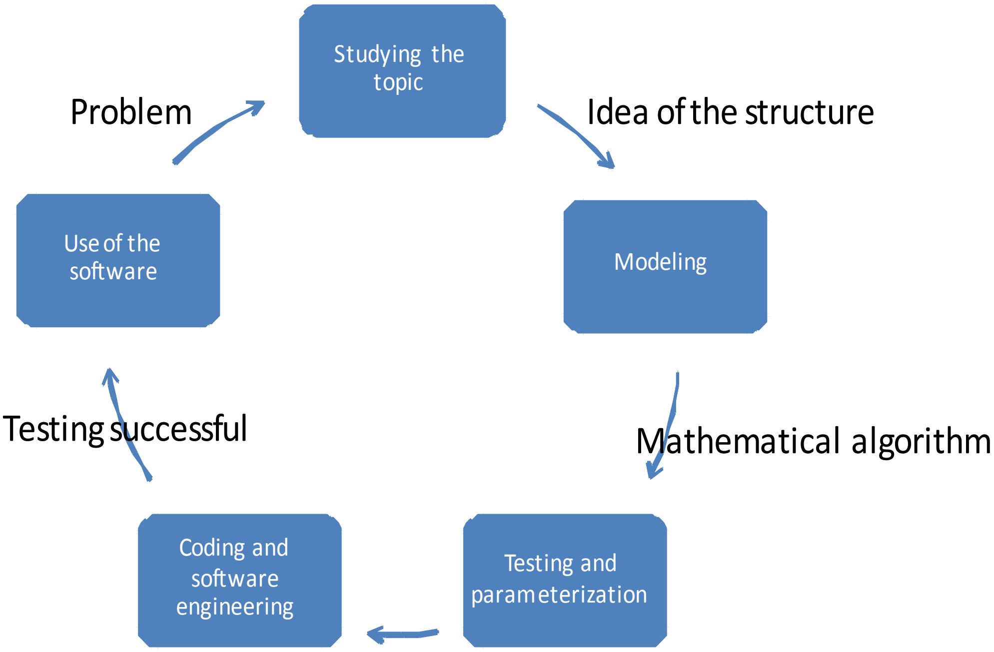


Figure 1.3 Mathematical modeling

The computational models for tactical simulations are the main contribution of this thesis. The models can be used in order to have the platoon level as the smallest unit level in comparative studies up to brigade level. The computational models have been tested in Sandis, a novel military operation analysis tool [P1]. Sandis clearly shows that a tactical simulator with platoon level analysis based on a Markovian approach (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004) can be programmed as a usable software tool. Also, adequate parameters of the model can be obtained from literature and field tests [P5, P6, P7, and P8].

The results of the combat loss models involved can be used in probabilistic risk analysis [P9, P10]. The medical model combines platoon level combat effectiveness with the goodness of the medical evacuation process during combat. It includes a novel calculation method for platoon combat effectiveness after battle casualties [P3] and a model for the subsequent evacuation process [P4]. A better mathematical method for simulations is introduced [P2] and automatic optimization of platoon level targeting [P11] helps the operators of the Sandis tool.

The software engineering of the Sandis tool lies outside the scope of this dissertation, but it was essential for testing and using the methods to address the research questions. The Sandis tool is being upgraded constantly. The comments on the tool and test simulations refer to the public version of Sandis used at the end of the 3rd International Sandis Workshop, held from August 31 to September 4, 2009, in Valkeakoski. (Hämäläinen, Lappi, & Åkesson, 3rd International Sandis Workshop, 2009)

As another limitation, only unclassified sources are used.

2. A REVIEW OF COMPUTATIONAL COMBAT ANALYSES IN THE FINNISH ENVIRONMENT

2.1 Some computational combat models for land warfare in the Finnish environment

When the study started, no battalion to brigade level Finnish combat simulation software was available on the open market. However, there are numerous international combat simulators and methods available. The simulators known to be in use in Finland are Kesi (GESI), employed for training staff officers at the National Defence University (MPKK) (Kuokkanen, 2003), and FLAMES, which is used by the Defence Forces Technical Research Centre (PVTT), but they are not intended for use in brigade level scenarios in order to research different technical or tactical alternatives.

Colonel Dupoy's QJM type score point calculations are used by both the National Defence University (MPKK) and the Finnish Defence Forces Technical Research Centre (PVTT). A Finnish Defence Forces Scientific Board (MATINE) funded a project in which Ilkka Karanka developed a stochastic way of using a score point method like QJM (Karanta, 2005), but such methods are unusable for detailed analysis of technical and tactical alternatives.

At the Norwegian FFI, Tony Kråkenes et al (Kråkenes, Ljøgodt, & Malerud, SIMULERINGSMETODER INNEN OPERASJONSANALYSE -En oversiktsstudie, 2007) made a survey of available combat models. Kråkenes' review did not include any commercial ready to use models, which could handle brigade level scenarios by using platoon/group level units in stochastic environment. This also indicated the need for a novel tool.

Mika Hyytiäinen considered computational combat models created for and applied in the Finnish environment in both his doctoral thesis (Hyytiäinen, Paikkatietoylivoima digitaalisella taistelukentällä, 2003) and a separate book about combat models (Hyytiäinen, Maasodankäynnin taistelumallit ja taktiset simulaattorit, 2004). The main contribution of his thesis was the use of geographical information systems (GIS) in combat modeling, but it also provides basic information about combat simulations.

In his brief study *Taistelun ja logistiikan simulointi* (*Simulating combat and logistics*), Capt. (eng) Jyri Lempiäinen collected information about Finnish combat models and actors such as universities and companies in the field of computational operational analysis (Lempiäinen, 2005). In his book *Kvantitatiiviset tutkimusmenetelmät operaatiotaidon ja taktiikan tutkimuksessa* (*Quantitative research methods in operational and tactical studies*) principal scientist Jussi Metteri described the state of the art in combat modeling from the point of view of the National Defense University (Metteri, 2006).

At the 2004 Nordic Military Operation Analysis symposium, the QJM strength score point method was presented as part of a study on the evaluation of the operational performance of electronic warfare systems (Lappi, A method to evaluate operational performance of electric warfare systems, 2004). However, the strength point calculation – which is the core element of the QJM and TNDM (Dupuy, 1990) analysis methods – was found to be too coarse for more detailed analyses. The idea of platoon level stochastic analysis was consequently introduced by Kangas and Lappi. (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004)

At the Nordic Military Operation Analysis Symposium of 2004, Tony Kråkenes (Kråkenes, Synthetic decision-making in the land combat model Dynacom., 2004) from the Norwegian Forsvarets Forskninginstitut (Defence Research Institute; FFI) gave a presentation of Dynacom, a Norwegian tactical simulator. Dynacom was rather similar to FLAMES, so it could not handle brigade level scenarios as the number of different entities became too large for practical analysis.

Figure 1.2 does not present an exhaustive overview of contemporary Finnish research and interest in combat simulations, but it does describe the usability of the simulation software in use. Other methods have been discussed for example in the seminar proceedings published by PVTT and the National Defence University (Hämäläinen, Lanchester and beyond, 2006) (Lehtinen, Calculating Combat, 2007). Studies have been published on special topics like helicopter warfare (Aherto, Saarelainen, Loikkanen, & Hynynen, 2002) and specific weapon system evaluations (Jormakka & Tuovinen, 2004). A short tutorial on combat modeling and Lanchester's combat equations is included in (Lehtinen, Operaatioanalyysiä sotilaille, 2003), and an analysis of the KESI simulator from the artillery point of view in (Lehtinen, On hexagonal grids in combat simulation, 2005). The stochastic forms of Lanchester-type combat models were also studied by Tuomas Hytönen (Hytönen, 2005), but the results are not directly usable for combat simulations.

Keijo Jaakola studied QJM and some direct fire models (Jaakola, 2005). This work was continued by Eiri Valanto with a focus on software engineering and user interface topics. Valanto created a demonstrator of a combat simulation in the commercial ARCGIS environment (Valanto, 2005). The demonstrator used the method presented in (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004). Teemu Murtola carried out the Matlab programming of the model and the research group of PVTT supported the work. Jaakola’s and Valanto’s theses focused on strength ratio analysis for operational planning.

The PVTT research group created Sandis, which uses the computational models of this dissertation. Apart from this dissertation, other publications have also dealt with Sandis and combat simulation. Three master’s theses have been published: Lauri Kangas studied a further simulation method published at the Nordic Military Operation Analysis Symposium 2004 in his master’s thesis (Kangas, Taistelun stokastinen mallinnus, 2005) and Risto Bruun (Bruun, 2009) developed further the weapon selective predictor corrector method [P2] and implemented it into the Sandis software. Juho Rutila studied the software engineering of the next upgrade of Sandis (Rutila, 2009).

Lappi and Kaasinen studied optimal parameters for a platoon state machine (Lappi & Kaasinen, Genetic optimization of tactical parameters in Sandis Combat simulator, 2008); Tony Kråkenes from the Norwegian FFI had a presentation on a similar problem at the Military operation analysis symposium in Helsinki 2004 (1st NMORS), in which optimal target selection was studied by using genetic algorithms (Kråkenes, Synthetic decision-making in the land combat model Dynacom., 2004).

A cooperation between PVTT computational model research group and FFI started from 1st NMORS and an official cooperation agreement was signed in August 2006. Many of Norwegian tactical simulator DYNACOM’s features were later designated as user requirements for the user action and data collection methods of Sandis. The results of the cooperation in the construction of the electronic warfare component for tactical simulators were published in 2008 at the 2nd Nordic Military OA Symposium (Pajukanta, Åsen, Sainio, Åkesson, & Lappi, 2008).

Jussi Kangaspunta (Kangaspunta, Portfolioanalyysi asejärjestelmien kustannustehokkuuden arvioinnissa, 2009) showed how simulated data can be used to optimize weapon systems using portfolio analysis. The Sandis simulator can be used in this type of analysis (Kangaspunta, Lappi, Liesiö, & Salo, 2008).

2.2 Probabilistic approach

That war has a probabilistic nature was already observed by Carl Clausewitz in his classic book *Von Krige* (Clausewitz, 1832 / 1998) p. 25. There are many random effects on the battlefield. This makes probabilistic risk analysis a reasonable approach in analyzing combat. In the appendix of his PhD thesis, Mika Hyytiäinen referred to Vainio's work (Vainio, 2001) and wrote that the analysis of the probability of success is one of the user requirements of a military operation analysis tool (Hyytiäinen, Paikkatietoylivoima digitaalisella taistelukentällä, 2003), Appendix 4, p. 13. For these reasons, probabilistic risk analysis – a well-established practice in fields such as fire protection engineering – was selected as a core part of a tactical simulator.

Combat simulation is an accepted method of military analysis and there are established engineering practices for the use of tactical simulations. International conferences and publications have addressed the topic of simulation practices for decades. Martin Gilljam from the Norwegian Forsfarets Forskninginstitut (FFI) has compiled a Nordic view of operation analysis and listed conferences, journals and organizations in the field of military simulations and operation analysis (Gilljam, 2005). The use of simulation in a military environment and its problems has been recently discussed by many authors. Good examples are the articles by Sanchez in the Wintersim 2006 Proceedings about the complexity of the models (Sanchez, 2006) and by Matsupoulos on the creation of a simulation framework (Matsupoulos, 2007).

There are also many good agent-based software tools available, like MANA from New Zealand and Pythagoras from the United States, but they do not feature built-in stochastic treatment of platoon losses.

The methods of fire risk analysis have analogies with combat analysis as elaborated in [P9]. Engineering practice is also described in works such as Björkman's dissertation (Björkman, Risk assessment methods in system approach to fire safety, 2005). The approach of combining physical calculations with stochastic values is common in fire risk analysis. For example, fire can spread from one room to another located above it through windows. In this case, the probability of the fire spreading is estimated using physical simulation and the results can be used in stochastic analysis (Lappi, Hietaniemi, & Kokkala, Ikkunan kautta julkisivulle leviävän palon todennäköisyyspohjainen riskitarkastelu, 2002)

The event tree method from fire protection engineering; see for example (Björkman;Baroudi;Hietaniemi;Lappi;& Kokkala, 2001), can also be used in probabilistic combat analysis. The analogies between fire protection engineering and stochastic combat modeling are described in Table 2.1.1.

	Fire risk analysis	**Combat analysis**
Simulation	Numerical fire simulation, for example mass and heat transfer calculations.	Technical combat simulation, for example fragmentation of indirect fire ammunition.
Risk analysis	System risk analysis and probability of successful countermeasures or system failure.	Military organization analysis and probability of successful operation or failure.
Cost-benefit analysis	Cost of different end results (price of investments, losses in different scenarios, insurance costs).	Goodness of different end states in combat simulation, costs of weapon system alternatives and different uses of firepower.
Decision making	Which combination of fire protection systems, redundant process systems and different layout is selected.	Which combination of weapon system, firepower and tactical alternatives is selected.

Table 2.2.1 Fire risk analysis and combat simulation

3. COMBAT MODELING FOR A SIMULATION TOOL

3.1 Stochastic model of unit strengths

3.1.1 Introduction to models

The creation of computational models for combat simulation is a typical mathematical modeling task. In addition to this modeling, the software team created a software tool using the combat models. The usefulness of created models cannot be readily shown if they are not implemented. Thus software for performing the calculations is essential in order to test the usefulness of the models.

The accuracy of simulated and modeled issues can start from physical analysis of sensors or fragments flying and hitting targets to platform level entities (soldier, vehicle) and end up with aggregated objects like a battalion at corps level. When creating a tool for brigade level combat environments, the limits for too accurate or too crude simulations become evident.

If each soldier is treated separately in a simulated combat environment and accurate maps are used with sophisticated weapon and sensor models, the results at the technical level can be useful, but war gaming and simulation time at the brigade level become too long as the number of separate entities in the game can exceed 10,000. In order to do fast war gaming for brigade level scenarios, the effects of the weapons should be combined and some average results with distributions should be used without losing the effects of the weapon parameters in the results.

At another end, traditional or improved Lanchester-Osipov equations with parameters calculated from simulated weapon data could be used for brigade level combat. In this case, the aggregated units might be battalion level, and the time span days or weeks. For the basic methods of mathematical military operation analysis, the reader can refer to basic textbooks, e.g., the article collections published by the Military Operation Research Society (Bracken, Kress, & Rosenthal, 1995) and Przemienicki’s textbook *Mathematical Defense Analysis* (Przemienicki, 2000).

These Lanchester-Osipov type models give average solutions rather easily if the combat loss parameters have been calculated from simulated or tested data. But a brigade is located in a large area with variable terrain, which means that the number of possible tactics and uses of weapon systems are practically infinite. If these tactical alternatives and weapon systems effects should be studied, the simulated units must be smaller than a brigade or battalion.

Thus it was necessary to arrive at a compromise between accurate simulation of weapon systems and their effects on each of the separate targets and the use of a large enough unit size in order to avoid too many entities in the game. In (Hyytiäinen, Paikkatietoylivoima digitaalisella taistelukentällä, 2003) p. 102, the platoon level was estimated to be the largest unit size for detailed analysis in Finnish (forest) terrain. Experiences from military service and participation in Major Sormunen’s research exercises (Sormunen, 2010) had given the same result, so the platoon level was selected as the smallest unit level needed for the analysis. However, the model can work at squad level, too, which is needed for example in guerilla type warfare.

The need to use risk analysis methods made the stochastic approach the natural choice. For example, Bhat includes the topic “military modeling” in his book *Elements of Applied Stochastic Models* (Bhat, 1984). Thus stochastic processes and Markovian modeling are known basic mathematical methods and there is a solid established mathematical background for the use of stochastic analysis for platoon or group level units. In order to determine the probability values, a well-established Markovian approach was selected. The probability distribution of unit strength can be obtained as the combat losses are modeled as state transitions between the unit strength before and after the event. For the mathematics involved, one basic starting reference is the textbook by Goodman (Goodman, 1988).

3.1.2 The platoon or squad level solution for simulation tools

In the thesis, we concentrate on methods of stochastic analysis for platoon level duels and use of weapon systems by and against platoons applicable in brigade level simulation scenarios. We do not try to elaborate analytical mathematical Lanchester-type duel models; instead, we aim at computational combat simulation models.

We will start with a brief review of Markov models. Markov chains are basic tools for certain stochastic processes and they are also used in combat analysis (Bhat, 1984); (Goodman, 1988). When using Markov chains, the phenomena are studied by using a discrete presentation of the world called "states". For example, an industrial machine can be operational or under repair (two states model) or a queue in a shop can have a value ranging from 0 persons to *N* persons (*N* + 1 states model).

In mathematical form, the discrete system can be written as a matrix equation. The following example presents a two state machine, in which the probabilities of a machine being operational or under repair are studied.

We denote the probability of an event by *p(*event*)*, e.g., *p(*one gets hit*)* is the numerical value of the probability that exactly one object will get hit during the time interval under consideration. A vector *P* is used if more than one probability value is used simultaneously in matrix calculations.

Let *P(*day *T)* be a vector with probability components *p(*machine operational *T)* and *p(*machine under repair *T)* during the day *T*.

$$(3.1) \quad P(T) = \begin{bmatrix} p(\text{machine operational} \quad T) \\ p(\text{under repair} \quad T) \end{bmatrix}$$

Let us assume that we have statistical data indicating that if the machine is working, it will stay operational until the next day with probability *p(*stay operational*)* and if the machine is under repair, it will still be under repair on the next day with probability *p(*still under repair*)*. In this case, we have a matrix equation

$$(3.2) \quad P(T+1) = \begin{bmatrix} p(\text{stay operational}) & 1 - p(\text{still under repair}) \\ 1 - p(\text{stay operational}) & p(\text{still under repair}) \end{bmatrix} \cdot P(T)$$

The probability vector *P(T)* is multiplied with a matrix in formula 3.2. The matrix is called the state transition matrix. In Markov chain modeling, the first step is to create the state representation of the studied problem and the second is to estimate the state transition probabilities. In the third step, the behavior of the system can be studied using analytical or numerical methods.

In discrete Markov models, the state transitions occur between the discrete steps (difference equation), and the continuous time models are systems of differential equations. If a continuous time model is calculated numerically using for example Euler's method, it can also be considered a discrete system with time stepping.

In classical form, the unit strengths of both Blue and Red are adjusted as single fighters are destroyed. The state transitions are usually modeled to be single soldiers or platforms at a short enough time step, so the change is from value N to $N-1$. See, e.g., (Hytönen, 2005) (Goodman, 1988) (Bhat, 1984). During a simulation of the combat, or in some special cases even in an analytical solution of the combat equations, the result is the probability distributions of Red and Blue strengths as a function of time.

In traditional models such as those in (Hytönen, 2005) the different distributions of soldiers in the area are not considered, neither are different actions taken by the soldiers. Secondly, the combat environment is changing and a single artillery shot can easily destroy many soldiers at the same time. Thus state transitions with only one soldier lost in a time step were rejected.

Kangas and Lappi (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004) presented a way of Markovian modeling that can be used to create a stochastic Markov model from any combat simulation model or test shooting statistics giving average losses during a time step. The idea is rather simple. If the losses of the unit are p% during a time step, we assume that the probability of a hit on a single solder of the unit is p%. The unit strength after the losses becomes a binomial distribution, which gives state transition probabilities for the Markov model.

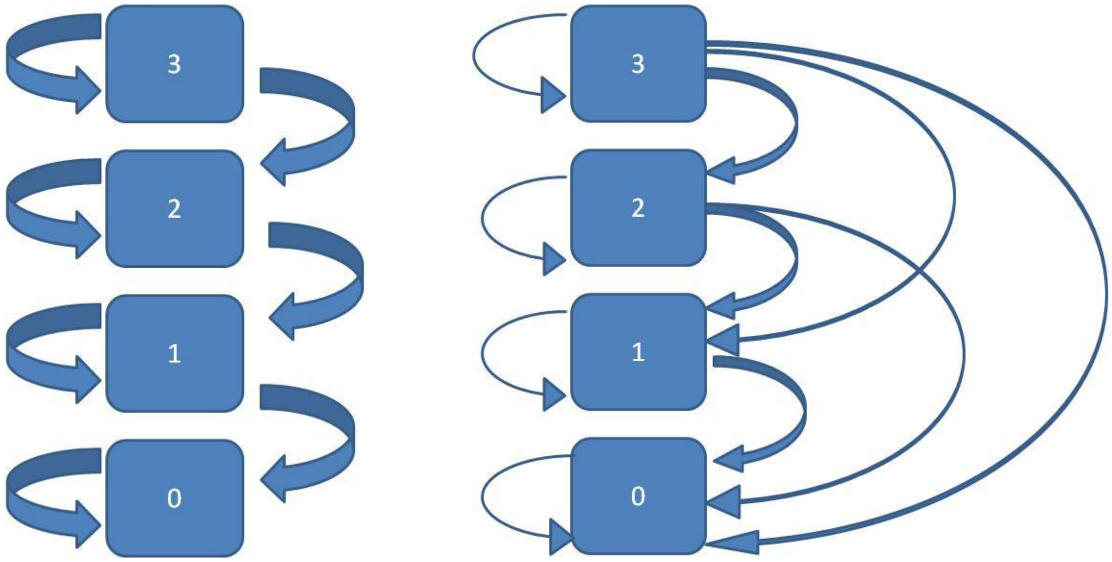


Figure 3.1 Examples of state transitions of the Markovian combat simulation models with three soldier units. An arrow from 3 to 2 represents the same difference in the strength of the unit. The example on the left shows only one event at a time, while the example on the right is a binomial model. When state transition probabilities are included, the numerical values can be calculated.

As a result, we have for each time step a state transition matrix A for all unit strengths. The matrix calculation for probability strength vector $\pi(t)$ is

(3.3) $A \cdot \pi(t_i) = \pi(t_{i+1})$.

Let p be the probability of a single soldier getting hit during the time step and let $q = 1 - p$. To illustrate the states let us first consider two soldiers or other entities in the same platoon as the targets. The states for this case are: two operational (π_2), one operational but the other not (π_1) and both not operational (π_0). The state transition can happen from two to two, two to one and two to zero, from one to one and one to zero and from zero to zero. In this simplified case, the state transition matrix A and probability vector π for unit strengths are

$$(3.4) \qquad A = \begin{bmatrix} q^2 & 0 & 0 \\ 2pq & q & 0 \\ p^2 & p & 1 \end{bmatrix}$$

$$(3.5) \qquad \pi(t) = \begin{bmatrix} \pi_2(t) \\ \pi_1(t) \\ \pi_0(t) \end{bmatrix}$$

When we elaborate this example to unit size n, we get a larger matrix. With unit strength n, the vector has $n+1$ probability values and the state transition matrix is a $(n + 1) \times (n + 1)$ square matrix.

The columns of $n+1$ state matrix A have binomial distribution values with hit probability $p(n)$ with n target entities.

Thus the values in the first column show state transitions from an unharmed unit with n target entities and hit probability p for each entity:

(3.6a) $P(\text{no one gets hit}) = A(1,1) = (1-p(n))^n$;
(3.6b) $P(\text{one gets hit}) = A(1,2) = \binom{n}{1} p(n) (1-p(n))^{n-1}$
(3.6c) $P(\text{two get hit}) = A(1,3) = \binom{n}{2} p(n)^2 (1-p(n))^{n-2}$
…
(3.6d) $P(\text{m gets hit}) = A(1,m+1) = \binom{n}{m} p(n)^m (1-p(n))^{n-m}$
…
(3.6e) $P(\text{all n get hit}) = A(1,n+1) = p(n)^n$

The next column with one entity hit at the beginning of the time step is rather similar, but it has a different average hit probability $p(n-1)$. The average hit probability is not the same as with n targets, because for example fewer targets can increase the number of aimed shots per target. In this column, the first probability is obviously zero, because shooting at an entity does not increase the strength of the unit. Of course unit strength can increase during the battle, but the recovery process is treated separately, not as a part of the weapon effect calculation model. As a result, the second probability vector (row) in the state transition matrix becomes

(3.7a) $P(\text{unit strength increases}) = A(2,1) = 0$

(3.7b) $P(\text{no one gets hit}) = A(2,2) = (1-p(n-1))^{n-1}$;

(3.7c) $P(\text{one gets hit}) = A(2,3) = \binom{n-1}{1} p(n-1) (1-p(n-1))^{n-1-1}$

(3.7d) $P(\text{two get hit}) = A(2,4) = \binom{n-1}{2} p(n-1)^2 (1-p(n-1))^{n-1-2}$
…

(3.7e) $P(m \text{ gets hit}) = A(2,m+2) = \binom{n-1}{m} p(n-1)^{m} (1-p(n-1))^{n-1-m}$

…

(3.7f) $P(\text{all } n-1 \text{ get hit}) = A(2,n+1) = p(n-1)^{n-1}$

With all the $n+1$ columns, the same kind of formula appears, so the matrix A needed for probabilistic strength analysis has been created. There are zeros in the upper right triangle, and a binomial distribution in the lower left. Let $q = 1-p$.

$$(3.8) \qquad A = \begin{bmatrix} (q(n))^n & 0 & \dots & 0 & 0 & 0 \\ \binom{n}{1} (p(n))^1 (q(n))^{n-1} & (q(n-1))^{n-1} & \dots & 0 & 0 & 0 \\ \binom{n}{2} (p(n))^2 (q(n))^{n-2} & \binom{n-1}{1} (p(n-1))^1 (q(n-1))^{n-2} & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \binom{n}{n-1} (p(n))^{n-1} (q(n))^1 & \binom{n-1}{1} (p(n-1))^{n-2} (q(n))^1 & \dots & \binom{2}{1} (p(2))^1 (q(2))^1 & (q(1))^1 & 0 \\ (p(n))^n & (p(n-1))^{n-1} & \dots & (p(2))^2 & p(1) & 1 \end{bmatrix}$$

When the state probability vector π is multiplied with the state transition matrix A, the probabilities of the states with higher losses increase. In mathematical terminology, the state “all entities have been hit” is an absorbing state.

These formulas apply in cases when the number of bullets shot is greater than the number of targets and the hit probability is not near 1.

If a weapon system with high accuracy is used, an adjusted model can be employed. If for example we shoot one anti–tank missile with 90% accuracy, the average losses are 0.9 tanks. If a platoon has three tanks, the average casualty percentage is 30%. In this case the binomial distribution is not accurate, since it incorporates positive probabilities for the loss of more than one tank, which would be impossible when only one missile is used. In this case, a more direct accurate probability formula for state transitions has to be used. Its basics are described in the following example.

In this simplified case of one missile shot, the state transition matrix becomes

$$(3.9) \qquad A = \begin{bmatrix} 0.1 & 0 & 0 & 0 \\ 0.9 & 0{,}1 & 0 & 0 \\ 0 & 0.9 & 0.1 & 0 \\ 0 & 0 & 0.9 & 1 \end{bmatrix}$$

In a general case, there are several different alternatives.

Let us first assume that more than one weapon is shot at the target. If we assume that no weapon is shot at the same target as another, the row of the state transition matrix becomes a binomial distribution from n to $n-m$.

If there are more targets than accurate shots, there are more alternatives. If the next shots are used to shoot targets that survived the first shots, we end up with a binomial distribution with more hits than targets set to state transition n to zero. In the case of three tanks and three missiles, the state transition matrix would become

$$(3.10a) \quad A = \begin{bmatrix} 0.1^3 & 0 & 0 & 0 \\ 3 \cdot 0.9 \cdot 0.1^2 & 0.1^3 & 0 & 0 \\ 3 \cdot 0.1 \cdot 0.9^2 & 3 \cdot 0.9 \cdot 0.1^2 & 0.1^3 & 0 \\ 0.9^3 & 0.9^3 + 3 \cdot 0.1 \cdot 0.9^2 & 0.9^3 + 3 \cdot 0.1 \cdot 0.9^2 + 0.9^3 & 1 \end{bmatrix},$$

or in another form

$$(3.10b)\ A = \begin{bmatrix} 0.1^3 & 0 & 0 & 0 \\ 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 \\ 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 \\ 0.9^3 & 1-(3\cdot 0.9\cdot 0.1^2+0.1^3) & 1-0.1^3 & 1 \end{bmatrix}.$$

If in this case five targets would be shot at with three missiles, the distribution would become

$$(3.11)\ A = \begin{bmatrix} 0.1^3 & 0 & 0 & 0 & 0 & 0 \\ 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 & 0 & 0 \\ 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 & 0 \\ 0.9^3 & 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 \\ 0 & 0.9^3 & 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 \\ 0 & 0 & 0.9^3 & 3\cdot 0.1\cdot 0.9^2+0.9^3 & 1-0.1^3 & 1 \end{bmatrix}.$$

As another alternative, we have some fixed targets that are shot twice (or are hit one more time than the others) if there are more weapons than targets. In this case the state transition matrix would be

$$(3.12)\quad A = \begin{bmatrix} 0.1^3 & 0 & 0 & 0 & 0 & 0 \\ 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 & 0 & 0 \\ 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 & 0 \\ 0.9^3 & 3\cdot 0.1\cdot 0.9^2 & 3\cdot 0.9\cdot 0.1^2 & 0.1^3 & 0 & 0 \\ 0 & 0.9^3 & 3\cdot 0.1\cdot 0.9^2 & 0.1^2\cdot 0.9+0.1\cdot(1-0.1^2) & 0.1^3 & 0 \\ 0 & 0 & 0.9^3 & 0.9\cdot(1-0.1^2) & 1-0.1^3 & 1 \end{bmatrix}.$$

In general, another option is to assume that all targeting is independent. Let the hit probability of a single shot be p and the miss probability $q = (1 - p)$. In this way, with m accurate shots all miss with probability q^m, which is the state transition probability from n units to n units.

The probability for one hit is the binomial distribution with

$$(3.13a)\ p(\text{one hit}) = \binom{n}{1}\, p\, q^{n-1}$$

and k hits

$$(3.13b)\ p(\text{k hits}) = \binom{n}{k}\, p^k\, q^{n-k}$$

In this case with n targets and m weapons shots, we first calculate the probability that the second shot hits the same target as the first one. With n targets

$$(3.14)\quad p(\text{second hit on the same target as the first one}) = 1{:}n.$$

The probability for one target being hit at least once by m accurate shots is determined as a sum of probabilities

$$(3.15)\quad p(1\ \text{target}) = P(1\ \text{hit}) + P(2\ \text{hits})\cdot(1{:}n)+P(3\ \text{hits})\cdot(1{:}n)^2+\ldots P(m\ \text{hits})\,)\cdot(1{:}n)^{m-1}$$

To get two targets we must have two hits on different targets, or three or more hits on two definite targets.

(3.16) $p(2\text{ targets}) \quad = P(2\text{ hits})\cdot[(n-1):n]+P(3\text{ hits})\cdot P(3\text{ shots hit 2 targets})+\dots$

A way to bypass the resulting long and clumsy formulas is to use the state transition matrix technique again. During the shooting process, the number of targets decreases, so for each accurate weapon we have state transitions from n to $n-1$ targets by assumption with probability p, and from $n-k$ to $n-k-1$ with probability

(3.17) $p(\text{from } n \text{ to } n-k-1) = p\cdot[(n-k):n]$

Thus the state transition matrix P for shooting first at n targets with random targeting is

(3.18) $$P = \begin{bmatrix} q & 0 & 0 & \dots & 0 & 0 & 0 \\ p & q+p\cdot\frac{1}{n} & 0 & \dots & 0 & 0 & 0 \\ 0 & p\cdot\frac{n-1}{n} & q+p\cdot\frac{2}{n} & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & q+p\cdot\frac{n-2}{n} & 0 & 0 \\ 0 & 0 & 0 & \dots & p\cdot\frac{2}{n} & q+p\cdot\frac{n-1}{n} & 0 \\ 0 & 0 & 0 & \dots & 0 & p\cdot\frac{1}{n} & 1 \end{bmatrix}.$$

Assuming n targets at the beginning, we have a state probability vector s with 1 at the top and others zeros. The state transition matrix from n targets shot with m accurate weapons is formed through matrix multiplication.

(3.19) $s(t+\Delta t) = P^m \cdot s(t)$

From this result we can get the state transition matrix A. If we create P using (3.18) for all unit strengths, we get the state transition matrix A for accurate weapon fire with each column having zeros in the upper triangle and in column i in lower triangle $P^m\, s$ from (3.19).
We have thus constructed both an average loss model and an accurate single shot hit probability model to create state transition matrix A for a single platoon as the target of a single weapon system.

If two platoons are in a firefight, the state probability matrix is needed for all number of Red shooters, because the average loss is dependent of the number of shooters. The end probability is the sum of all state probabilities multiplied with all probabilities of each fighting combination. If only one unit is shooting at the target platoon, the result is

(3.20) $\pi(t) = [\sum p(i\text{ shooters})\cdot A(i\text{ shooters})]\cdot \pi(t-\Delta t)$

If a unit is the target of more than one weapon system or unit, the cumulative effects of different firing systems are calculated by multiplication of different state transition matrices.

Let the target unit have state transition matrix A(“unit 1” shooting, i), when the shooting “unit 1” has strength i. Then by taking the sum of products from formula 3.20 the state transition matrix for unit one becomes

(3.21) $A(\text{unit 1 shooting}) = [\sum p(\text{unit 1 has } i \text{ shooters})\cdot A(\text{ unit 1 with } i \text{ shooters})]$.

Let $\pi(t)$ be the target unit’s strength vector. Let there be n shooting units and let the strength distribution after time step be $\pi(t+\Delta t)$. Then as the final result we get

(3.22) $\pi(t+\Delta t) = A(\text{total}) \cdot \pi(t-\Delta t),$

where the state transition matrix $A(\text{total})$ is a product

(3.23) $A(\text{total}) = A(\text{unit 1 shooting}) \cdot A(\text{unit 2 shooting}) \cdot \ldots \cdot A(\text{unit } n-1 \text{ shooting}).$

In formulas 3.1 – 3.23, the computational bases of the simulation are presented.
The Markov chains have no memory, and all information on earlier events is included in the states of the model. During the simulation the parameters of the state transitions are upgraded at each time step and rich enough states are used, and thus the lack of memory did not become an issue during the simulations.

3.1.3 Soldier state machine

Lappi [P3 2006] combined a soldier state machine with the model. It enabled the study of medical effectiveness and the secondary effects of combat losses. The soldiers committed to the evacuation process of the wounded were included in the analysis.

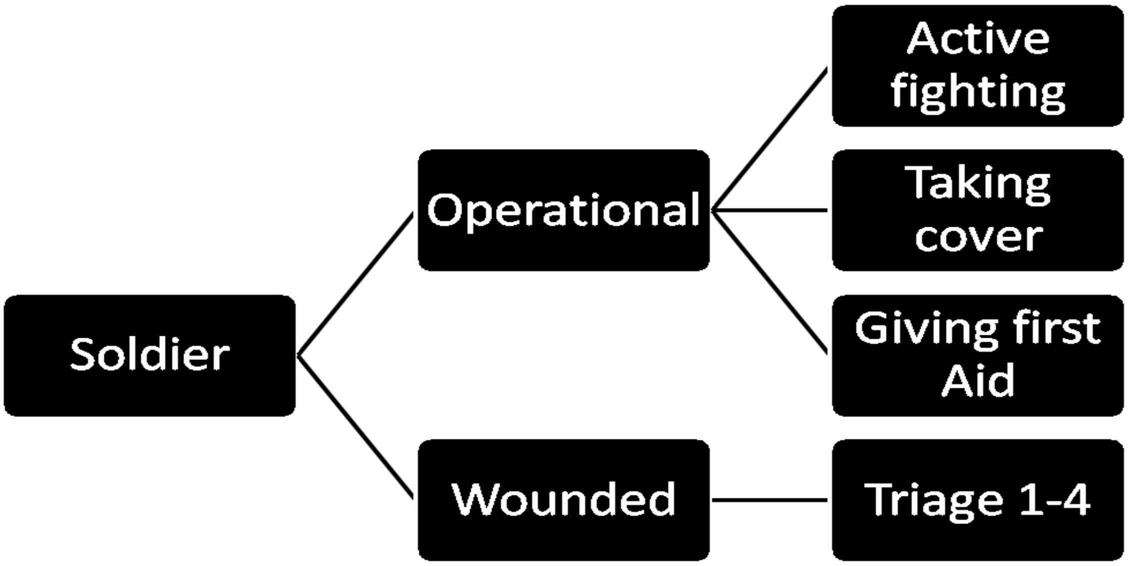


Figure 3.2 A simplified state machine for soldiers at the platoon level [P1, 2008].

The operational strength of the fighting unit is its nominal strength minus the personnel giving first aid to the wounded. This approach was selected during Major Jari Sormunen’s field research studies after discussions with Mr. Kari Stenius from the military medical establishment, who also took part in Sormunen’s research exercises.

In this way a new break point calculation was obtained: the unit is considered defeated if the operational strength of the platoon is less than one. Within a reasonable simulation time, the model gives a break point after 25-60% losses depending on the medical evacuation parameters, which does not conflict with the literature, see e.g. (Hembolt, 1971) pages 35-37.

The unit strength distribution calculation needs the average hit probability for each soldier in each operation state, which can be obtained from any deterministic or stochastic calculation or other source. Thus the model changes deterministic basic values to distribution form. The soldier state machines account for the different types of targets at the platoon level, avoiding an overly crude model with equal hit probabilities for all the entities of the platoon.

These two state machines are the core of the probabilistic approach to combat simulation. They still simplify the real situation, as the state probabilities of two fighting platoons are considered independent, such that the Blue platoon strength does not correlate with that of Red in these calculations. In real life we could assume that, for example, in a duel between a Blue and Red platoon, large losses from the first bullets in the Red target platoon would correlate with low losses for the Blue platoon. These kinds of correlation effects are not automatically considered in the mathematical model.

3.2 Indirect fire model

Artillery and mortars are used to suppress the enemy and to cause damage to units, equipment and fortifications. A single gun can shoot a single shot at a single target, but artillery is usually used to shoot at target areas with tens or hundreds of shells. In the stochastic model, the average hit probabilities of artillery fire are needed in order to determine the values for the state transition matrix for losses and soldier states.

Indirect artillery fire causes damage by fragments, pressure and heat. The fragments fly from different directions from the exploding ammunition, thereby leading to different effects as a function of angle and height of burst. Different ammunitions have different fragment mass distributions, fragment shapes, initial velocities, and fragment fan angle properties, thus leading to differences in losses.

In the target area, single shell hits can be treated as random processes. The deviations for the shells hitting the target area can be estimated from field tests and experience. Thus in the artillery model we have two separate random processes: hitting distribution of the ammunition and probability of effective hits with ammunition explosions and fragments.

A good overview of artillery fire effects was published in Tiede ja Ase 26 by Major M Koskimaa. (Koskimaa, 1968)

The fragments cause the most damage to targets. Surprisingly, artillery calculations in many simulations do not use an accurate fragmentation model. Other possible approaches are also available, such as mass of shells per area tables (Evans), “cookie cutter” model and exponential decay (Stanag 4654 Indirect Fire Appreciation Modelling, 2007) and test-based tables like in (Keinonen, 1954). These would give reasonable enough results for combat analysis if their parameters were to be adjusted for all different situations. As an extremely simple method (Evans) shows the observed real combat effectiveness of WW2 artillery weapons; if adjusted with some new effects, this method would be fast and rather accurate, also.

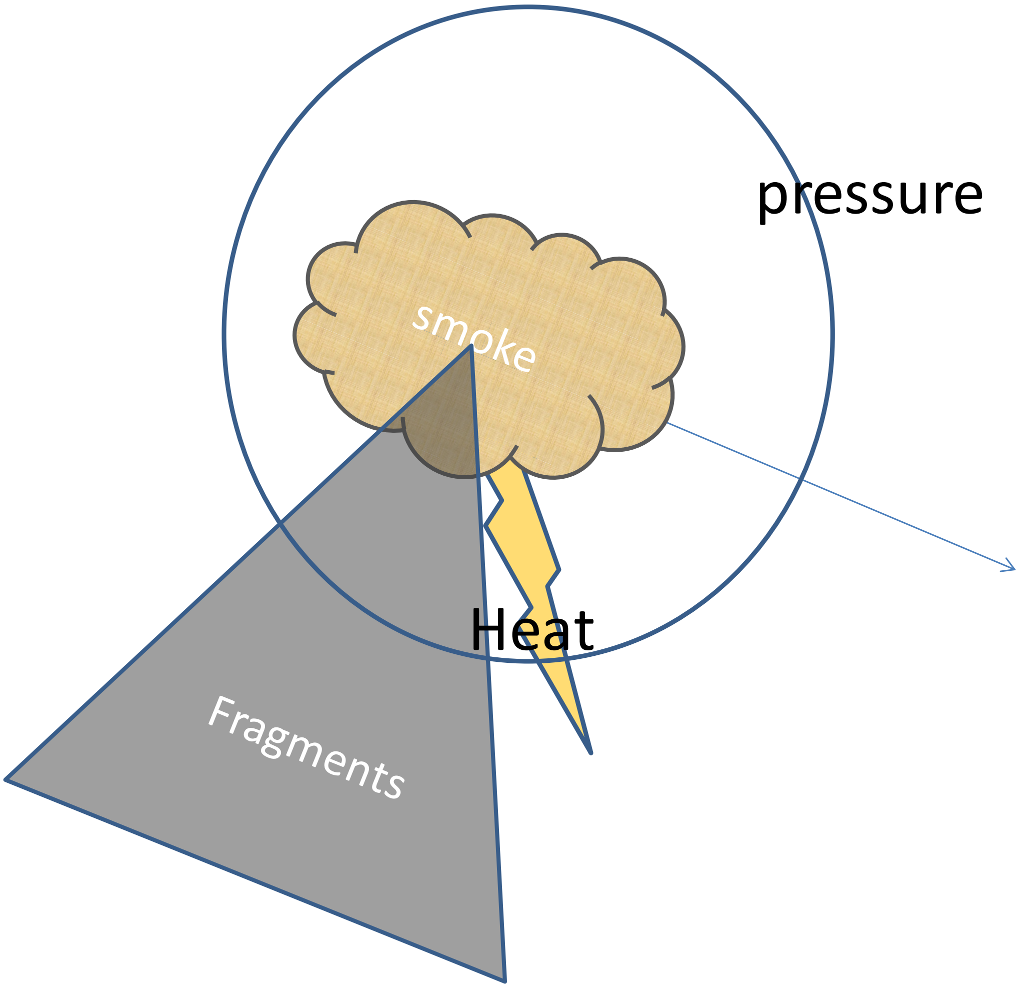


Figure 3.2.1 Artillery effects: fragments, heat, pressure and smoke. Fragments also fan forward and backward.

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Many software tools like “Pythagoras” give two options for artillery models (“cookie cutter” and exponential Carlton) (Bitinas, Henschield, & Truong, 2003), p.53. Some parameters are also available for these models, but they do not use any real model for damaging the target

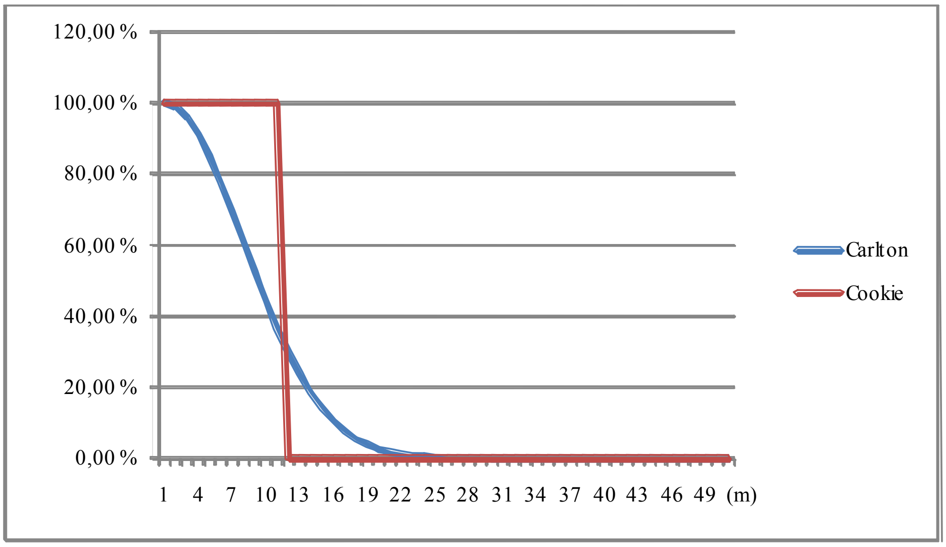

Figure 3.2.2 Probability of a hit as a function of distance (in meters) for the "Cookie cutter" and exponential Carlton models (Bitinas, Henschield, & Truong, 2003), *p. 53.*

In order to be able to calculate the different effects associated with angles of impact, fragment distribution and initial velocity as well as pressure threshold limits, a more accurate model was selected and coded. It is rather detailed compared to other alternatives used in simulations. The artillery model calculates the probability of a single entity getting a hit as a target of indirect fire and the results can be expanded to platoon level combat losses [P5].

The model and calculation methods are described in [P1], and the effectiveness and the goodness of the model were validated for mortar fire and a procedure for other ammunition was created in [P5] and [P8]. Artillery fire tests were conducted in October 2008 by a research team led by the author in cooperation with Karjalan Prikaati.

The model combines the vulnerable areas and pressure threshold levels of targets with the properties of ammunition. A protection level is specified for the vulnerable area in RHA steel plating equivalents. The target is damaged if the fragments penetrate its plating or the pressure thresholds are met.

The accuracy of shooting guns and ammunition are used to set the distribution of hitting point probability.

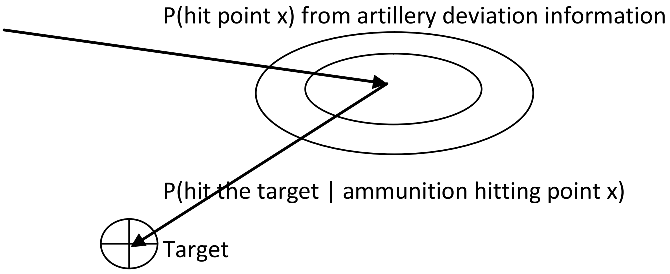

Figure 3.2.3 Probability of hitting a target is an (infinite) sum of two products P(x) and P(hit|x).

The probability of the target being hit is calculated using the area around the target. The ammunition has a probability of hitting each point around the target and from each hitting point there is a probability of fragments hitting the target. The probability of a single round of ammunition hitting the target is a sum of all products:

$$P(\text{hit with a single shot}) = \sum [P(\text{ammunition hits place } x_i) \cdot P(\text{fragment hits the target} \mid \text{hit in place } x_i) \tag{3.24}$$

Integration is done from the point of view of the target: the target has a radius for vulnerability to fragments or pressure impacts. Only the vulnerable area around each target is integrated to get the $p(\text{hit point } x)$ values, which are multiplied with fragmentation model hitting probabilities.

The parameters for this model are available: the shooting tables give the angle of impact, the mass of explosives is known and there is public data about fragment size and distribution. More accurate classified data is available, as the fragmentation of single rounds of ammunition has been tested. The results have been studied and the needed test data for the fragment angle and size distribution has been calculated by Army material command (MAAVMATLE).

3.3. Medical evacuation model

The medical model was constructed in order to gain some insight into the indirect effects of combat losses on fighting capability and the evacuation process. The medical model covers both the platoon level effects on combat effectiveness [P3 2006] and the evacuation chain from the platoon level to the evacuation hospitals [P4 2008].

The action inside a platoon was expected to be as follows: if a soldier gets hit, the other soldiers move him away from fire and the wounded soldier receives first aid from another soldier. After first aid, the wounded soldier is transported to a casualty collection point by other soldiers, who then return to continue the firefight. During the medical evacuation process, the soldiers who help the wounded, transport them to the casualty collection point and finally return to the combat formation are not effective in combat action. The wounded will be transported from platoon and company level treatment and collection points to the field hospitals.

In principle, there is nothing new in the simulation of the evacuation process of combat losses. For example, evacuation has been studied in the Naval Postgraduate School by Buoma (Bouma, 2005) and a model was created at the Helsinki University of Technology by using Arena, a commercial simulation tool (Jaakkola, Iso-Mustajärvi, Jalkanen, & Myllylä, 2005). In this context, the used model should fit the probabilistic approach and platoon level unit state machines. Thus a computationally fast and accurate enough model was required.

In publication [P3] a state machine representation of the evacuation was presented. The soldier state machine was introduced in Figure 3.2, in which the states are active, wounded, helping and evacuating the wounded and returning to the combat formation. The model and parameters are based on observations during the field exercise and study led by Major Jari Sormunen (*Komppanian hyökkäyksen menestystekijät*). Because both the field data and simulated data from Arena seemed to be close enough to the data from the simple model in [P3], it was selected for platoon combat efficiency calculations instead of more complex models. The parameters and model accuracy should be reconsidered if new data becomes available.

In the second phase of the evacuation process described in [P4], the wounded persons are categorized in four classes: mild wounds (triage III), intermediate (triage II), serious (triage I) and lethal including dead or those who are likely to die regardless of the care they might be given (triage IV).

The evacuation of the wounded from platoon level to company level and onwards is handled by two types of units: the evacuation unit and the treatment facility, which can be located at any unit level.

The evacuation unit is used to transport the wounded between different levels of treatment units. At each treatment facility there are three basic states: “waiting for treatment”, “in treatment” and “waiting for transportation or return to the combat formation”. Each state is further divided into four variables, one for each category of severity. If treatment is delayed or the waiting times become very long, the condition of the wounded deteriorates.

The calculation is similar to the unit state machine; the state transition matrix is multiplied with the original state probability vector. In this case, there are state transitions among the wounded to both better and worse conditions.

In this study, we concentrate only on the simulation model. Accurate numerical data on patient state transition probabilities are studied by the military medical establishment.

3.4 Predictor-corrector method

In the land combat environment, most of the time the units are moving or are in stationary positions waiting for combat or in rather stationary firefight positions. However, there are sharp changes when units first come in contact and open fire or become targets of direct or indirect fire. These incidents happen in a one-second time scale, but after the first bullets, the firefight and medical evacuation process has a time stepping of one minute or longer.

There is a trade-off between simulation time and simulation accuracy. The need for faster simulations requires time steps that are as long as possible, but overly long time steps cause unrealistic results. In platoon level land warfare, a minute is a reasonable time considering movement and combat actions. In most cases, we can assume that the parameters and unit action remain constant during a time step of this size; however, this time step is too long for many situations, especially when shooting starts. For example in an artillery fire or ambush situation, the unit states are not constants during the time step, thus leading to different hit probabilities within the time step. This leads to cumulative errors in simulation.

The problem with sharp changes in the combat environment can be solved by much shorter or adaptive time stepping or advanced mathematical modeling. In [P2], an advanced mathematical model is presented.

We start with a mathematical formulation of the problem. Simulation with time steps can be considered as a numerical solution of a differential equation. Euler’s method for solving differential equations is practically the same as a simulation with time stepping and using constant values for simulated entities during the time step. However, the constant values during the time step can cause errors if the situation evolves faster.

The formula for Euler’s method is

(3.25) $y(t_{i+1}) = y(t_i) + (t_{i+1} - t_i) \cdot \mathrm{d}y(t_1)/\mathrm{d}t$.

In the formula $y(t)$ is the situation (the values of all calculated functions) at time t, subtraction $(t_{i+1} - t_i)$ is the time step, and the derivate $\mathrm{d}y(t_1)/\mathrm{d}t$ is the difference of the values with respect to the time. In this case, the derivate is considered constant for the time step.

As an example, let us consider a duel between two infantry units, one soldier against a full platoon. The platoon is ambushed and the soldiers are not in cover. Then a component of $\mathrm{d}y/\mathrm{d}t$ is for example the loss rate of the target platoon soldiers. The constant derivate is in this case the same, as the target soldiers just stand as targets during the entire time step. When the next time step begins, the unit has suffered severe losses.

After the time step, the unit is taking cover and starting to evacuate its losses, so the combat effectiveness can be near zero and the unit does not shoot back at the enemy. Thus, the number of shots against the lone enemy soldier will be less than in a real case, and in fact the culmination point of the battle could be reached just from the error caused by the too long time step.

Traditional ways of increasing accuracy and avoiding cumulative errors have been to use either shorter time steps with adaptive integration or better integration methods, for example Heun's or Runge-Kutta methods. In these methods, a prediction step is calculated first and then the results are corrected using the calculated values; for this reason, these are referred to as predictor-corrector methods. These well-known methods have even been presented in some high school level textbooks, see for example (Hemmo, Lappi, & Lundahl, 2003).

There are problems with these traditional mathematical methods in this case. The theoretically better results with, e.g., Runge-Kutta methods have mathematical assumptions for the function: it is supposed to be differentiable. But in situations when shooting starts or ends, the combat loss functions are not even continuous. With a human in the loop taking tactical decisions, the shorter time step not only decreases the speed of simulation, but also easily increases the workload of the operators.

The mathematical solution to the problem is a novel calculation model for the combat environment. In the weapon selective predictor-corrector method, each time step is calculated twice [P2].

A calculation is first done with the starting values of the unit and then with its end values. The first step is a normal Euler's method calculation, so let y_e be the result of the Euler step calculated using the formula (3.25). Then we have two situations $y(t_i)$ and $y_e(t_2)$, and the derivates for the calculations are calculated for both cases. The end state $y(t_{i+1})$ has the formula

(3.26) $y(t_{i+1}) = y(t_i) + (t_{i+1} - t_i) \cdot [w_1\, \mathrm{d}y(t_1)/\mathrm{d}t + w_2\, \mathrm{d}y_e(t_2)/\mathrm{d}t)]$; $w_1 + w_2 = 1$

The positive weights w_1 and w_2 are not fixed to $w_1 = w_2 = ½$ like in Heun's method, but are weapon selective. In this case we have a state transition within the time step, and the unit action parameters change depending on the weapon system used against it.

Let us study the different methods using the traditional example

(3.27) $\mathrm{d}y/\mathrm{d}t = y$; $y(0)=1$, The analytical solution $y = e^t$, where e is Neper's number ($e \approx 2.7$). The results from Euler's method with time step 1 and ½, Heun's method with time step 1 and ½ and function selective results with time step 1 and $w_1 = 3 - e$ and $w_2 = e - 2$ are presented in Table 3.1.

	time	0	0,5	1	1,5	2
Analytical solution	y(t)	1	1,648721	2,71828183	4,481689	7,389056
Euler's method, timestep 1	y(t)	1		2		4
Euler's method, timestep ½	y(t)	1	1,5	2,25	3,375	5,0625
Heun's Method, timestep 1	y(t)	1		2,5		6,25
Heun's Method, timestep ½	y(t)	1	1,625	2,640625	4,291016	6,9729
Function selective Heun, timestep 1	y(t)	1		2,71828183		7,389056

Table 3.1 Solutions of equation 3.27 using different methods

The parameters $w_1 = 3 - e$ and $w_2 = e - 2$ were adjusted to give the right answer for $y(1)$. The weights depend on step size, so the values for step size 1 should be adjusted for other values. In this simple mathematical situation, the weights could be adjusted to fit the situation exactly, but in general the weapon parameters are only estimates.

In combat simulations, the parameters w_1 and w_2 can be fitted by for example using field test data or heuristic analysis of the unit soldier actions during the time step. The parameters for the weapon selective predictor-corrector method can also be estimated by using simulated results of more accurate simulators like FLAMES.

For example, we have two alternatives: six guns shoot one round each or one gun fires six times during a one-minute time step. With the first alternative, we have predictor values weighted as 1, because all the rounds hit the target simultaneously. In the second case, the soldiers of the target unit will take cover after the first hit, so as a first estimate the predictor step has a weight of 17% and the corrector 83%.

To give a numeric example, let the hit probability of a single shot be p for first shot and $\tfrac{1}{5}p$ for soldiers taking cover. So direct calculation using elementary probabilities gives the hit probability for one minute with simultaneous impact $1 - (1 - p)^6$ and for single shots $1 - (1 - p)(1 - \tfrac{1}{5}p)^5$. If $p = 0.1$, the hit probability for six guns shooting simultaneously should be 47% and for one gun firing six times 19%.

The direct predictor-corrector method gives values of 47% for the predictor step and 11.4% for the corrector step. The result with the weapon selective predictor-corrector method would be 17% with weights of $w_1 = 17\%$ and $w_2 = 83\%$.

As a result we can see that the weapon selective predictor-corrector method improves the results. There is no need to use shorter time steps if the weapon models include the parameters for weights w_1 and w_2.

4. RESULTS

4.1 Computational models

In order to ensure that the simulation would be fast enough, the unit aggregation level was set to a platoon, but also squad level can be used. As a result of this work, computational models for a platoon entity needed for a novel military operation analysis tool have been created. The stochastic calculation model enables probabilistic success analysis and gives wider insight into the situation, as it demonstrates random effects on the battlefield. The models have been coded as software, making them available for tactical studies [P1].

The weapon selective predictor-corrector method improves accuracy and enables longer time steps [P2]. The medical evacuation model shows the secondary consequences of combat losses and the need for medical evacuation resources during evacuation from the platoon level to an evacuation hospital [P3] [P4]. The artillery model gives losses to platoon size units from indirect fire, including all weapons with explosives and fragments. It uses powerful adaptive integration and simplified physical models for fragmentation and pressure [P5], thus leading to better accuracy than traditional cookie cutter or exponential decay models. Field testing increases the accuracy of parameter data and validates both indirect and infantry fire models [P6] [P7] [P8].

The results are in probability distribution form and can thus be used in probabilistic risk analysis [P9] [P10]. Automatic target selection helps the persons running the simulation to use the Sandis software [P11] and documents the calculation procedure used in combat simulations.

4.2. Calculation examples of the basic models

4.2.1. The Sandis software for brigade level war gaming

In [P1] there is an overall description of the models and the Sandis software using them for comparative analysis. The platoon level models are tested in Chapter 4.2, and an overview of published larger level war gaming examples is presented in Chapter 4.3. Some parts and models of the Sandis software are used in the war gaming, although they are beyond the scope of this dissertation.

For brigade level war gaming, the Sandis calculates the radio communication environment, combat losses, ammunition consumption and medical evacuation process at the platoon level, as the man in the loop is responsible for tactical decisions. The results from Sandis simulations are the strength distributions of the units and operation success probability as well as a killer–victim scoreboard and medical situation values.

The platoon level unit model in brigade level scenarios is the most important difference between Sandis and the other tools available. The computational models use Markovian combat modeling as described by (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004), which gives reasonable loss distributions compared to the field tests and literature [P5] [P6] [P7] [P8]. The weapon system parameters fit the model, as the integration parameters are also adjusted to fit the reality [P2]. Automatic target selection [P11] is needed for practical simulation work in order to perform brigade level analysis in a reasonable time.

The difference in the combat effectiveness of a platoon after casualties with different evacuation procedures can be studied using the medical evacuation model [P3] [P4]. Also the break point analysis is connected in medical evacuation [P3].
By employing these models, the Sandis tool can be used in probabilistic risk analysis [P9] [P10]. The use of other tools and system analysis may be needed before running Sandis simulations, but the basic state transition computations create the needed probability distribution of any combat model with average losses.

The probability of success gives an advantage for decision-making procedures. The problem with probabilistic analysis is the number of different paths and simulated cases, which increase to infinity. Thus only the most important different alternatives can be studied with Sandis combined with event tree analysis [P10].

4.2.2 Platoon level game

In the simulated game, two identical platoons meet in an open forest environment. The simulation was made using the September 2009 version of the Sandis software, and the units were set on a white map.

In the first game, only infantry light weapons are used and in the second a mortar unit is also used. The mission for both platoons is to advance and shoot at the enemy, if possible. No tactical maneuvers take place, so the platoons keep fighting until they are “defeated”. A unit is considered “defeated” if its losses become so severe that all operational fighters are evacuating the wounded. In this case the platoon is given the order to move backward and try to avoid further combat.

If the unit can advance, it will do so. Enemy fire forces the soldiers to take cover, so the advancing speed of a unit in a firefight is extremely slow if the unit is under effective fire.
The tactics are simplified in order to see the effects of the computational methods. The parametric data in this game is collected from field tests and from the mortar point of view from public sources.

The hit probabilities of the platoons are constructed by Lappi and Pottonen [P6, 2006] and the field tests by Lappi et al. [P7, 2008]. The difference between the platoons is from field tests. The first platoon has the hit probabilities of the best unit: Group 1, 28 March 07 at 13:20 and 13:35, in the test and the Red platoon has average values [P6, 2008].

The hit probabilities have the same functional form, which was extrapolated from (Keinonen, 1954) by using weighted averages with a weight of 2 for a semiautomatic rifle (7.62x53R) and a weight of 1 for a 9 mm Suomi submachine gun as reference. The level of hitting probability was calculated with field tests, which were in good correspondence with results directly from (Keinonen, 1954) transformed to the needed parameters by using methods in [P6, 2008].

	Approximation [1954]	Average shooters [P6]	Good shooters [P6]
distance (m)	Basic hit probability	Basic hit probability	Basic hit probability
0	3.89%	4.53%	9.33%
50	3.82%	4.45%	9.17%
100	2.66%	3.10%	6.40%
200	0.94%	1.10%	2.26%
300	0.68%	0.79%	1.63%
400	0.57%	0.67%	1.38%

Table 4.2.1 Basic hit probabilities for open terrain

Mortar ammunition data is also needed. The data needed is fragment size and mass distributions and the initial velocity of the fragments; furthermore, the angle of hit is needed.

The amount of explosive is 1.72 kg in TNT equivalent. Fragment initial velocity was 1200 m/s, height of explosion 0.25 meters and the mass distribution with angles is shown in Table 4.3.2.

start angle (degree)	end angle (degree)	average mass (kg)	number of fragments	remarks
0	5	0.03	1	one big fragment forward
0	10	0.00163	1046	fan of small forward
65	115	0.00163	5580	effective fan to sides
170	180	0.00163	349	backward fan

Table 4.2.2 Fragmentation data

The mortar data is the same as used in [P5, 2008]. As we can see from page P5-9 to P5-10, the simulated losses from mortar fire have good correspondence with the actual field experiments described in the model description and test reports [P5 2008],[P8 2008].

4.2.3 Gaming in detail

The game starts with two platoons 1 km from each other. The starting situation is shown in Figure 4.2.1. The platoons are given orders to advance, which can be seen as a gray line starting from the center of the platoons. In a simplified model programmed in this version of Sandis, the unit is a circle or, to be exact, seven integration points located in the center and corners of a hexagon. Any other configuration of integration points is also possible.

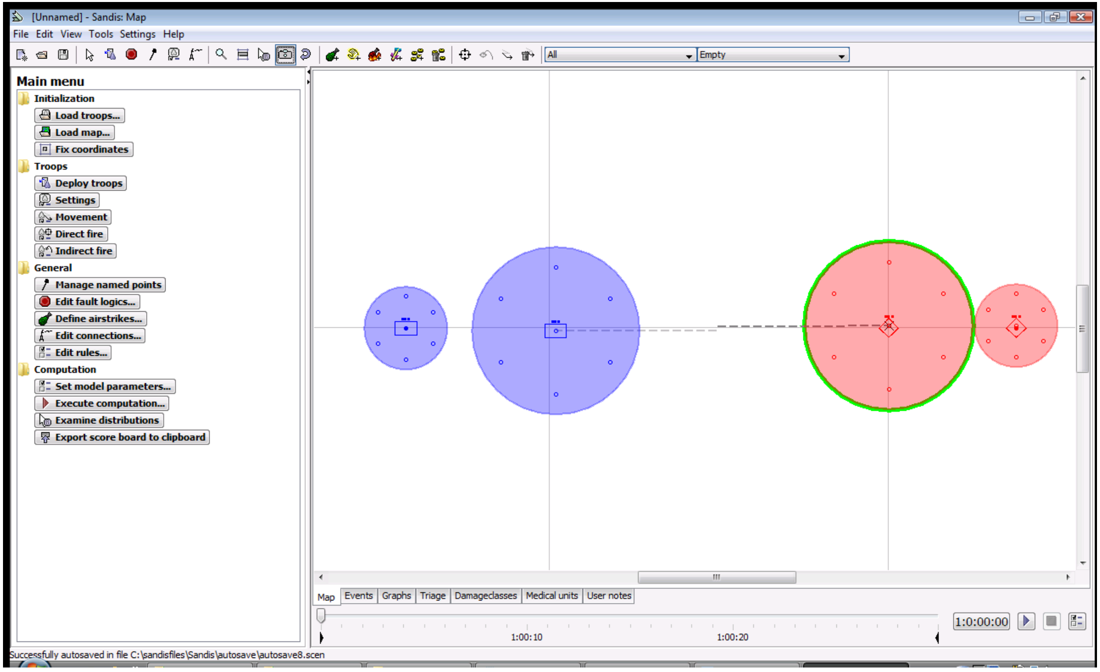

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Figure 4.2.1 Starting situation

The units start the firefight 16 minutes after starting time. After three minutes of firefight, the results are visible. In the second scenario, at this point Red uses mortars against the Blue unit. In the first firing, good shooters gain an advantage, as seen in the unit circles: the white area represents average losses.

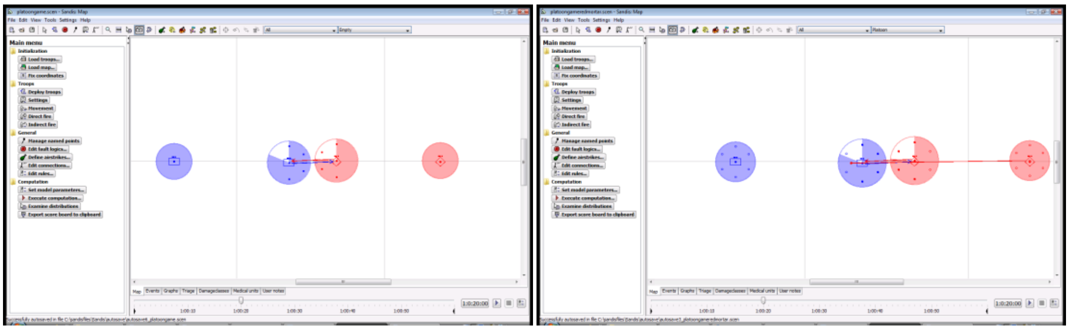


Figure 4.2.2 Situation after 20 minutes. The mortar is used at right-hand side.

When the game continues, both units suffer losses. The mortar fire is aimed a little behind the nearest units to avoid friendly fire casualties on the Red side. Thus the indirect fire affects the firefight after some time when the nearest units need their backup.

Because the fighting units are distributions, the cumulative results represent the conditional probability of shooting by those parts of the distribution that have not been defeated. To do an accurate probabilistic risk analysis, different alternatives must be selected as described in P9 and P10. In Figure 4.2.3, the basic simulation is conducted to the end.

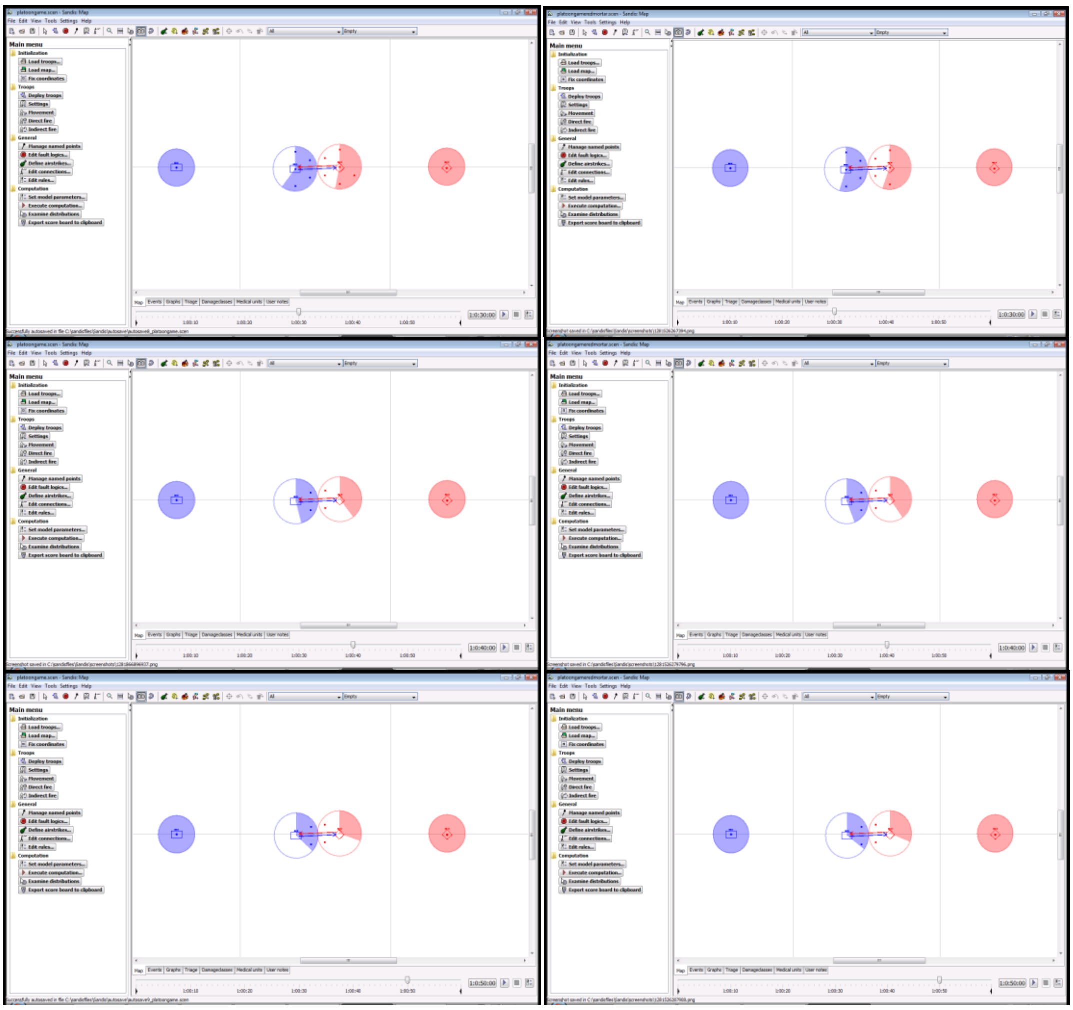
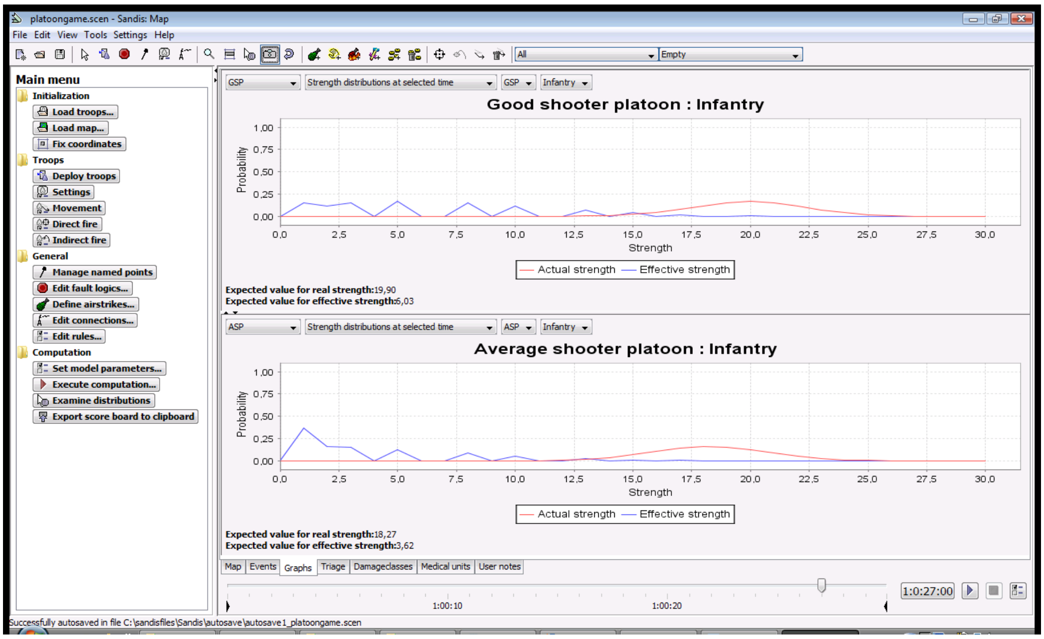


Figure 4.2.3 Game on the map after 30, 40 and 50 minutes. The basic case is on the left. In the case on the right, Red carries out a mortar strike.

The simulation results can be seen as average curves as a function of time and as distributions for all time steps. In Figure 4.2.4 we can see the unit strength distributions. Actual strength is the number of unwounded soldiers and effective strength is the number of soldiers who are not wounded or taking care of the wounded. The average actual strength of the good shooter platoon is only 9% better, but in effective strengths the difference is 74%.



Expected value for real strength:19,90
Expected value for effective strength:6,03

Expected value for real strength:18,27
Expected value for effective strength:3,62

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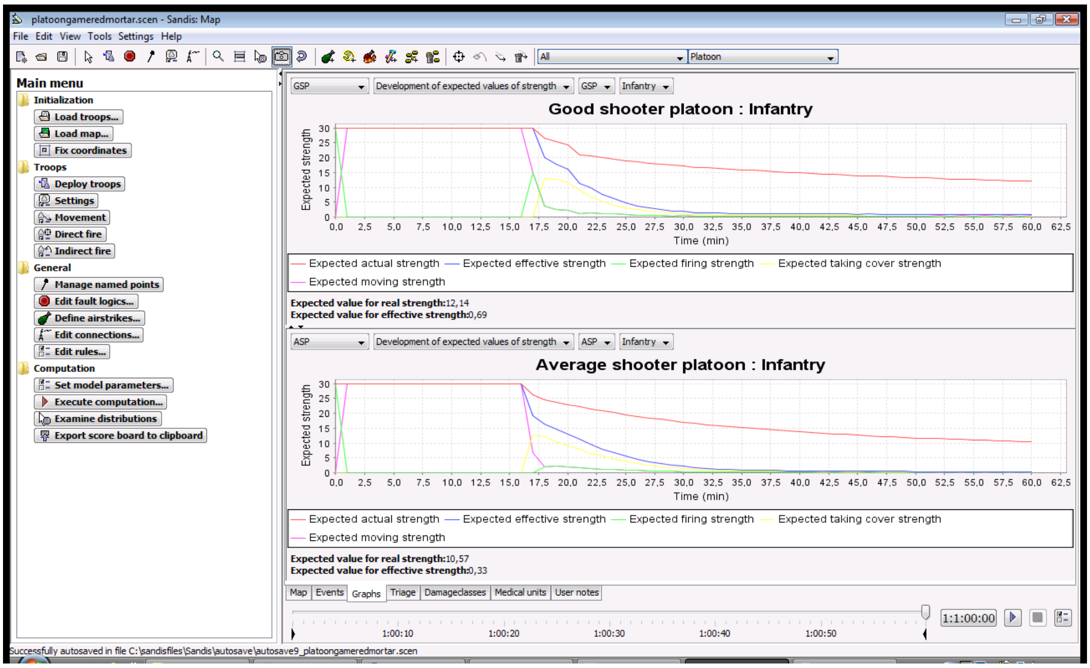
Figure 4.2.4 Strength distributions of both platoons when Red used mortars after 30 minutes

Also, the stochastic nature of the combat becomes visible. The distributions vary from 15 to 25 soldiers simply due to the random nature of combat. Firing for one minute with two mortars turns the tide a bit better for average shooters at this stage.

The average values are also interesting and available as a function of time. In this form, different state distributions of the units also become visible. Figure 4.2.5 presents average strength as a function of time.



Expected value for real strength:12,14
Expected value for effective strength:0,69

Expected value for real strength:10,57
Expected value for effective strength:0,33

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Figure 4.2.5 Average values as a function of time (the mortar case).

When the shooting starts, the loss rate is highest during the first minutes. For this reason, the predictor-corrector method is useful, because it makes possible state transitions to the state "take cover" in less than one minute of time. From the results, we can see the effect of mortar fire at the 20 minute-point as a sharp edge in the actual strength curve. The expected actual Blue strength goes down by 16% due to the combined effect of mortar and rifle fire, but the Blue firing strength drops more than 50% as the larger portion of soldiers take cover instead of shooting.

From the lower curve we can see the cumulative effect of losses. The Red platoon loses an average of 3.6 soldiers (12%) due to accurate fire from the Blue fighters. Medical evacuation and first aid double the effect, and almost all the fighters of the rest of the platoon take cover during most of the time steps. In the simulation only 10% of the firepower is used against the enemy because of suppression and evacuation after casualties. Still the Red firepower forces the Blue platoon to also take cover, so according to this model firing back at the enemy is essential.
To see the probabilities for Blue and Red operation success, failure curves are needed. These are used for probabilistic risk analysis and operation success calculations as described in [P10]. Fault tree gaming and cluster success analysis are not visible in a game with only one operational unit. The failure probability curve shows the probability of being defeated if the fight continues. It is a conditional probability, and to get real failure and success values the game must be cut to different branches of an event tree.

Expected value for real strength:16,49
Expected value for effective strength:1,48

Expected value for real strength:16,68
Expected value for effective strength:1,94

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Figure 4.2.6 Failure probability curve

When the results are interpreted correctly, after 27 minutes there is a significant probability of Red losing the fight. At that moment the game is split into two options: Red escapes and is considered defeated. The probability distribution uses values with Red defeated. If Red is not defeated, the probabilities in the probability distribution are adjusted to those with Red not defeated [P10 p. 51].

The end results with and without mortars are shown in Tables 4.2.3a and 4.2.3b

The results show the need to study conditional probabilities and split the game into event trees. The computational models can be used to get reasonable probability values for the platoon level. When these platoon level results are combined to company level, companies can be used in battalion level clusters for failure or success analysis. The overall probability of operation or unit mission success becomes available when these sub-clusters are combined. This kind of total success probability is considered to be a useful measure of goodness for comparing alternatives, not an accurate estimate of the actual success probability.

Time		Good shooter platoon		Average shooter platoon	Time	Cumulative probabilities			
		Probability | fight continues		Probability | fight continues		Fight continues	Good shooters win	Average shooters win	Both units beaten
27	Beaten	0 %		23,90 %					
	Operational	100 %		76 %	27	76 %	24 %	0 %	0 %
		Game continues with 76% probability							
30	Become beaten	25,20 %		58,10 %					
	Beaten (cumulative)	25,20 %		44,94 %					
	Operational	74,80 %		55,06 %	30	31,34 %	49,48 %	10,56 %	8,62 %
		Game continues with 31% probability							
33	Become beaten	51,40 %		83,60 %					
	Beaten (cumulative)	35,03 %		70,21 %					
	Operational	64,97 %		29,79 %	33	6,07 %	63,78 %	13,83 %	16,33 %
		Game continues with 5,45% probability							
36	Become beaten	85,20 %		97,00 %					
	Beaten (cumulative)	77,22 %		89,93 %					
	Operational	22,78 %		10,07 %	36	0,14 %	65,02 %	14,30 %	20,54 %
40	Become beaten	94,10 %		99,10 %					
	Beaten (cumulative)	74,10 %		91,06 %	40				
	Operational	25,90 %		8,94 %		0,00 %	65,05 %	14,31 %	20,63 %

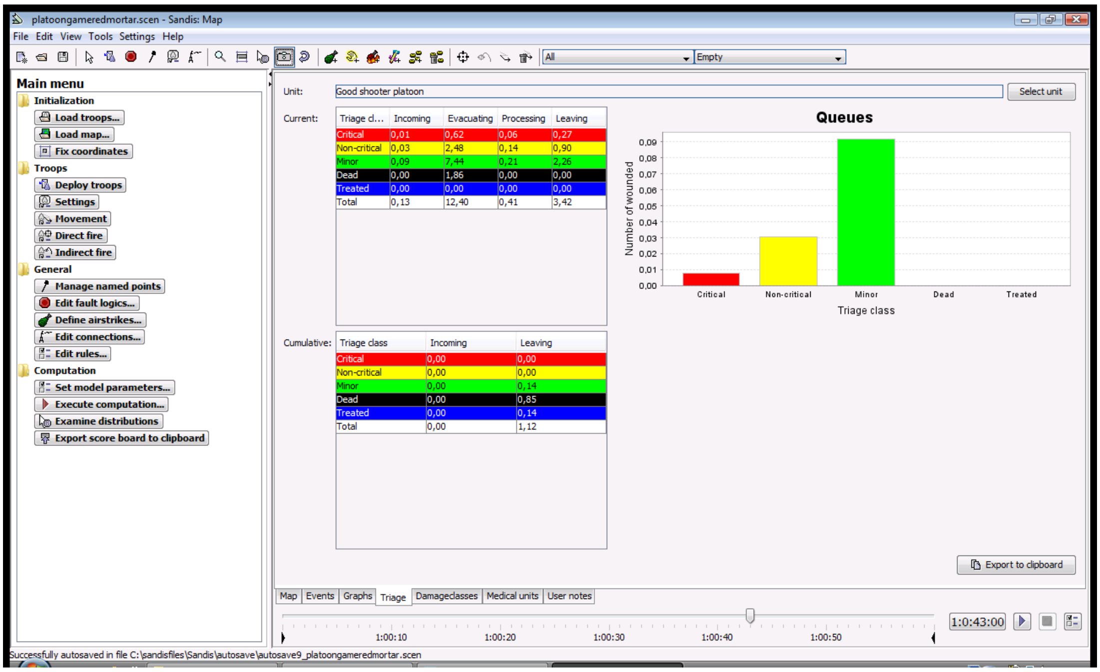
Table 4.2.3a Probability distribution of end results of the game with infantry weapons only

Time		Good shooter platoon		Average shooter platoon	Time	Cumulative probabilities			
		Probability | fight continues		Probability | fight continues		Fight continues	Good shooters win	Average shooters win	Both units beaten
27	Beaten	0 %	0 %	23 %					
	Operational	100 %		77 %	27	77 %	23 %	0 %	0 %
		Game continues with 76% probability							
30	Become beaten	66,20 %		47,10 %					
	Beaten (cumulative)	66,20 %		31,03 %					
	Operational	33,80 %		68,97 %	30	17,88 %	31,34 %	35,02 %	15,76 %
		Game continues with 31% probability							
33	Become beaten	81,40 %		76,00 %					
	Beaten (cumulative)	44,97 %		65,20 %					
	Operational	55,03 %		34,80 %	33	3,42 %	37,76 %	37,82 %	21,00 %
		Game continues with 5,45% probability							
36	Become beaten	89,90 %		90,90 %					
	Beaten (cumulative)	81,65 %		73,85 %					
	Operational	18,35 %		26,15 %	36	0,16 %	38,22 %	38,55 %	23,06 %
40	Become beaten	96,40 %		98,70 %					
	Beaten (cumulative)	80,39 %		95,03 %	40				
	Operational	19,61 %		4,97 %		0,00 %	38,25 %	38,56 %	23,19 %

Table 4.2.3b Probability distribution of end results of the game with mortar fire

There is an option for probability clusters in Sandis, so the software and models can be used in probabilistic success analysis. The leaves of the probability tree are platoon level probabilities, which create a total success analysis by combining company level success with platoon level clusters. Company level clusters are used at the battalion level and battalion level clusters for operation success analysis.

Platoon effectiveness after combat casualties is available in Figures 4.2.4 – 4.2.5. Medical evacuation data shows the situation in medical evacuation and treatment units. The current situation is available for each simulated minute, as is the cumulative amount of casualties treated in all the medical posts during the scenario. The patient queue shows the number of casualties waiting for treatment. If the queue is long, the status of the casualties weakens and some might even die. This indicates insufficient medical resources supporting the fighting units.



Unit: Good shooter platoon

Current:

Triage cl...	Incoming	Evacuating	Processing	Leaving
Critical	0,01	0,62	0,06	0,27
Non-critical	0,03	2,48	0,14	0,90
Minor	0,09	7,44	0,21	2,26
Dead	0,00	1,86	0,00	0,00
Treated	0,00	0,00	0,00	0,00
Total	0,13	12,40	0,41	3,42

Cumulative:

Triage class	Incoming	Leaving
Critical	0,00	0,00
Non-critical	0,00	0,00
Minor	0,00	0,14
Dead	0,00	0,85
Treated	0,00	0,14
Total	0,00	1,12

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Figure 4.2.7 Medical treatment unit data. Queues on the right and treatment numbers on the left.

In addition to the results directly available from Sandis, a killer-victim scoreboard is also created. It includes average losses for all shooter–target pairs and it can be exported to other software like a spreadsheet for further analysis. The killer-victim scoreboard is used to see the difference between different weapon systems. The effects of friendly fire and the most important weapon systems can be seen from the scoreboard.

Firing side	Firing unit	Firing weapon class	Target side	Target unit	Target weapon class	Loss
Red	Average shooter platoon	Infantry	Blue	Good shooter platoon	Infantry	18,69
Red	120 mm mortar	WpnSys	Blue	Good shooter platoon	Infantry	2,74
Blue	Good shooter platoon	Infantry	Red	Average shooter platoon	Infantry	22,73
Red	120 mm mortar	WpnSys	Red	Average shooter platoon	Infantry	0.0
Red	120 mm mortar	WpnSys	Blue	Mortar Platoon	Weapon system	0.0

Table 4.2.4 Killer-victim scoreboard. Mortar fire caused average losses of 2.74. The 0.0 losses from Red mortar fire indicated that there was a theoretical risk of friendly fire casualties or casualties to Blue mortar platoon, but average losses were less than the threshold limit.

4.3. Usability of computational models in brigade level scenarios - the Sandis software

4.3.1 Miscellaneous publications

There are several publications on the use of Sandis. Sandis was used to gain artillery success data for portfolio analysis (Kangaspunta, Lappi, Liesiö, & Salo, 2008) on the basis of Janne Laitonen's simulations (Laitonen, 2008), in which a battle group with a strong battalion with supporting artillery attacked a mechanized battalion. There were variations in weapon types and numbers, and the results could be used in portfolio analysis.

During the International Date Farming Workshop (IDFW) 18 arranged by Naval Postgraduate School, Sandis was used in a civilian crisis situation. (Heath, Dolk, Lappi, Sheldon, & Yu, 2009). Medical evacuation after a train accident was studied, and the medical evacuation model was found useful in evacuation logistics analysis.

Another type of study was written by Capt. Pekka Puotiainen in staff officers' course EUK 61. In his thesis (Puotiainen, 2009) discussed the use of the Sandis tool as part of operational planning. As a result, Puotiainen considers that Sandis can be used in brigade level operation analysis, but software engineering and documentation are still under construction.

4.3.2 The 3rd International Sandis workshop

The third international Sandis workshop was held in September 2009 in Valkeakoski. During the workshop, four different cases were calculated. The following is based on workshop proceedings (Hämäläinen, Lappi, & Åkesson, 3rd International Sandis Workshop, 2009). Four different cases were simulated. The first case was static analysis, because the target unit did not shoot back at the shooting units. The other three cases were dynamic, in which a fight between Red and Blue units was simulated in a war gaming situation. Thus the results depend on the tactics selected by the players.

Case 1. Static Analysis of Artillery Alternatives.
By Bernt Åkesson

Dr. Bernt Åkesson studied the effectiveness of artillery weapons in his workshop tutorial and presented the use of indirect fire models in statistical analysis. In his study, the results clearly showed the relative effectiveness of MRSI with artillery units starting the firing "direct to impact". In this study, the platoons were set on the map as targets for artillery fire. The model with units taking cover was found useful for studying differences between simultaneous and traditional use of ammunition.

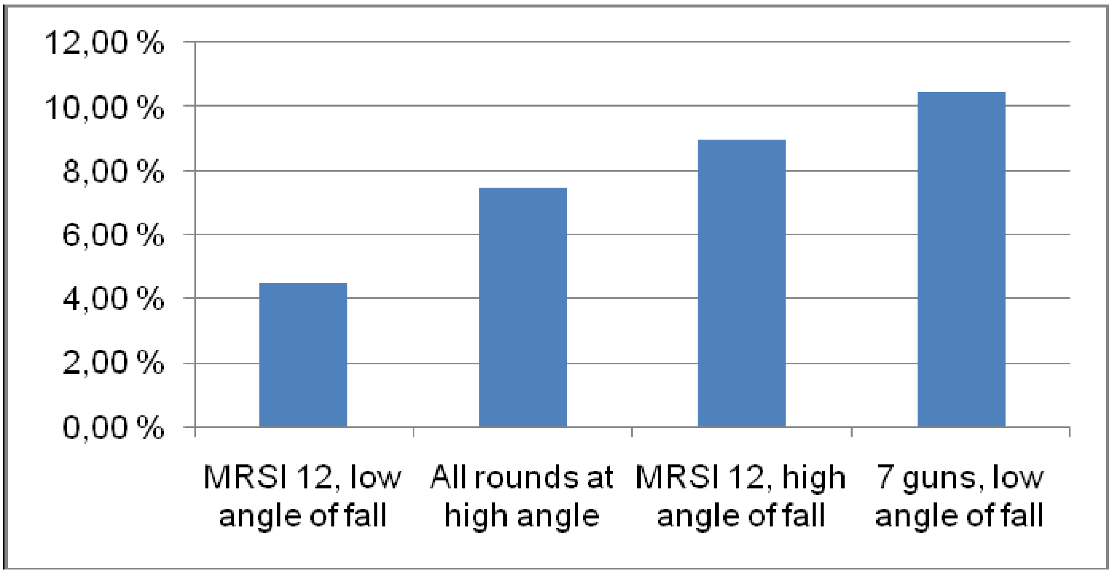

Figure 4.3.1 Results from 3rd International Sandis Workshop by Dr. Åkesson. (Figure 5.3 from original publication)

The simulation time for this kind of static analysis was an hour, because parameter data for artillery was available. As the artillery model has been in good correspondence with the test results [P5], the indirect fire model is useful in artillery studies.

Case 2. Suitability of Sandis Software to Small Scale Military Problems – A Case Study: Does the Use of Mortar Reduce Convoy Vulnerability in an Asymmetric Warfare Situation?

By Anna Lindberg, Tuomas Liukko, Juha Arpiainen and Juhani Hämäläinen

In the second case, convoy vulnerability was tested. The units were squad level and a goal was to test the Sandis software in a small-scale simulation setting. The situation is presented in Figure 4.3.2.
The ambushing Red had 2 Cells with 6 men each, 4xRPG-7 (light anti-tank weapon) and 6 assault rifles per cell, 1 Cell with 6 men, two 81 mm mortars, 6 assault rifles. Red had off-road vehicles, mines of model TMA4 (anti-tank mine), remote control firing systems, explosives (TNT) and basic communication equipment (radios or similar).
The Blue convoy consisted of 5 Infantry fighting vehicles, 2 main battle tanks, 2 fuel trucks, 12 other trucks and mortar vehicles in an alternative formation of the simulated scenario.

The difference between the two simulated alternatives materialized after 14 minutes of fighting, when Blue gained situation awareness and could start using the mortars effectively. One clear difference with the Blue mortars was the ability to counter Red's 81 mm mortars with accurate 120 mm Blue mortar fire. As a final conclusion, the mortars turned out to be useful to convoy security.

The computational models used in this game were the indirect fire model, direct fire model and advanced integration. Distributions and success probability calculations were not used. The computational models were useful in this case, but the limitations of the software meant that the units had to be circular, and this was found to be a problem. As a remark, the circular unit formation can be changed to any other shape with little software engineering. As a further task, a feature should be implemented in the software to enable the use of different shapes without the need for Java coding.

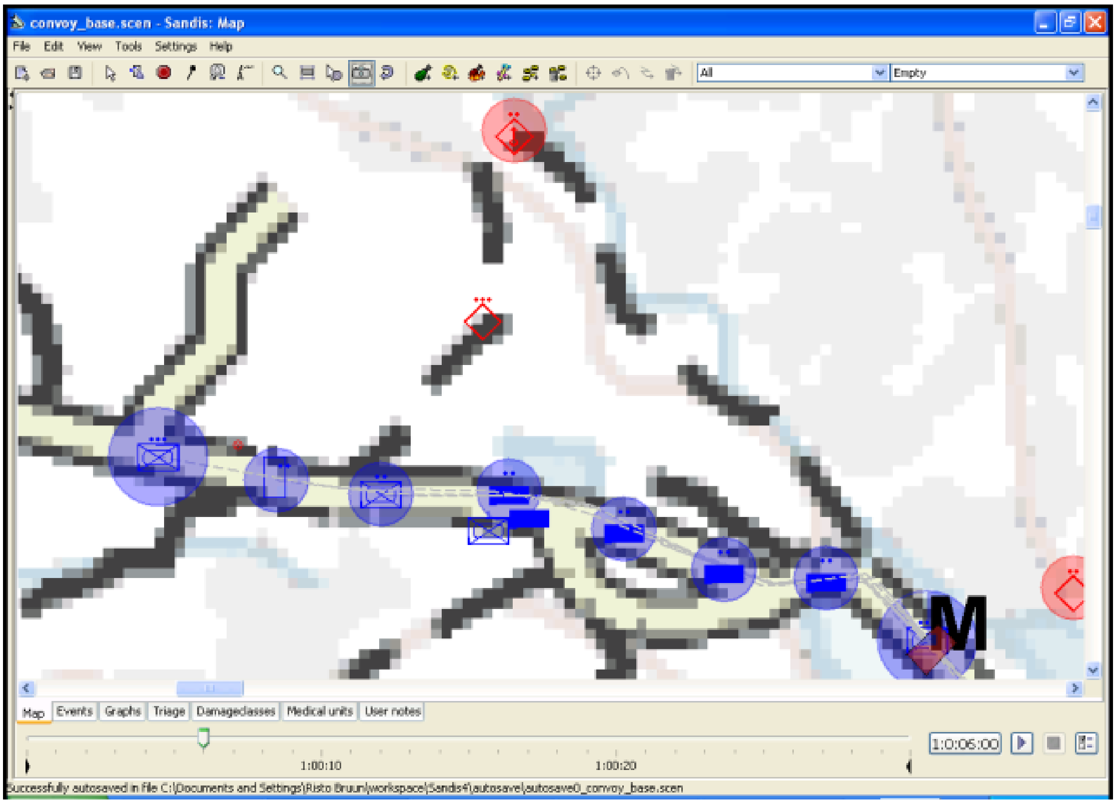

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Figure 4.3.2 Convoy and guerillas. The original figure was: "Figure 4.1: The formation of the convoy at the 7th minute, after entering the minefield."

Case 3. A Study on Different Tactics for Repelling an Airborne Landing

By Bernt M. Åkesson (team leader), Linus Bosaeus, Juuso Österman, Risto Bruun and Jussi Sainio

In this case an airmobile Red battalion is landing on the west side of a river in order to take a bridge defended by a separate infantry company. A Blue mechanized battalion with supporting artillery is making a counterattack in order to keep the bridge. Due to the location of the artillery, it has to move to a new position in order to support the mechanized battalion in the counterattack. The alternatives were to counterattack immediately without artillery support or after a delay with artillery support. All pictures are copied from the original proceedings.

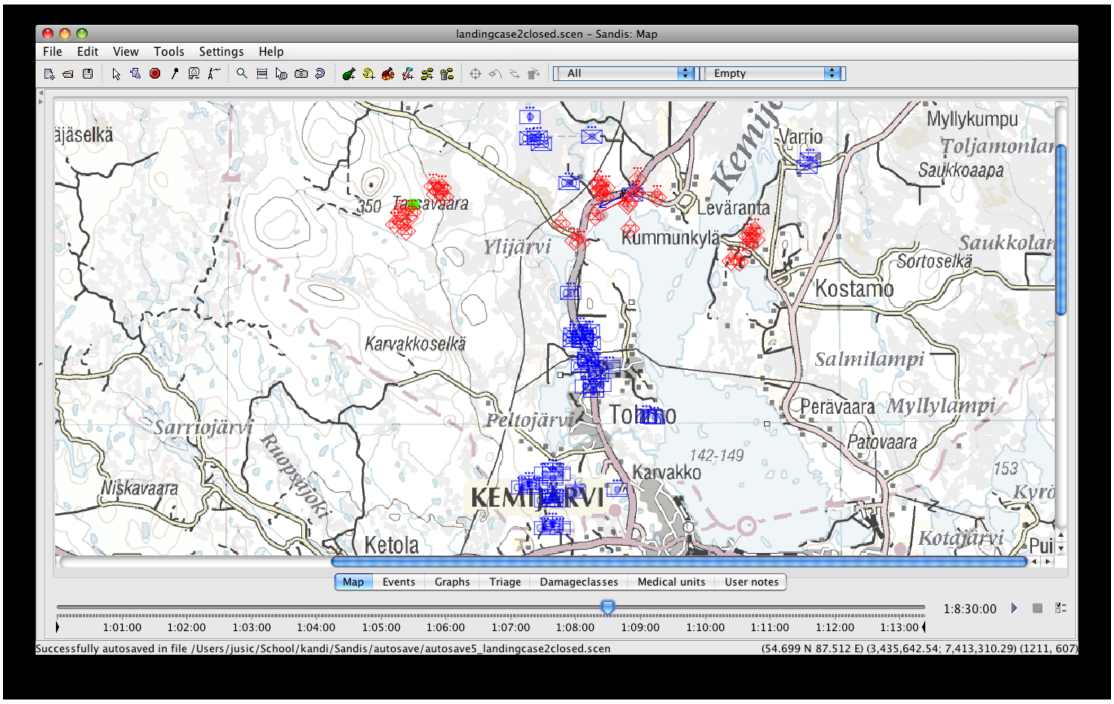

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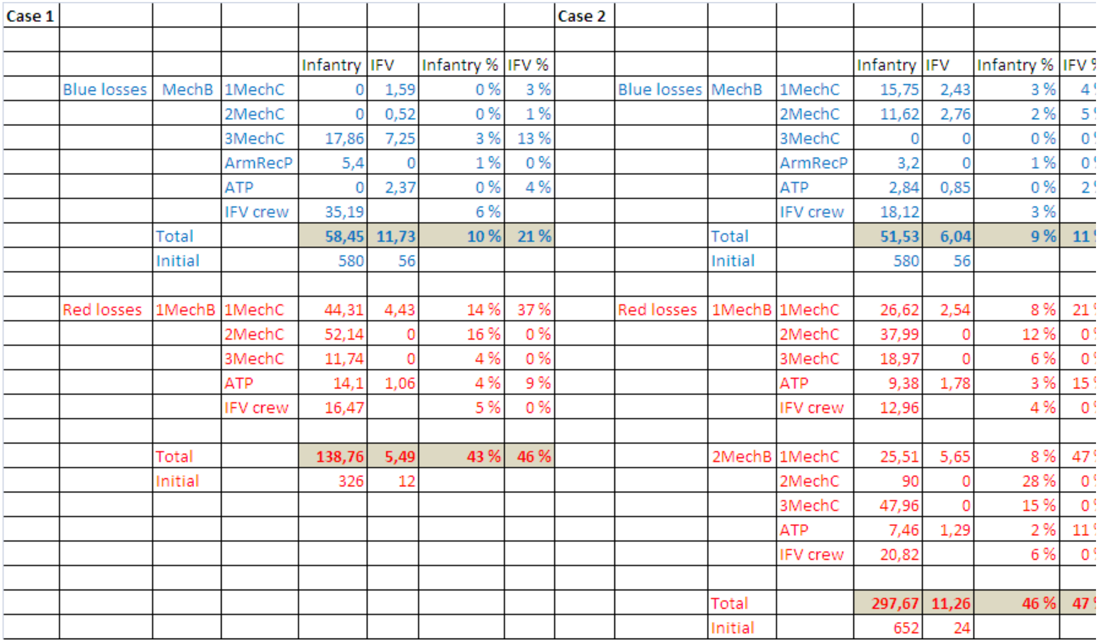
Figure 4.3.3 Blue battalion attacking from south to north, Red airborne landing on Tarsavaara. Local company withdrawing to north.

The units in the game were a Blue infantry company (local guard), a mechanized infantry battalion, and an artillery battery. Red had a mechanized battalion with fewer vehicles due to hard landing conditions.

The combat time of the simulated fight was 19 hours. The first part of the fight is the Blue local company defending the bridge against the landed Red. At this time, the Blue battalion is starting attack preparations. Blue can launch an unprepared attack four hours earlier than an artillery-supported prepared attack. During these four hours, Red can bring reinforcements to Tarsavaara, strengthening the enemy forces.

The simulated time was 19 hours and two alternatives were calculated. The workshop time for simulations was three workdays, so battalion level calculations can be done in a reasonable time. In these scenarios, probabilistic success analysis was not used, and the success analysis was based on average losses in Table 4.3.1. In a research environment, more time should be spent on these kinds of problems with more options for Red, including at least the worst Red action against our plan and the most probable one. The probabilistic approach would show risks and help in sensitivity analysis.



Case 1								Case 2							
				Infantry	IFV	Infantry %	IFV %					Infantry	IFV	Infantry %	IFV
	Blue losses	MechB	1MechC	0	1,59	0 %	3 %		Blue losses	MechB	1MechC	15,75	2,43	3 %	4
			2MechC	0	0,52	0 %	1 %				2MechC	11,62	2,76	2 %	5
			3MechC	17,86	7,25	3 %	13 %				3MechC	0	0	0 %	0
			ArmRecP	5,4	0	1 %	0 %				ArmRecP	3,2	0	1 %	0
			ATP	0	2,37	0 %	4 %				ATP	2,84	0,85	0 %	2
			IFV crew	35,19		6 %					IFV crew	18,12		3 %	
		Total		58,45	11,73	10 %	21 %			Total		51,53	6,04	9 %	11
		Initial		580	56					Initial		580	56		
	Red losses	1MechB	1MechC	44,31	4,43	14 %	37 %		Red losses	1MechB	1MechC	26,62	2,54	8 %	21
			2MechC	52,14	0	16 %	0 %				2MechC	37,99	0	12 %	0
			3MechC	11,74	0	4 %	0 %				3MechC	18,97	0	6 %	0
			ATP	14,1	1,06	4 %	9 %				ATP	9,38	1,78	3 %	15
			IFV crew	16,47		5 %	0 %				IFV crew	12,96		4 %	0
		Total		138,76	5,49	43 %	46 %			2MechB	1MechC	25,51	5,65	8 %	47
		Initial		326	12						2MechC	90	0	28 %	0
											3MechC	47,96	0	15 %	0
											ATP	7,46	1,29	2 %	11
											IFV crew	20,82		6 %	0
										Total		297,67	11,26	46 %	47
										Initial		652	24		

Table 4.3.1 Results of attack with and without artillery

Case 4. Cost Effectiveness Study of Indirect Fire Systems

By Peter Rindstål, Kosti Jokinen, Esa Lappi and Juho Rutila

In the scenario with different ammunition and indirect fire systems were compared with main battle tanks and the results were used to demonstrate cost-effectiveness studies with Sandis. In the scenario, the Blue battalion is attacking the Kemijärvi airstrip. The defending company is kept in defensive positions, but the Blue unit had three variations to support the attack with the same imaginary cost: Tank Company, Mortar Company with anti-tank guided ammunition and Mortar Company with cargo ammunition. The starting situation of the war game is shown in Figure 4.3.4.

In the game, some problems occur with anti-tank weapon parameters, but in this situation 120 mm mortars were better against mechanized infantry compared to main battle tanks, because in the forest the tanks could not use their main gun before coming into the range of infantry anti-tank weapons. The mortars were able to support the attacking battalion during the whole scenario. Because the Red armor capability had the same problems as the Blue main battle tanks, the guided anti-tank ammunition for mortars did not provide a significant advantage to infantry anti-tank weapons, but cargo ammunition was effective against both Red infantry and infantry fighting vehicles.

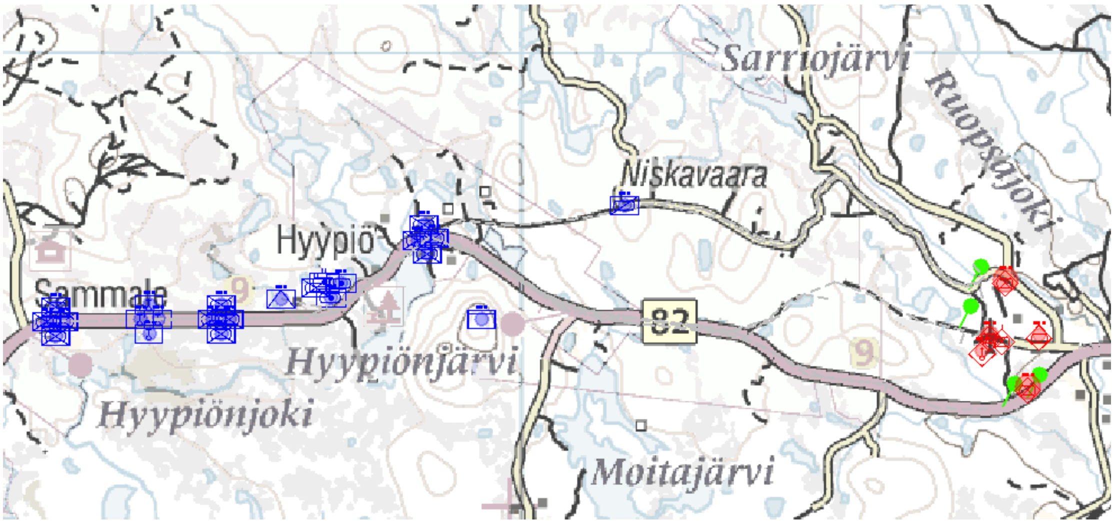


Figure 4.3.4 Starting situation of the war game

The models were easy to use in a battalion level scenario. The differences between alternatives could be analyzed by using the indirect fire model. The infantry fight in the forest seems to work properly, also. As earlier, the three days available in the workshop was not to analyze tactical alternatives, such as Red gaming or a proper probabilistic approach.

Further work could include the validation of the calculated results in the field and with other simulation tools.

4.3.3. Example of the implementation process of the models using tactical simulator “Sandis”.

The computational models were implemented in the Sandis software, which also features other models and solutions that are beyond the scope of this dissertation. The modeling of the Sandis tool emerged from the expressed needs of the Defense Forces. During planning, an almost permanent task is the comparison of different alternatives, using techniques such as cost effect analysis. The development of Sandis started from an analysis of the simulation tool requirements and of the combat environment in which the tool was intended to be used. This preliminary analysis was in certain instances performed with inadequate resources, which gave rise to difficulties in the succeeding phases. After the question and environment were clear, the models available were studied and the need for independent analysis was discussed. During this phase, earlier tools and models were used and the first mathematical models implemented using Matlab or spreadsheet tools.

Software engineering started in 2005, when conscript scientist Teemu Murtola programmed the first Matlab version, where all Blue and Red unit strengths were calculated against all Red and Blue strengths using the method described by (Kangas & Lappi, An Example of Markovian Combat Modeling, 2004). In this way the fight between two probability distributions was tested and found to be feasible for use in a simulation tool.

With the stochastic model initially coded by Teemu Murtola, the probability of a single entity getting hit in a platoon level unit is needed for formula (3.4). The combat losses inflicted on a platoon or squad by another shooting platoon or squad with infantry weapons were studied experimentally by the Finnish Defence Forces during the 1950s (Keinonen, 1954). As forest conditions and bullets have not changed since that time, Lappi and Pottonen [P6 2006] created the necessary parameters for the model from the data on the test shootings from the 1950s.

In order to estimate the accuracy of the old data, Lappi, Mäki & Vulli [P7 2008] tested the results by using live and simulated fire and compared them to the other tests with simulators. The test data was in good compliance with earlier studies. Because reasonable parameters were available, the computational method could be used. The time step was selected to be one minute and platoon size units can be studied for direct fire combat analysis.

The Sandis tool and the models in it were developed using a feedback cycle, in which the needs of the customer, the necessary model resolution and presentation of the results were repeated. The models and accuracy of the results evolved during the test process. The parameters usually improve after modeling during the years when the model is used.

In the Sandis work, the software engineering starts with first models. The programmed draft version of the software model decreased the time needed for testing and the preliminary methods give results for the customers, thus ensuring that the code fits the most important customer requirements. During the final software phase, the model and tool are usually tested and validated.

After the models are completed and software engineering done, the research questions can be studied using a war gaming procedure. Since part of the war gaming has been done already in the testing phase, work on real analysis can begin sooner. During the war gaming, the selected scenarios are simulated in order to compare alternatives. The relative difference is used for decision analysis. A procedure for using Sandis results was published by (Kangaspunta, Lappi, Liesiö, & Salo, 2008) and use of the models in a specific new software and simulation by (Laitinen & Lappi, 2008). Another public study of Sandis is the 3rd international Sandis workshop proceedings (Hämäläinen, Lappi, & Åkesson, 3rd International Sandis Workshop, 2009). A non-military simulation was made in IDFW18 (Heath, Dolk, Lappi, Sheldon, & Yu, 2009).

An example of modeling and medical model development is briefly described in order to show the time needed for model upgrades of the Sandis tool.

The created platoon level medical evacuation model was programmed as a part of the Sandis software in Summer 2006. The model and Sandis software were presented to Medical General Pentti Kuronen in January 2007. After the presentation, further analysis was required by General Kuronen. Mr. Kari Stenius from SOTLK became the contact person between the PVTT modeling and software team and the military medical establishment. The needs were discussed during a five-day simulation exercise in February 2007. The first computational model was created and the software project plan was ready in March 2007. Software engineering started in June after a one-week military exercise for parameter estimation. During the exercise, the details were discussed and the final version of the mathematical model written for software engineering. Software engineering was performed by Sami Mäki during the Summer 2007 and also by Santtu Pajukanta in August 2007. A presentation of Sandis with the new model was held for the military medical establishment in September 2007 and the results were published at the 2nd Nordic Military Operation Analysis Symposium in November 2008 [P4].

In general, as in the medical example, a half-year process is needed to create a new sub-model in the Sandis or similar tool. Usually, the steps start from the needs of the customer, which can be for example purchasing or planning military organization. This input is process time t=0.

1) Modeling phase starts; after preliminary study there is a second discussion with the customer (t= 0-1 months)
2) Parameter evaluation at least for modeling purposes (t = 0-1 months…years)
3) Test coding with Matlab or Excel (t=1-2 months)
4) Programming as a part of Sandis (t=3-5 months)
5) Verification of software and test use (5-6 months)
6) Validating parameter data and model with new customer needs during the usage phase (6 months…years)

Parameter estimation is a never-ending process, as weapon systems and tactics develop all the time. The models also need to be upgraded during the years of use. For example, the current artillery model [P5] has evolved with three different steps. There are many topics for future research to improve different models in the September 09 version of Sandis. So far the immediate needs of PVTT's customers have been selected to the top of the to-do list.

5. DISCUSSION

Simulation software needs mathematical models. The models presented in this thesis are useful for three reasons. They can be programmed as a part of simulation software [P1], there are ways to obtain parameters for them [P5, P6, P7] and although the validation process is not complete, they seem to give reasonable and useful results.

The first requirement, usability in software, is proved with the existence of the Sandis tool and Laitinen's and Kaasinen's works (Laitinen & Lappi, 2008), (Lappi & Kaasinen, Genetic optimization of tactical parameters in Sandis Combat simulator, 2008).

There are preliminary parameters for a platoon size firefight. They are based on the literature and field tests. The medical evacuation simulation does not currently have the best parameters, but even with preliminary parameters it gives a better understanding of the combat effectiveness of different units and the differences between different medical evacuation alternatives. Data farming could be used in order to see whether differences in the parameters cause significant differences in the results.

For the indirect fire model [P5], good parameters have been obtained and the field test partly validated the model and used parameters of the indirect fire model [P7] [P8].

In the published situations, the software seems to give good enough results for comparative analysis (Hämäläinen, Lappi, & Åkesson, 3rd International Sandis Workshop, 2009). In the comparative analysis, the research question and the parameters and the model for the question should be accurate and the other parts of the battlefield good enough to provide a reasonable background for comparative cases.

The mathematical models seem to work properly with the Sandis tool and the models have been used in the analysis of tactical scenarios. But there are numerous problems with the use of models and Sandis software: parameters, role of game players, the long and labor-intensive time needed for analysis and the software engineering. There is a need for further studies, such as on models for urban environments, vehicle model parameter testing and improvements concerning the terrain effects of indirect fire.

The parameters for the models are still partly inaccurate; for example, the parameters for the medical treatment model are still the first estimates used in the September 2009 version of Sandis. All new equipment must have their parameters, so constant work is required to update the parameter files; this work has just started. Parameter management can be performed with Luomu software (Hämäläinen, Hierarchical Parameter Structures for Military Operational Analysis, 2008).

The role of the game players is essential for the results. If the forces are not used in a reasonable way and invalid tactics are employed, the results from the computational models can be badly biased even in comparative analysis. Thus, a log of user actions is an essential part of the use of the models and any tactical software.
The time needed for analysis is rather long, and includes the work of the simulating team. The picture from Dr. Åkesson (Fig. 5.1) shows the time and labor needed in Sandis scenarios compared to real time when using platoon level units as the smallest entities.

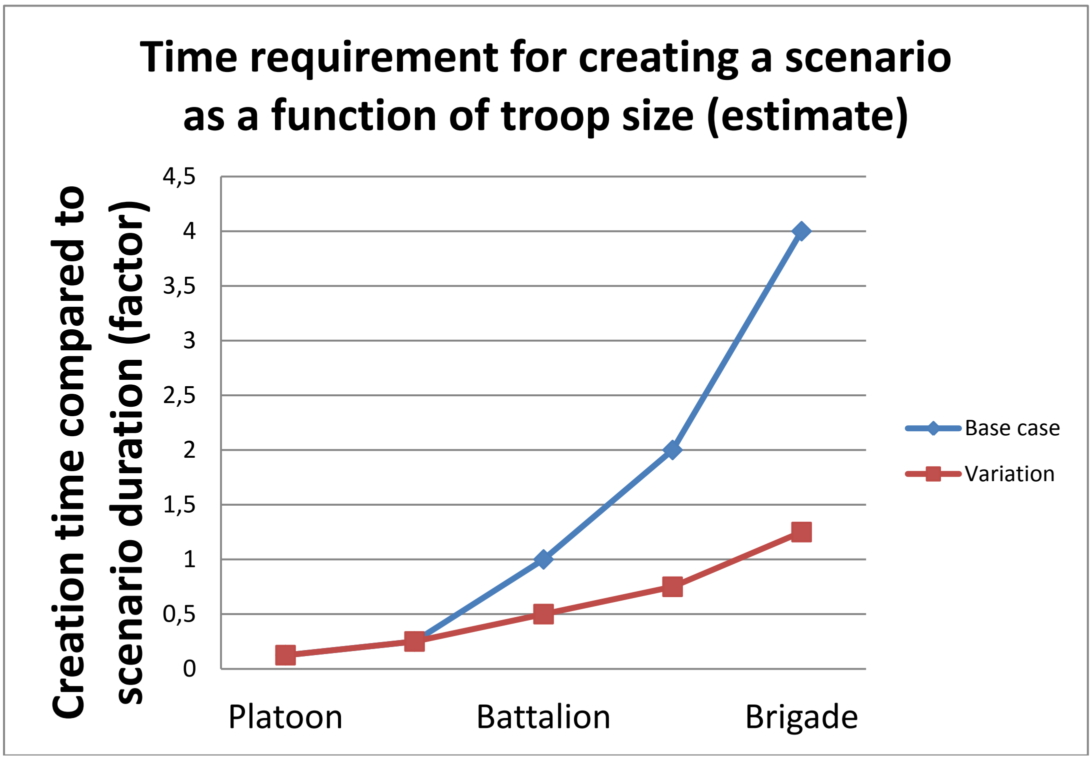


Figure 5.1 Time needed for Sandis analysis. The value of 1 for a battalion indicates that a one-day battle will take one day to be simulated by Sandis. The variations (recalculation of the same basic scenario with some differences) for comparative analysis take half of the time. (Figure by Dr. Bernt Åkesson.)

The time-consuming gaming part of the simulation process is a clear limitation in the use of tactical simulators like Sandis. At this stage, the presented mathematical methods are numerically fast enough for the simulation process, as most of the time is used for moving the units on the map according to the tactical manuscript.

War gaming is labor intensive and needs both tactical and engineering experts during the procedure. For example, three alternatives for a brigade level battle lasting one week take about 12 man-weeks of work.

In this thesis, a computational model for a platoon or squad as the smallest entity was created. In future studies, there will be a need for parameters and gaming procedures for different environments. Good enough versions of some essential models are still required, e.g. urban terrain models and, for example, some parameters for vehicle duels.

Some of this future work can be achieved using a two-stage approach, where for example tank duels are first simulated with FLAMES or other platform entity level simulations and the results are taken into the Sandis simulation. If the data from more detailed simulations is not available before Sandis simulations, the needed two-stage simulation time can be much longer than the estimates in Figure 5.1.

Practical work at headquarters and in the research community requires recorded results from other simulators and databanks containing many calculated scenarios and ready to use examples to be used as starting points for new users and in time-sensitive situations. The library of different scenarios and parameter tables are to be included in further work.

Although most models are working properly in Sandis, software engineering is also one of the future tasks. A master's thesis by Juho Rutila suggests a new architecture for Sandis (Rutila, 2009), but the new version of Sandis had not been programmed yet by summer of 2010. Furthermore, many subprograms and models have not been optimized with software engineering.

On the other hand, the computational models have been used to calculate results for different scenarios. These computational models provide a new tool for the Finnish military operation analysis environment. The models can be used in tactical analysis and operational planning, and it is hoped that they will also serve as a tool for teaching tactics and tactical thinking.

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Publication I

Esa Lappi. Sandis Military Operation Analysis Tool. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

In e-proceedings under subdirectory “Session 4”.

I

Sandis Military Operation Analysis Tool

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Abstract

Sandis is an operation analysis tool which has been created in Finnish Defence Forces Technical Research Centre (PVTT) since the year 2002 and with co-operation with FFI since 2006. It can be used for cost-effect and tactical analysis from platoon to brigade level and is used in PVTT.

The man in the loop is responsible for tactical decisions and Sandis calculates combat losses, ammunition consumption and medical evacuation process.

Sandis is based on state machines, Markovian combat modelling and has fault tree analysis for combat operation success probability calculations. The results from Sandis are the strength distributions of the units and operation success probability as well as a killer –victim –scoreboard and medical situation average values.

Weapon models are based on peace-time field tests and literature.

1. Introduction

Sandis is a military operational analysis tool for comparative analysis. The work to create an operational analysis tool started in 2002 in Finnish Defense Forces Technical Research Center (PVTT) and Sandis has been used since 2005 for combat analysis, from platoon versus platoon up to brigade versus brigade level. Norwegian FFI has been involved with Sandis since 2006, and the radio communication and EW model is the "CalcRadio" from FFI.

The input of the tool is 1) weapon and communication characteristics, 2) units and their weapons, 3) fault logic for units and operation success, 4) map and 5) user actions for units in company or platoon level.

The output is 1) the operation success probability [13] and for each minute time step, 2) probability for each unit been at state beaten, 3) unit strength distributions, 4) average combat losses and the killer-victim scoreboard, 5) ammunition consumption, 6) radio network availability and 7) medical evacuation logistics and treatment capacity analysis.

Sandis has been used for scenario-based comparative analysis, in which a scenario with red and blue forces has been calculated with different alternatives, for example an attack with or without electronic warfare support or cargo ammunitions for artillery. The differences, not the absolute values of results, have been studied for cost-effect analysis or the analysis of different operation alternatives.

2. Model description

2.1 Overall calculation principles

Sandis uses Markovian combat modeling [1] and is a state machine -based operation analysis tool. The strengths of the units are probability distributions and combat losses are modeled as loss probabilities which cause state transitions of the individual soldiers. Thus the results are distributions of strengths, not a single value.

If for example an artillery fire causes average losses of 5% to a 10 soldiers unit, the result in Sandis is a binomial distribution of unit strengths with parameters p=95% and n=10 as in table 1.

Unit strength	0	1	2	3	4	5	6	7	8	9	10
Probability	0.000%	0.000%	0.000%	0.000%	0.000%	0.006%	0.096%	1.048%	7.463%	31.51%	59.87%

Table 1. Unit strength distribution for 10 soldiers after 5% average casualties.

When two platoons have a duel, all combinations (30 versus 30, 30 versus 29 etc.) are calculated and weighted with their probabilities to form the strength distributions for the next time step.

The platoon level combatants have their own state machine shown in figure 1 and all combatants with the same state are treated equally.

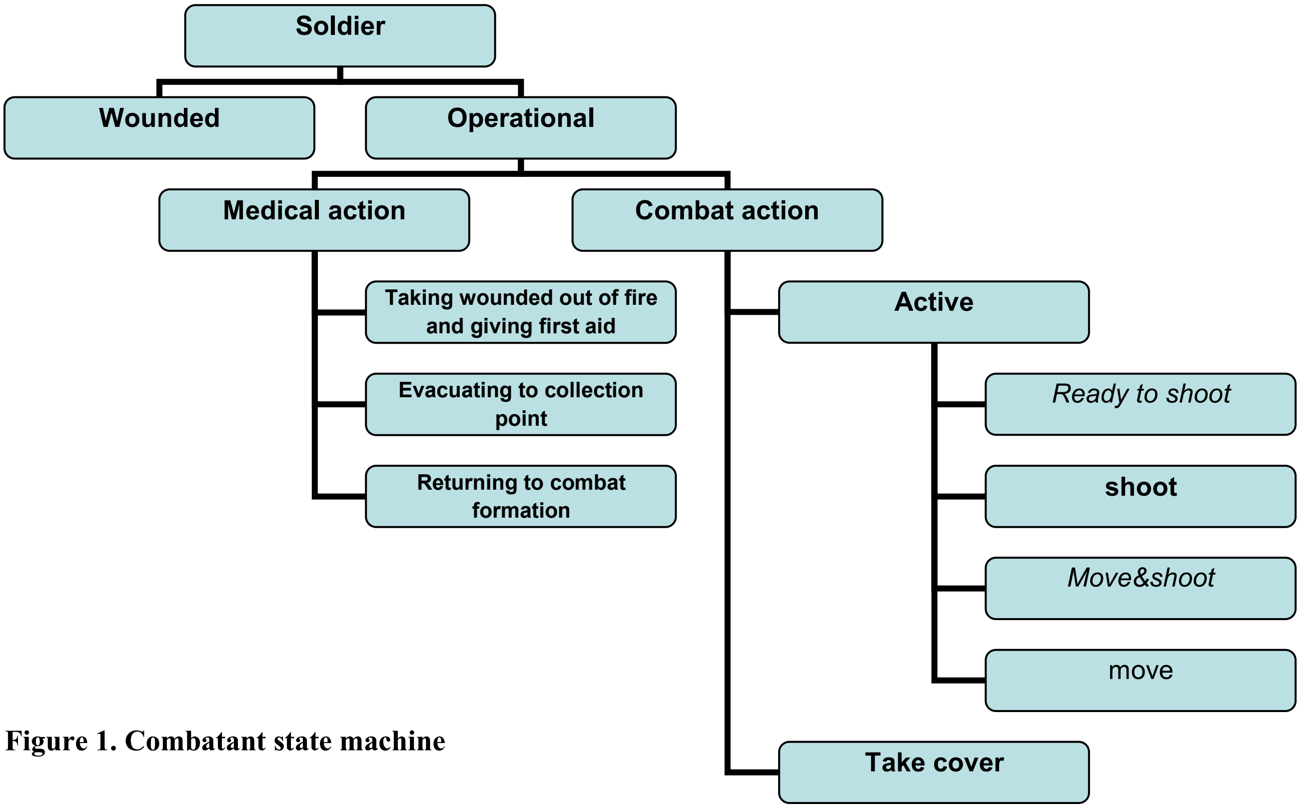

Figure 1. Combatant state machine

The platoons can be equipped with radios, jamming devices and "weapons", which have different categories: infantry weapons, weapon system, truck, light tank (or infantry fighting vehicle) and main battle tank. Weapon system category is for e.g. mortars and guns, truck for unarmored vehicles and tank categories for armored vehicles.

For each direct fire weapon a distance-based hit probability is given for each target category, as well as the probability of kill if a hit occurs. The hit probabilities for each weapon depend also on the states of the shooter and the target, the terrain and the fortification level of the units.

The units also have communication states, and there is an option for action states (attack, defend, move etc.). These are used for unit action analysis.

2.2. Infantry light weapon model

In the infantry light weapon model two models are considered: aimed fire and area fire. The basic hit probabilities are calculated for a shot as a function of distance, terrain, fortification and unit state. [2] For each light infantry weapon a hit probability is calculated using formula

$$P(\text{hit}|\text{n shots}) = 1 - (1 - P(\text{hit}|\text{ one shot}))^n.$$

The area fire hit probability per shot is vulnerable area divided by the total area. For a single soldier this can be for example 0.2 m^2 vulnerable area / (3m height times 200m width).

The aimed fire hit probability is given as a function of distance for each weapon and each target action state. The number of shots for each target is distributed between the action states so that the firing enemy soldiers are the primary targets with a larger number of shots than the soldiers in *take cover* –state.

To give a simplified example, let us consider a case where a group of 30 soldiers is the target of 600 bullets. The soldiers are divided to states *shooting* (10 soldiers) and *take cover* (20 soldiers). Then, for example, 500 bullets are aimed at the shooters (50 each) and 100 for those taking cover (5 each). Let the single shot hit probabilities be p(hit|target a shooter) = 1% and p(hit|target takes cover) = 0,1%.

$P(\text{a shooter gets a hit}) = 1 - (1 - P(\text{target a shooter}))^n = 1 - (1 - 0.01))^{50} = 39{,}5\%$

$P(\text{hit in a state take cover}) = 1 - (1 - P(\text{hit}|\text{ one shot}))^n = 1 - (1 - 0.001))^5 = 0{,}5\%$.

So the shooters have 39,5% losses and binomial distribution with expected value of 6 and those who take cover suffer insignificant losses. The losses of the platoon will be 4/30 = 13%.

2.3 Indirect fire model

In the indirect fire model ammunition characteristics, weapon and fire control deviations and the target's positions are considered. The first part of the deviation is due to the targeting and the second from the weapon-ammunition combination used. The fragment hit probability and pressure damage probability are calculated as function of distance from the hit point of the ammunition. The probability of a fragment hit hit is the product P(ammunition hitting point x) * P(target at point y) * P(hit by fragment| target in y and hit point x) (Figure 2).

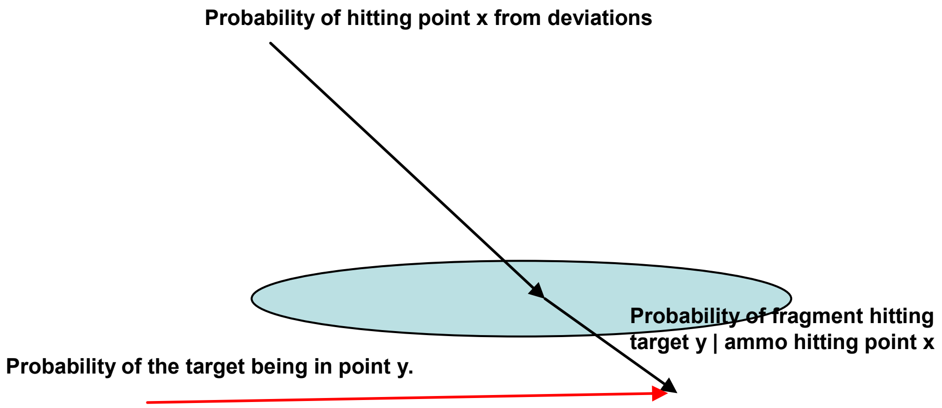

Figure 2 Artillery model

The fragment hit model uses the fragment distribution from [3]. The pressure model is based on the TNT equivalent from chemical engineering [4]. The target platoon is divided into a group of target points, and an adaptive integration method is used to calculate hit probabilities inside the ammunitions effective radius. The model has been validated for mortars in field tests [5].

2.4 The soldier state transitions and medical model.

The state transitions from operational to wounded result directly from the casualty models. Then for each wounded soldier n_1 soldiers are transferred to state *give first aid* for a time t_1. Then n_2 soldiers assist to evacuate the wounded to the collection point with time t_2, and then the evacuation team returns to the fighting formation in average time t_3. Parameter values $n_1=1$, $t_1=5$ min, $n_2=2$, $t_2=30$ min, and $t_3=20$min were determined during one of the field exercise studies by major Jari Sormunen. [6] [7].

Soldiers under fire have to take cover. There is a rule of thumb from the Second World War: 50% casualties in a minute stop all combat action. [8] A partly linear and partly exponential model has been created to fit this rule and the risk of getting hit determines the percentage of soldiers taking cover. Another solution could be to calculate optimal state transitions by using genetic algorithms [9].

When the wounded reach the evacuation point, the medical evacuation model starts. The wounded are grouped in to four categories: minor wounds, mid-state wounds, major wounds and dead or hopeless.

Medical units are devided into “connection type” evacuation units and treatment units. The treatment units are arranged in a hierarchy, where patients are gradually transported from company-level treatment units to battalion-level and so forth. Each have three slots for the four classes of combat casualties: awaiting treatment, in treatment and awaiting transport to the next level treatment unit. The medical unit parameters are the number of patients in each category it can give treatment to and the respective average treatment times. A queue forms if the number of wounded exceeds the treatment capacity or the capacity of the evacuation unit transporting the wounded to the next level of treatment.

Evacuation connections have parameters for transporting time and the number of wounded the connection can transfer.

There are state transition parameters for wounds getting worse in absence of treatment during the evacuation and treatment process. Thus for example the difference in number of dead can be compared with different evacuation alternatives.

2.5 EW and communication –model

The communications and usability of EW are calculated with Norwegian (FFI) CalcRadio [10]. Using CalcRadio, the state of each unit's VHF communications is then calculated:

State 1. Unit has communications to supporting artillery and superiors as well as between the platoons of the unit.

State 2. Unit loses

a) command connections or

b) supporting artillery

State 3. Unit has no communications between the platoons.

The effect of the communication state on the combat is decided by the operator, i.e. "the man in the loop". In state 2a the unit does not react to enemy action not spotted by the unit, in 2b there is a delay to supporting artillery and mechanized units move with extremely low speed in state 3, for example.

3. Software implementation

3.1 Subprograms

Sandis can use the separate parameter management tool Luomu by Insta Defsec. The parameters and their sources are stored in the Luomu database. [11]

Another subprogram is the troops editor for creating the military organizations used in the simulation. Units and their weapons and equipment are stored in xml format to be used in the wargames..

The software component for the actual combat gaming is called the "map" program. The units are placed on a map, their movement and use of firepower are given as input. Combat losses, medical evacuation effectiveness, killer-victim scoreboard, use of ammunition and state of the communication connections are produced as the output.

3.2 Creating a scenario and the gaming

The use of Sandis requires information about the probable combat situation. The blue units and blue battle plan and the red units and the red plan are considered as a basis for the analysis. The goals of the operation are considered, and the units' fault logics are set to follow the operation success logic. The unit movements and the use of weapon systems must be considered for each company. The overall combat decisions form a background for analysis and can be later revisited when revising the feedback from the simulated results.

The unit losses cause automatic action in the platoon level, but other combat actions require the man in the loop. For example, one could first simulate only the first 30 minutes, and then study the results before continuing. If the actions of some unit are not realistic, the simulation is backed up to the point where the unrealistic behavior emerges, the unit's actions corrected and the simulation continued again. The gaming is a sequence of simulation, results analysis and readjustments.

The gaming is repeated with different actions or parameters to perform comparative analysis.

3.3 The analysis of the results

The fastest values gained for comparative analysis are the overall success probabilities of the operation and combat losses. The results can be studied in detail for each time step (one minute) and the overall scenario results. The result from a simulation coud be, for example, that with the support of weapon system A the enemy losses were 4,2%, our own losses 2,1% and the operation success probability 62%, but without system A enemy losses were 3,4%, our own losses 3,1% and the operation success probability 23%. Usually the difference, not the individual results themselves, is used for further analysis.

The results can be exported to a spreadsheet editor for further analysis. The data contains detailed information about all losses: the shooting platoon, the shooting weapon system, the target platoon and the target type. The data shows which weapon systems caused the losses (e.g. Mortars 20%, artillery 62%, direct fire from tanks 11%, infantry light weapons 7%). Evacuation and ammunition consumption are also considered.

The results can also be used for operation planning. We have two alternatives for operation calculated with Sandis. The results are used to help the decision maker to decide between the options and improvements to the plan for, for example, the use of supporting artillery between different targets or the allocation of resources for medical evacuation.

3.4. Some cases

There are two different types of cost effect analysis. In dynamic cases we want to see the effects of the studied weapon systems to the whole combat environment and the operation success probabilities. In static cases we just compare different shooter target alternatives with different weapon systems.

Sandis has been used in dynamic, brigade level combat analysis since 2006. For example, there have been defensive cases with a battalion versus a brigade, a counter-attack with a mechanized battle group using different kinds of artillery and EW configurations for cost effect analysis. An example has been the MATINE project [12], where Sandis was used as a battle simulator in dynamic analysis.

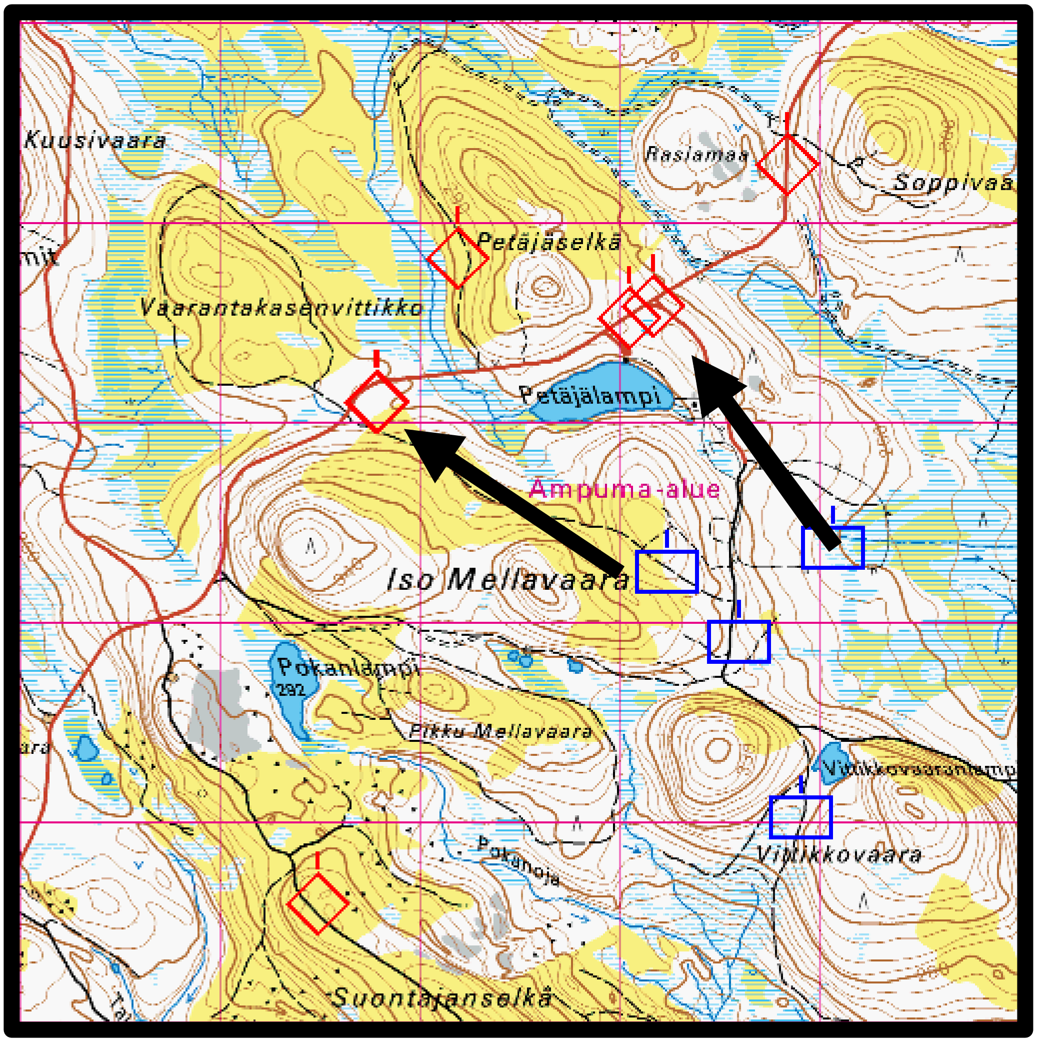

Figure 3 Example of dynamic calculation used in portfolio analysis [12].

An example of static calculation is indirect fire. The predicted losses in a target spread in a 500m x 700m area are shown in Figure . The pie charts show the average survival probabilities in the target area. Detailed distributions of strengths are also calculated.

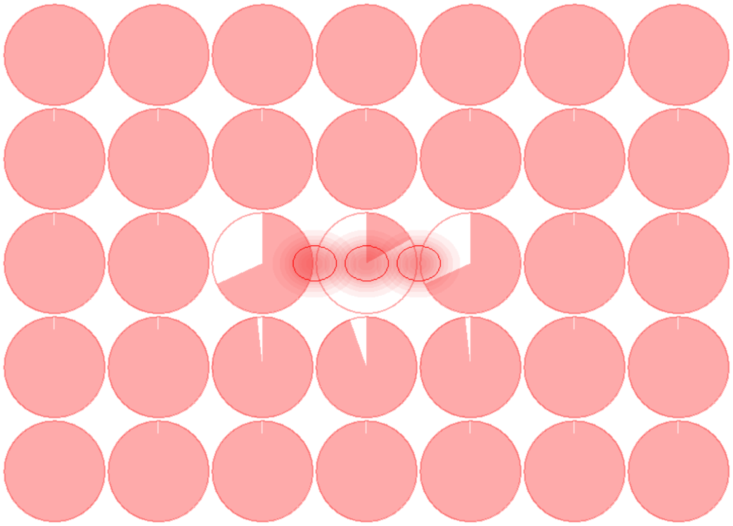

Figure 4 A study on the effects of artillery fire to a 700m x 500m target. A full red circle is at 100% strength.

4. Conclusions

There is a novel operation analysis tool available for comparative analysis. The software is still under construction and has to date been used only as a tool for researchers. In spite of its limitations, Sandis has been used by the Finnish Defense Forces since 2006. It has been useful in comparative analysis for peacetime acquisition problems. It has also been tested to support the military training of staff officers. The first experiences are promising and Sandis will be used in military exercises in the future.

The use of Sandis for operational planning in brigade headquarters is unclear. There is also an ongoing research work on the topic at the National Defense University 2008-2009 Staff officers' course by captain Puotiainen.

In conclusion, Sandis appears a promising tool for brigade level comparative analysis.

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Publication II

Risto Bruun and Esa Lappi. A Weapon Selective Predictor-Corrector Method for Combat Simulations. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008

In e-proceedings under subdirectory “Session 1B”.

II

A Weapon-Selective Predictor-Corrector Method for Combat Simulations

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Abstract

Usually combat simulations are based on the classical Euler method. Better predictor-corrector methods such as Heun's method are not usually considered in combat simulations. The suggested method uses Heun's method augmented with weapon specific weighting of the predictor and corrector steps to solve the differential equations in simulating combat. The method can be implemented in the Sandis combat simulator [1][2].

Sandis calculates using a time step of one minute, while in actual combat changes can take place in just a few seconds. Decreasing the time step increases the amount of time to run the simulation, while many models do not scale to arbitrarily short time steps or the available test data for parameters has been collected on a much coarser time resolution. The presented predictor-corrector method can model sub- time step phenomena without decreasing the time step, being easy to implement in existing simulators such as Sandis.

As an example a test case involving mortar fire is considered. The AMOS advanced mortar system and a traditional mortar company were compared in a simulation using Sandis. The resulting expected casualty rates after a one minute strike in open terrain are presented in the table below.

Calculation Method	AMOS	Mortar
Euler	28 %	28 %
Weapon-selective Heun	27 %	25 %

Keywords

Combat models, Sandis, differential equations, step size.

1. Introduction

Combat simulation can be considered as numerically solving an ordinary differential equation or, to be more precise, a system of differential equations. In combat simulations time is usually the independent variable, and we want to calculate combat losses and the end position of the troops, which are the dependent variables. The parameters are, for example, hit probabilities as a function of distance, terrain, weather, the amount of losses per hit or probability of a kill if there is a hit, and lots of technical parameters for the weapons and vehicles in the combat model. As a result we have a system of differential equations with lots of variables and parameters.

The initial values are the locations of the military units and their missions and tactics used in the battle. The solution shows what happens during the simulated combat and what the end situation is. When different tactical manoeuvres, the map and use of different weapon combinations are considered, an analytical solution of a combat situation is practically impossible as is a general solution of such system of differential equations. However, a simulated solution or a realisation of the situation becomes available. The tactics and optimal use and configuration of different weapon systems can use “man in the loop” -methods, in which a human player makes some of the judgements during the simulation or changes the original simulation using information from the previous events of the ongoing simulation.

During the simulation, the lines of sight, speeds, locations, use of weapon systems etc. are calculated for a definite situation. The initial situation starts to change as a function of time. After every time step we have a new situation, which is the beginning of the next step. The combat losses, movements, locations etc. are changed and the next time step is calculated using the new values of the combat variables. If the differences between actions of the troops, their locations and other combat variables are little, the error with constant variables during the time step is not a problem, but if the combat variables change rapidly and the values at the beginning of the time step differ significantly from those at the starting point, the simulated values don’t fit reality. Mathematically speaking, the Euler method can have a significant error.

Metteri [10] and Lempiäinen [9] wrote about the state of art in Finnish combat simulation environment and when the simulation methods were studied, mathematically speaking only Euler method is used. Thus there exists a need for improvements.

2. Numerical Methods for Ordinary Differential equations

2.1. Basic formulas

Numerous methods exist for solving differential equations numerically. The basic methods, Euler, Heun and Runge-Kutta and their error formulas can be found in almost all mathematical textbooks with differential equations. [3, p 942-950][4][5]. For brevity, only the principles and basic error analysis is shown here.

We want to find the function $y(t)$, when the differential equation

$$\frac{dy}{dt} = f(y,t) \tag{1}$$

and the initial value $y(t_0)$ are given.

In all methods, the calculation starts with the initial value, and the differences are then calculated using equation (1) first at the point $(y(t_0),t_0)$ and then at the next point, which will be the previous point + the differences. The methods have different ways to estimate the differences in y during the time step Δt. The function y can be multi-valued, in which case $y(t_0)$ is a vector.

In Euler method the difference Δy is calculated directly from equation (1):

$$\frac{dy}{dt} = f(y,t) \approx \frac{\Delta y}{\Delta t} \Leftrightarrow \Delta y \approx f(y,t)\cdot\Delta t \tag{2}$$

and the formula for the subsequent values $y_{n+1} = y(t_{n+1}) = y(t_n+\Delta t)$ is

$$y_{n+1} = y_n + \Delta t \cdot f(y_n, t_n). \tag{3}$$

The Heun's method (improved Euler) corrects the results using a predictor value:

$$y^*_{n+1} = y_n + \Delta t \cdot f(y_n, t_n). \tag{4a}$$

$$y_{n+1} = y_n + \tfrac{1}{2} \Delta t \cdot [\, f(y_n, t_n) + f(y^*_{n+1}, t_{n+1})] \tag{4b}$$

The classical fourth order Runge-Kutta (RK4) method uses 4 values to calculate each step. In the formula the first value is calculated as with Euler, but then other values are used. RK4 calculates 4 estimates for the differences of y during one time step, and calculates a weighted average of them as the final step:

$k_1 = \Delta t \cdot f(y_n, t_n)$	*Euler step*	*(5a)*
$k_2 = \Delta t \cdot f(y_n + \tfrac{1}{2} k_1, t_n + \tfrac{1}{2} \Delta t)$	*Step to midpoint*	*(5b)*
$k_3 = \Delta t \cdot f(y_n + \tfrac{1}{2} k_2, t_n + \tfrac{1}{2} \Delta t)$	*Second midpoint*	*(5c)*
$k_4 = \Delta t \cdot f(y_n + k_3, t_n + \Delta t)$	*Step using endpoint*	*(5d)*
$y_{n+1} = y_n + \tfrac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)$	*Final step*	*(5e)*

RK4 and other Runge-Kutta methods are widely used in mathematics and engineering.

2.2. Time steps and error analysis

The error of the basic Euler method is of the first order, Heun's of the second order, and RK4 of the fourth order. The error formula includes the assumption that the function *f* is differentiable and the values of the second or fourth derivative do not change rapidly.

If that condition holds, the error can be estimated using simulated values. The simulation is calculated with time step $2\Delta t$ with a result y^{**} and Δt with a result y^{*}. When the step size doubles, the error becomes approximately 16 times larger for RK4 and 4 times larger for Heun's method. Thus we have simple error formulas for both RK4 (6a) and Heun's method (6b).

$$\varepsilon \approx \tfrac{1}{15}(y^{*} - y^{**}) \tag{6a}$$

$$\varepsilon \approx \tfrac{1}{3}(y^{*} - y^{**}) \tag{6b}$$

If we calculate these two values and the approximate error is less than our error tolerance, we have a short enough time step. Because shorter time steps lead to longer simulation times, it is desirable to keep the time step as long as possible. An optimal step size yields the desired accuracy with minimal computing time. Modern programmatic solvers use adaptive methods to optimise the step size during the calculation. [3, p. 959-951]

2.3 The special features of combat simulation

When a combat simulation program has been written, the mathematical idea of the simulation is in principle rather simple. All knowledge of the units and their tactics and weapons are included in the function *f* and we just solve a differential equation (1) numerically. The simulation and all combat effects develop step be step by the rules defined in the simulation code. Thus the use of more accurate mathematical methods should not be a problem.

In actual combat, the action of the unit can change in one or two seconds, or it might take hours depending on the unit size and equipment. For example, when an ambushing unit starts to shoot at the enemy, the situation changes and so do all the values of function *f* in the combat simulation. Thus the function *f* is not differentiable at those situations and basic error analysis for differential equations cannot be applied. Thus the traditional methods and their step size controls are not directly usable.

To avoid this problem, we present a modified Heun's method with weapon selective weights for the start- and end point values for each time step. The formula for the weapon selective predictor corrector method is:

$$y^{*}_{n+1} = y_n + \Delta t \cdot f(y_n, t_n). \tag{7a}$$

$$y_{n+1} = y_n + \Delta t \cdot [\, w_s \; fi(y_n, t_n) + w_e \, fi(y^{*}_{n+1}, t_{n+1})], \tag{7b}$$

where w_s is the weight of starting point of the time step and w_e the weight of the end point of the time step; $w_s + w_e = 1$. Weights are calculated using field tests and other simulations.

If e.g. an artillery unit fires grenades so that all the ammunition hits the target at the starting point of the time step, all the combat damage is calculated using the state of the troops at the starting point of the time step: $w_s = 1$ and $w_e = 0$. If the same amount of ammunition hits the target during the whole time step, the troops can take cover during the time step. This can be incorporated into the integration algorithm by using weapon selective weights at both ends of the time step, corresponding to the distribution of the weapon's effects along the time step.

3. Example

Consider a simulation comparing an advanced mortar system (AMOS) company and a traditional mortar company, both firing 96 120mm grenades at an infantry company. We wish to calculate the loss probability (shaded area in Figure 1). The "slope" of the loss probability p is a function of the states of the model, which are known only at the beginning of the time step ($t=t_1$).

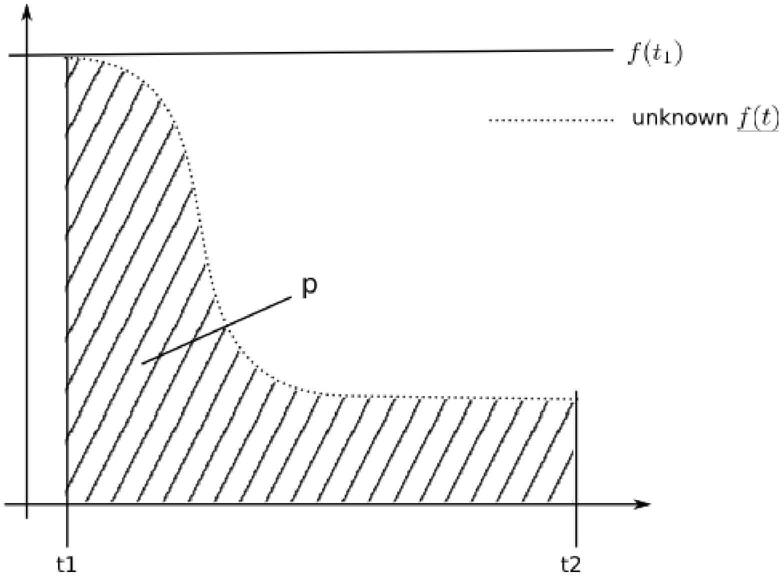

Figure 1

First, we execute the calculation using the values (state and strength distributions of the troops) at the beginning of the time step (forward Euler, Figure 1). Since Euler's method does not take into account the change in the target function during the time step, there is a significant error (shown in red in Figure 2).

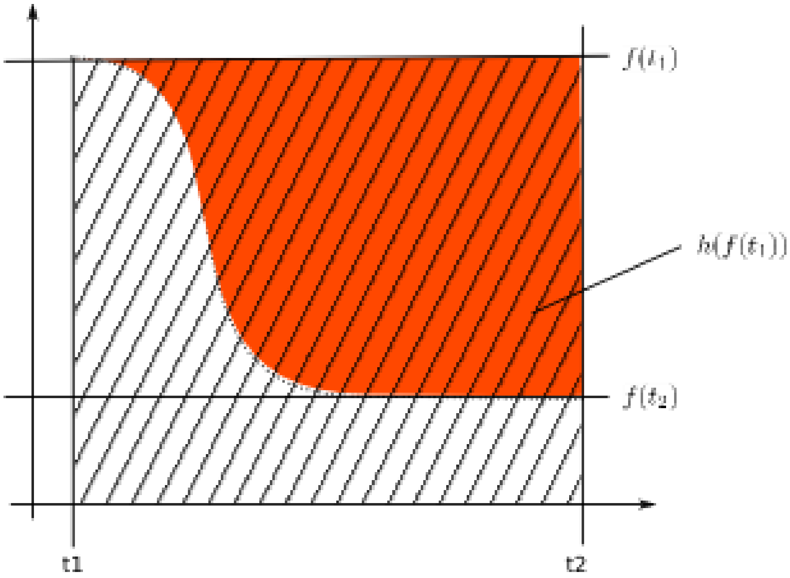

Figure 2 Calculation of the prediction value with Euler's method

This is the "predictor step", resulting in a prediction of the integration result and the resulting states. In the corrector step, the same calculation is repeated with the results of the prediction step as the starting values, or the "slope" of the predicted loss probability at $t=t_2$. This yields a corrector result, i.e. the effects of the weapon systems as if at the end of the time step.

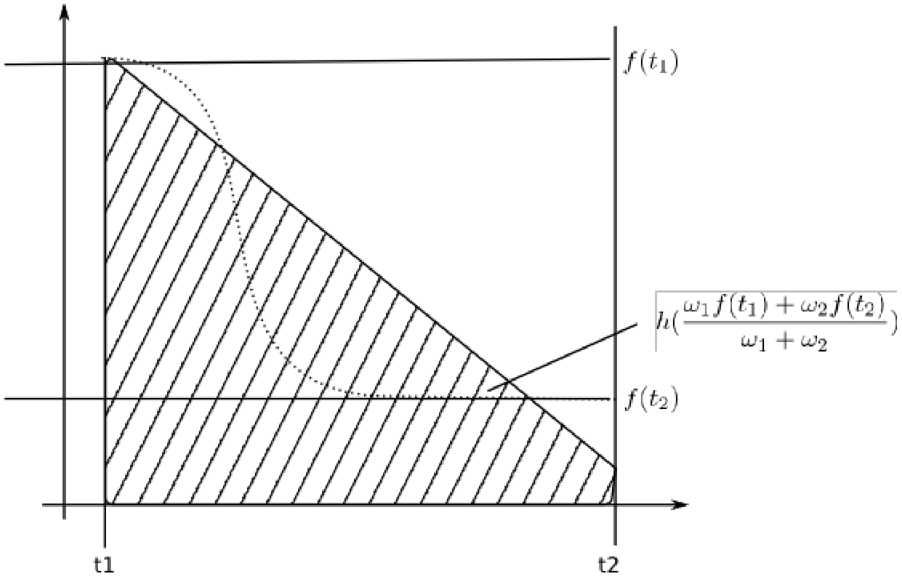

Figure 3 Weighted average of the predictor and corrector values

Finally, we obtain the final result by using the weapon selective parameters as the weights in the Heun's method formula (7b) for each weapon, adding up the resulting effects of different weapons and updating the model states. The traditional mortar fire is (in this example) evenly distributed along the one minute strike, while first of the grenades fired by the AMOS company hit the target simultaneously at the beginning of the time step. This sub-time step behavior is incorporated in our model by each weapon systems parameters w_s and w_e. Table 1 shows the (dummy) parameters used for this example and the simulation results in Sandis.

Weapon system	w_s	w_e	$h\,f(t_1)$	$hf(t_2)$	$h(w_s\,f(t1) + w_e(f(t2))$
AMOS	0.8	0.2	0.285	0.205	0.269
Mortar	0.5	0.5	0.285	0.205	0.245

Table 1

Although this example only shows the calculation of one loss probability, calculation of the other parts of the simulation proceeds in exactly the same way.

4. Discussion

4.1 Decreasing the time step

Decreasing the time step would increase the time to run the simulation. The method presented herein roughly doubles the amount of calculations compared to using Euler. [1] With the same budget, the time step could, at most, be halved, which does not address the problem of e.g. the simulation of AMOS in our example. Also, required lengths of time steps vary, and taking the minimum would mean enormous amount of time steps. An adaptive time step length could be used to help with this.

4.1 Higher Order Methods

Higher order methods, such as the popular 4th order Runge-Kutta, require calculation of more points along the used interval, in effect more time steps. This would either require shortening the time step (see above) or averaging the result over several longer time steps, while our original problem are the weapon effects that take place inside a fraction of a time step. The discontinuity of the system thus discourages the use of higher order schemes with the same time step.

5. Future Work

Parameterization, namely finding the values for w_s and w_e in (7b), has to date been done in a straightforward manner by considering the timescale of the different weapon systems. However, not a lot of empirical data can be found about e.g. about how a platoon under indirect fire initially takes cover. This leaves the need for empirical data for parameterization and especially validation of the implicit assumption that the parameters are independent from time and of other weapon effects.

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[1] The method doubles the computation time asymptotically, as every time step is calculated twice. However, several computationally intensive parts of the calculations of a time step need not be calculated again in the corrector step, e.g. hit probabilities from shrapnel to troops in different states.

6. Acknowledgements

The authors wish to thank Bernt Åkesson and Kosti Jokinen for suggestions and improvements to the manuscript.

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Publication III

Esa Lappi. A Markov chain-based method to evaluate combat value of a platoon after battle casualties. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

A Markov chain based method to evaluate combat value of a platoon after battle casualties

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Abstract

A model to evaluate evacuation of wounded and its effect on military units battle value has been created. When the number of battle casualties (wounded and dead) is known, the evacuation model calculates the average number of soldiers, which are needed to give first aid to the wounded, to carry them to the collection point of the wounded and returning to the battle formation. Thus, during the time of evacuation process the effective battle value of the unit (platoon or company) is less than number of non-wounded soldiers and we have two strengths for each unit as function of time: nominal strength and effective strength.

The overall model was based on finite state machines and created by a Markov chain with state transition matrix of size 25 times 25. Because of the lack of battle loss and other parameter data, a simplified model was created and implemented in Sandis, a operational analysis software tool created in PVTTEIOS. The simplified model has also been used in cost-effectiveness analysis of different evacuation methods.

The model was created and tested during a company-level research project led by major Jari Sormunen from Army Academy.

Keywords: battle value, evacuation, wounded, combat models, Markov chain, finite stete machine, effective strength

1 Introduction

The battle casualties are mainly wounded and need first aid and to be evacuated. Thus the medical care and evacuation needs manpower, which is not available to the battle during the evacuation process and then the effective strength of the unit is not equal to the nominal strength.

The topic of this paper is a calculation model to estimate platoon level combat effectiveness as function of time and battle losses, when evacuation of wounded is considered as a part of military action. The model is based on discrete state machine analysis of the soldiers, and uses Markov chains and n-step transition probabilities. Two models have been created. In the first model number of states is 25 and the battle casualties are separated to dead and four levels of different injuries. The evacuation time and the personnel needed to evacuation process vary between the states. The second model is a simplified one with only one average type of wounded soldiers.

2 The combat environment

The combat environment of the analysis is infantry in battle. The analysis level is platoon and company level. When a soldier is wounded, the nearest comrade gets the injured out of fire and gives the first aid. Then medics continue medical care and platoons own soldiers carry the wounded to the collection point, from where the support platoon transports the wounded and the soldiers of the fighting platoon returning to the battle formation.

In Finnish tactics, separate platoons can be beyond roads in forest area, and evacuation of wounded starts by hand. The distance to the collection place of injured can vary from few dozens of meters to kilometres. Thus battle losses and evacuation times are varying a lot. In order to evaluate platoons combat effectiveness during a battle, a simulation model was created. The simulation model can be used for both effectiveness analyses of different evacuation and medical material and methods and as a part of larger battle simulations. The combat situation gives parameters for the model: battle loss rates, average evacuation times and time of returning from evacuation mission to fighting formation.

3 The Markov model

Observations showed the great importance of different evacuation plans and methods to combat effectiveness. In order to calculate the true battle values of the platoons, a Markov model of platoon was created. In the model each soldier has a discrete state.

As in all Markov type models, a result is a probability distribution. Probabilities of the states are usually in vector form: the first state's probability as first value, second as second etc. The probability vector $P(t)$ is a function of time. If we want to calculate probability distribution $P(t+\Delta t)$ after time period Δt, we need state transition matrix Pt, whose components $Pt(i,j)$ are the state transition probabilities between states i and j. Matrix multiplication

$$P(t+\Delta t) = Pt \cdot P(t) \tag{1}$$

gives directly the next probability distribution. If we let $\Delta t \to 0$, we end up with a system of stochastic differential equations. If state transition matrix *Pt* is constant, the system of differential equations is linear, and has analytic solution

$$P(t) = e^{At} P(t_0). \tag{2}$$

In the equation (2) matrix A is state transition matrix for the differential equation, which can be easily calculated from matrix *Pt*. [1, p.201]

If we consider step Δt, after n skips a probability distribution at the time

$$t = t_0 + n \cdot \Delta t \tag{3}$$

with the result

$$P(t) = Pt^n \cdot P(t_0) \tag{4}$$

In both cases, P(t) is easily calculated for any time interval t_b-t_a. If combat conditions and thus state transition matrix is changing during the time, we can simulate the results by using time or event stepping.

If we have the states and the state transition matrix for evacuation process of fighting platoon, we can calculate expected values of soldiers in each state as a function of time *t*.

4. Description of the developed model

The states of the intrododuced model for evacuation are:

1. Fighting soldier

2a. Injured (artillery weapons)
2b. Injured (bullets)

3. Knock out (not medical care needed, recovers automatically after a while)

4a Minor injure,
    4a1. at field,
    4a2. first aid,
    4a3. during evacuation,
    4a4. at collection point

4b Injure,

    - 4b1. at field,
    - 4b2. first aid,
    - 4b3. during evacuation,
    - 4b4. at collection point

4c Major injure,
    - 4c1. at field,
    - 4c2. first aid,
    - 4c3. during evacuation,
    - 4c4. at collection point

4d Serious injure,
    - 4d1. at field,
    - 4d2. first aid,
    - 4d3. during evacuation,
    - 4d4. at collection point

5. Dead

6 First aid personnel:
    - 6a. Soldier getting injured from fire
    - 6b. Soldier giving first aid to injured
    - 6c. Soldier carrying injured to collecting point
    - 6d. Soldier returning to battle formation

In the model, every soldier is in one of these discrete states. The corresponding state transitions depend on the combat situation. Probability of state transition from a soldier to either class of injured during time Δt is a parameter given by other calculations or observations. Transition probability from injured (artillery) or injured (bullet) to the four seriousness levels of injuries is based on statistical analysis of injuries of different weapons [2], [3].

Further analysis of medical evacuation model is based on the observations and estimates of the times of each action. If an evacuation-connected action (for example rescue) is estimated to take time $T(i,j)$, the transition probability is

$$P(i,j) = \frac{\Delta t}{T(i,j)}. \tag{5}$$

The model has forced state transitions: a number of a single soldier giving first aid to a single wounded must be the same as the number a single wounded getting first aid from single soldier. The expected value $E(i)$ of soldiers from unit size N for the state i is

$$E(i) = N \cdot P(i) \qquad (6)$$

This has been taken account in the simulation code by fixing number E(i) equal for connected states.

The model was coded to matlab with preliminary parameters. The exact parameter values and field tests to get them would need further studies.

A simplified model was also made, because of the instant need of results for training purposes, cost-effectiveness analysis and to be used as a part of combat simulation code “Sandis”.

In that model only one class of injuries was used, and a rough average of carrying personal per one average wounded was used. In field four men were carrying the badly wounded, and some could walk and needed only one soldier to escort them. Thus only two men were used to carry the injured and the time of carrying was also estimated.

To get the model available for larger users, an Excel spreadsheet was also made by author and Mr. Teemu Murtola for the simplified model. The simplified spreadsheet-model has also been further developed in PVTT.

5 The results

The important values are the effective strength and nominal strength. The effective strength describes the true combat potential of the forces. The nominal strength is the amount of non-wounded soldiers of the unit.

To demonstrate the analysis a few cases are calculated. The figure (1) was created by using simplified Matlab code during a military exercise in October 2004. The evacuation times were 40 minutes and returning times 20 minutes. Loss rates for wounded carrying soldiers were 2% of those in fight.

The loss rate and evacuation times are from exercise lead by major Jari Sormunen. Observations by the author and detailed data collected by Mr Kari Stenius and Mr Pekka Kiiski.

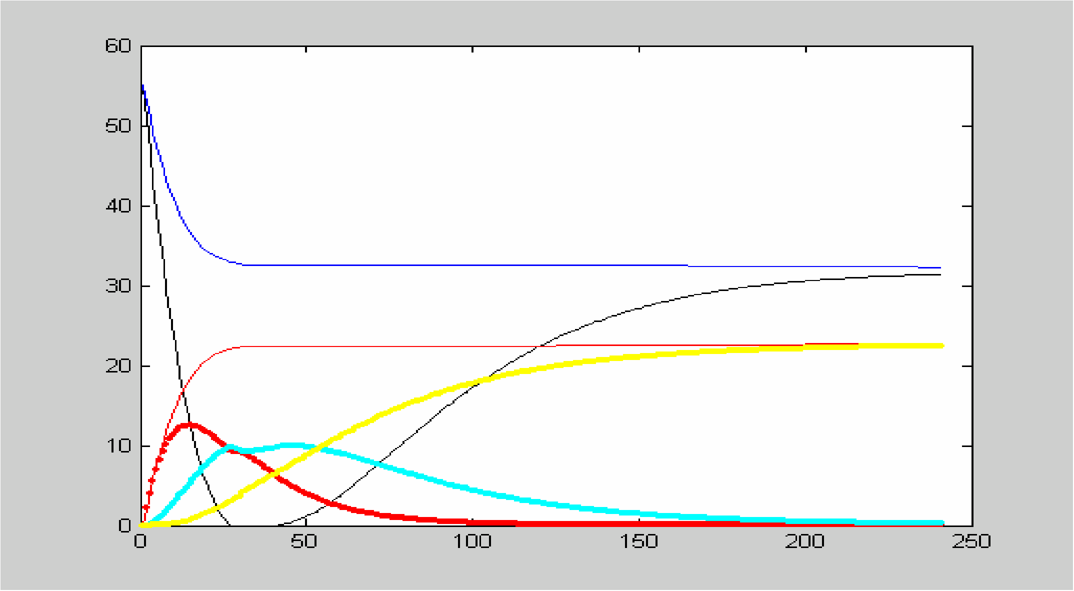


Figure 1. Calculation results from loss data of an attack exercise. Time is in minutes and 55 soldiers initial value. Black line is effective strength and blue nominal strength. Narrow red line is total number of battle casualties and bold red line wounded that are on the field and bold blue line number of soldiers carrying the injured

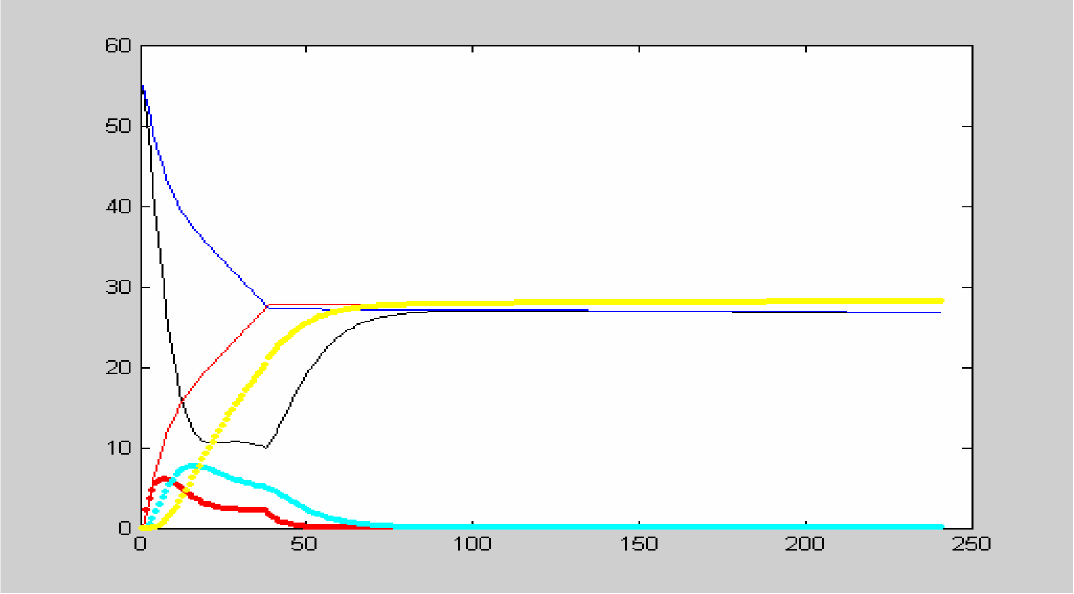


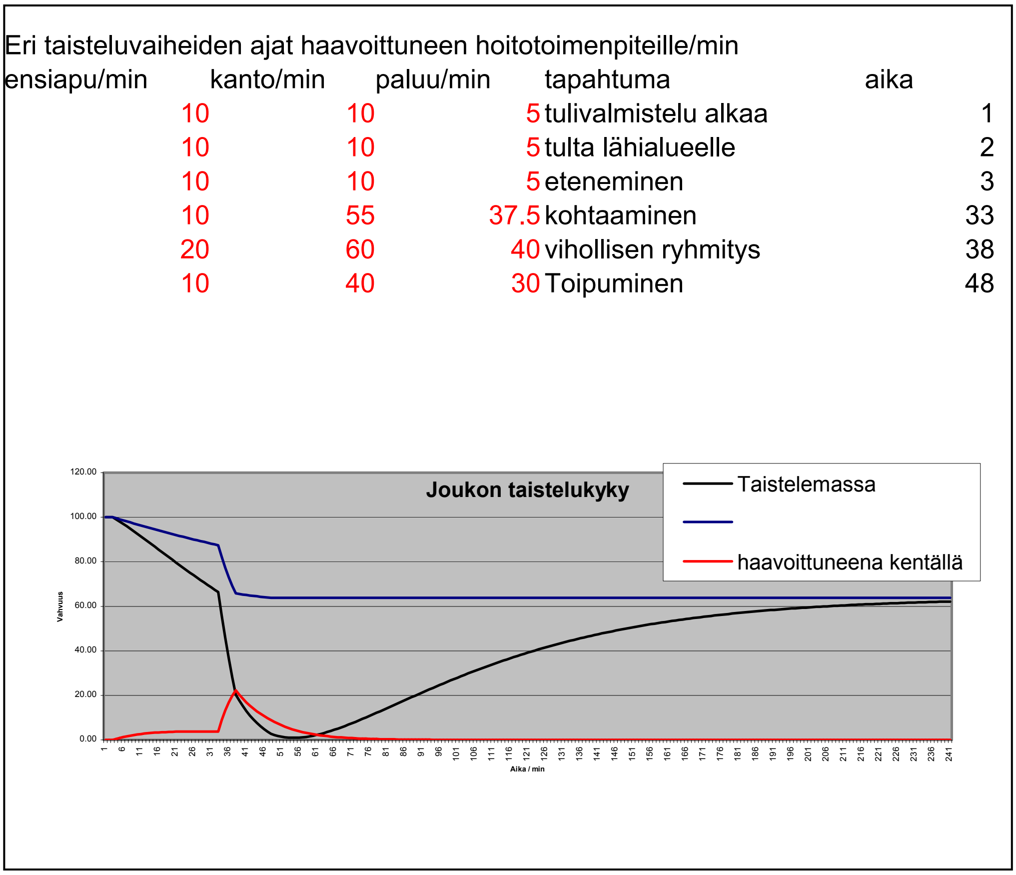
Figure 2. Calculation results from more effective evacuation.

The calculated results demonstrate the crucial meaning of effective evacuation methods and equipment. The first attack would have stopped after 30 minutes, when all soldiers were carrying their wounded comrades to the evacuation point.

Results show also the difference between the nominal strength and the effective strength and the importance of such calculation for combat simulation codes.

The Excel spreadsheet can be used for comparative analysis. The user sets parameters for evacuation times for combat and gets a result as a chart. The parameters can be chanced for comparative analysis by any user.

The sheet has event stepping for different combat situations of the platoon and 1 minutes time stepping for state transitions.



Eri taisteluvaiheiden ajat haavoittuneen hoitotoimenpiteille/min

ensiapu/min	kanto/min	paluu/min	tapahtuma	aika
10	10	5	tulivalmistelu alkaa	1
10	10	5	tulta lähialueelle	2
10	10	5	eteneminen	3
10	55	37.5	kohtaaminen	33
20	60	40	vihollisen ryhmitys	38
10	40	30	Toipuminen	48

Figure 3. Calculation sheet. A result from spreadsheet analysis (in Finnish) used for cost effectiveness analysis.

The method have been used to cost-effectiveness analysis of different evacuation methods and equipment. The battle value of infantry units using for example different evacuation carpets and vehicles can be calculated in numerical form. Thus comparative analysis can be conducted and results used.

Other use of the method has been training. Often during the military exercises with simulators, the wounded and first aid are not considered. The need to avoid battle loses is demonstrated by using these calculations. Results from simulated combat can easily be used as input parameters for excel calculations and results presented to the soldiers after the trill.

6 Discussion

The presented calculation method is a simplification of the actual combat situation. It considers platoon as a homogenous unit with equal parameter values. Its parameters need to be more accurate and assumption of exponential distribution for first aid, evacuation and returning times cause some error. The results haven't been verified with historical data. Thus the method and especially the results using current model and current parameters are probably not accurate.

On the other hand, in Finnish research environment the calculation method has been a clear advance compared to older calculation methods. The method is numerically effective and uses simple linear matrix operations. Thus, the method is numerically fast. It has been written in easy to use form (spreadsheet) and delivered to the users. These features are superior to Monte-Carlo methods and codes simulating individual injured.

The medical model gives a new practical method to evaluate break points inside other combat simulations: the unit stops to fight, when the number of effective fighters equals zero. At the simulations, the fighting effectiveness is weakened by battle losses. These features are part of PVTT's operational analysys software tool Sandis ("Sannolikhet distribution basered strid simulation"). This is a clear improvement to traditional calculations: for example Lancaster equations have been used with break point as certain percentage of battle losses (30-50%) [4, p.9-13].

Acknowledgements

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Publication IV

Esa Lappi, Bernt Åkesson, Sami Mäki, Santtu Pajukanta and Kari Stenius. A Model for Simulating Medical Treatment and Evacuation of Battle Casualties. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

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A Model for Simulating Medical Treatment and Evacuation of Battle Casualties

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Abstract

On the battlefield there are fighting units, different levels of medical facilities and a need for transportation between them. This paper presents a state machine -based model for simulation of evacuation and medical treatment of battle casualties.

The model inputs are battle losses from the combat model, medical units and the transportation connections between units. The combat model gives the battle casualties and their triage classes. Evacuation units and treatment facilities have different waiting and treatment parameters for different triage classes. The model outputs are the number of patients in each facility and transport unit as a function of time for each triage class. Based on these simulated results it is possible to identify bottlenecks in the evacuation and medical treatment process.

The model has been implemented as part of operational analysis software Sandis [1]. A simulated example will be presented. This model could be used to support the Nordic Battle Group.

1. Introduction

Sandis is a software tool for operational analysis, which has been developed in collaboration between the Finnish Defence Forces Research Centre and the Norwegian Defence Research Establishment. It can be used for simulating brigade-level combat operations. A description of Sandis can be found in [1].

Sandis calculates battle losses and it is possible to pinpoint the time and place where they occur. Therefore it is also well suited as a tool for analyzing medical treatment and evacuation of casualties from the battlefield. The medical model in Sandis was developed with two goals in mind: firstly, to create simple methods for studying the relationship between combat ability and effectiveness of medical treatment and secondly, to evaluate the evacuation of wounded from platoon level through company, battalion and brigade levels to the evacuation hospital.

The evacuation is performed in two phases: first at platoon level and then from company level onwards. In the first phase the wounded are taken to the company aid station. This part of the medical model was implemented in 2006 and has been described in [2].

In the second phase of the evacuation the wounded are moved from platoon level onwards. This model was implemented in the summer of 2008. The wounded are divided into four categories (triage classes) based on the severity of the injuries: minor, non-critical, critical and dead or dying. Based on these categories a state machine was developed that takes into consideration the average transportation time and the performance of the treatment facilities.

2. Methods

2.1 Evacuation at platoon level

The numerical model used to evaluate the combat performance of a platoon is based on a state machine, in which the states of a single soldier are shown in Figure 1.

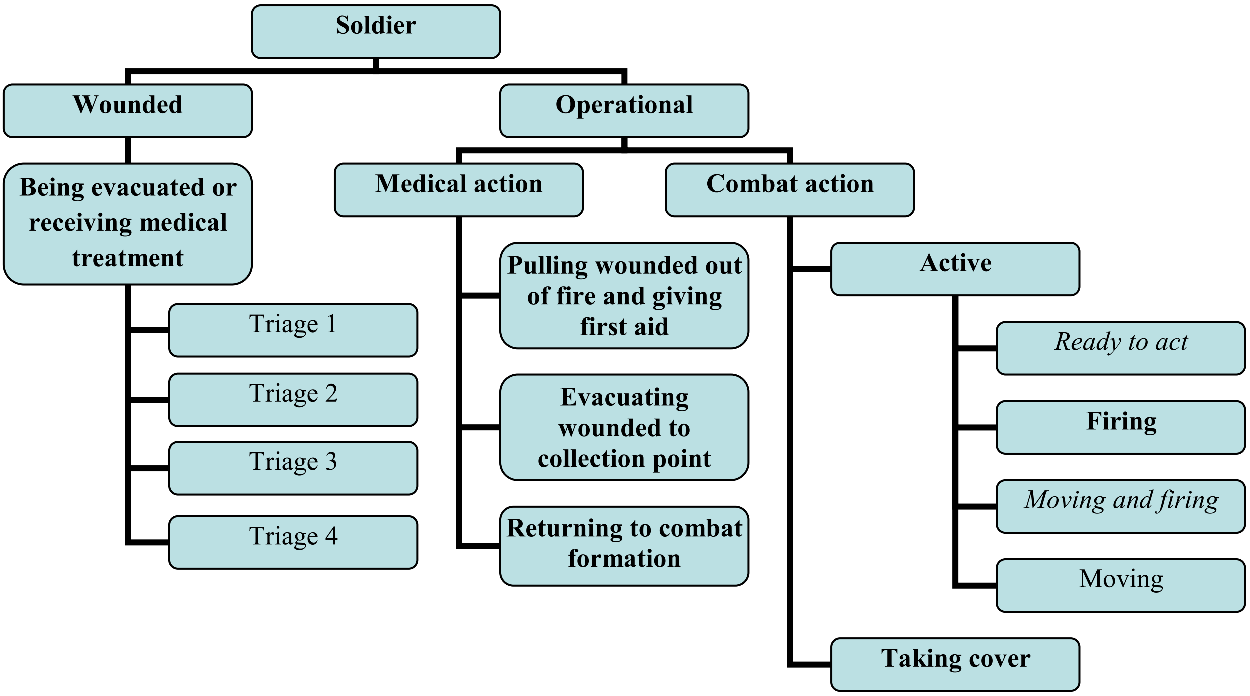


Figure 1. The state machine for a single soldier.

The combat losses are calculated in the combat model, in which the losses are affected by the firing weapon systems and ammunition, the state of the troops, their fortification level and the terrain and the firing distance. When a soldier is wounded, the soldier next to him pulls him out of the fire and gives immediate first aid. Next, a number of soldiers evacuate the wounded to the evacuation point and return to combat afterwards. Each of these steps takes a certain amount of time. Since soldiers from fighting platoons participate in evacuation, the combat ability of the platoon is lowered by more than just the number of casualties. Thus the criterion for the platoon being beaten can be obtained directly from this model.

The model is realized as a Markov chain and a state machine. A similar method has been used in fire safety evaluations [3]. The average time for each step is obtained through field tests [5].

2.2 Transport and medical treatment model

The evacuation of the wounded from platoon level to company level and onwards is handled by two types of units. The first unit type is the evacuation unit, which contains the unit strength and vehicles as part of the troop database. The operator sets the evacuation connections during simulation and gives the average evacuation time and standard deviation for the connection. The times include the return trip. The evacuation units can suffer losses from weapons fire. Losses to the evacuation units affect their evacuation capabilities.

The second unit type is the treatment facility, which can be located on any unit level. Its inputs are the average treatment times and the standard deviations for each category of severity (minor, non-critical, critical and dead or dying) and the number of simultaneous patients. If there is unused capacity for treating critical injuries it is used to treat less severe injuries. The initial percentages of wounded in each triage category are based on literature and field tests [4].

At each treatment facility there are three basic states: “waiting for treatment”, “in treatment” and “waiting for transportation or return to the combat formation”. Each state is further divided into four variables, one for each category of severity. If treatment is delayed or the waiting times become very long, the condition of the wounded deteriorates.

The model can be represented as a Markov chain, where the patients move from one state to the next through the evacuation chain. This contains the state transitions for both treatment and state changes without treatment. Given the average time μ and the standard deviation σ of the time the number of states can be calculated as $N = (\mu/\sigma)^2$. However, the number of states is set to be at least 2 and at most μ/σ.

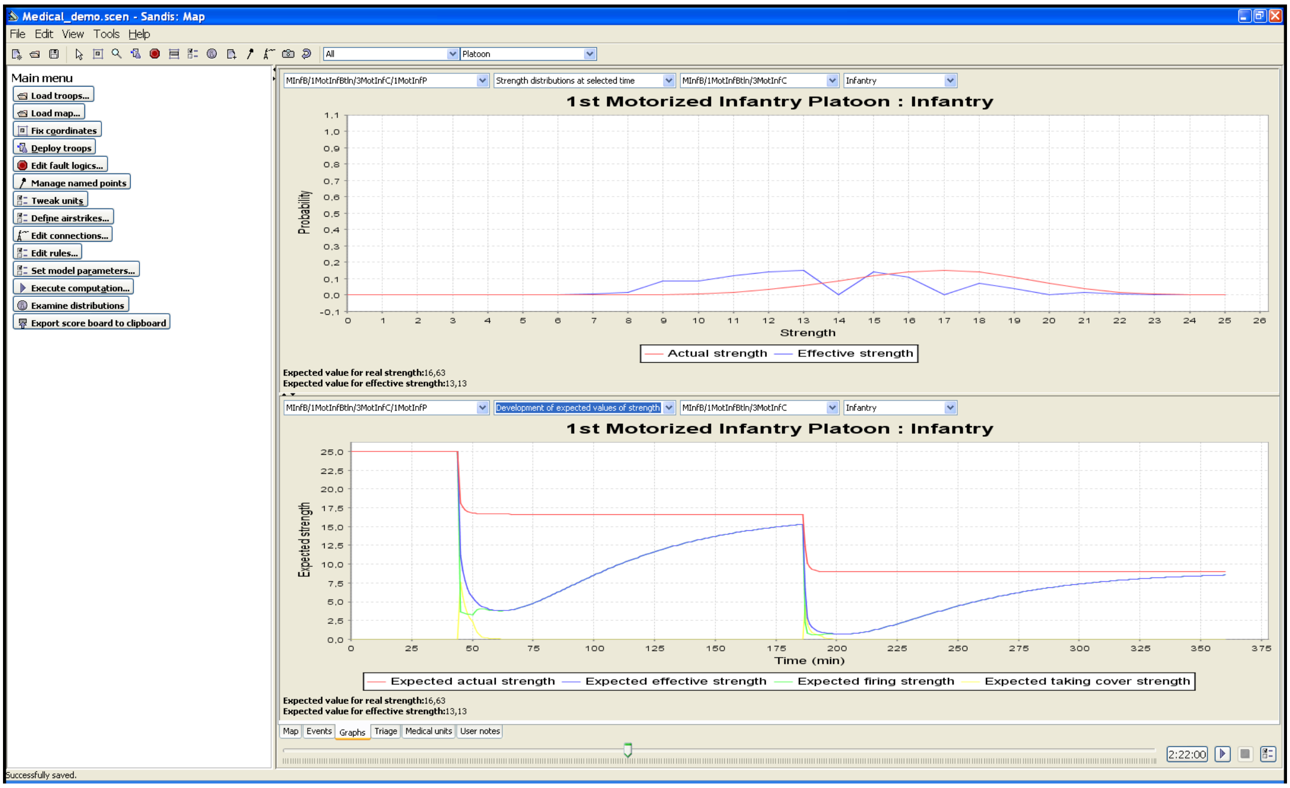
The evacuation connections are derived from a generic connection system, which is also used for describing communications and command connections. The system is described in [6].

3. Results

The model described in Section 2 has been implemented as a part of Sandis. The software can be used to evaluate medical logistics from platoon level to the evacuation hospital. The operator sets up the evacuation connections between the medical units and enters the parameter values (average transportation times and standard deviations)

The parameters for the treatment facilities are also set by the user. Parameters related to the treatment of patients are capacities, average treatment time and standard deviations of treatment times for each triage class. The user can also set the rate at which the condition of patients waiting for treatment of transport deteriorates. In addition, there are parameters for describing how the conditions of the patients improve after treatment, i.e. the percentages of patients in each triage class that move to a new class after treatment. After the simulation the user can study the situation in the treatment facilities and then make the necessary changes to the scenario and rerun the calculations.

A simulated example, in which a motorized infantry brigade attacks a mechanized infantry battalion, is used to illustrate the features of the evacuation model. The evacuation and medical treatment process of the brigade is studied. Figure 2 depicts the strength distribution of a single platoon at a specific moment. Figure 3 shows a screenshot of the battlefield, with the evacuation connections shown as red lines, whose thickness indicates the number of patients being transported. Two new views related to the medical model have been added to Sandis. The first view, shown in Figure 4, gives an overview of the medical situation in all medical units in the scenario. The second view gives more detailed information of the situation in each medical unit. This view is seen in Figure 5.



MInfB/1MotInfBtln/3MotInfC/1MotInfP | Strength distributions at selected time | MInfB/1MotInfBtln/3MotInfC | Infantry

Expected value for real strength:16,63
Expected value for effective strength:13,13

MInfB/1MotInfBtln/3MotInfC/1MotInfP | Development of expected values of strength | MInfB/1MotInfBtln/3MotInfC | Infantry

Expected value for real strength:16,63
Expected value for effective strength:13,13

Successfully saved.

Figure 2. The output from Sandis for each unit. The upper graph shows the unit strength distribution for the selected time step. The lower graph shows the strength development as a function of time for the duration of the simulation. The red line in the graph represents the nominal strength and the blue line represents the effective strength. The difference between the two values is the number of men performing evacuation.

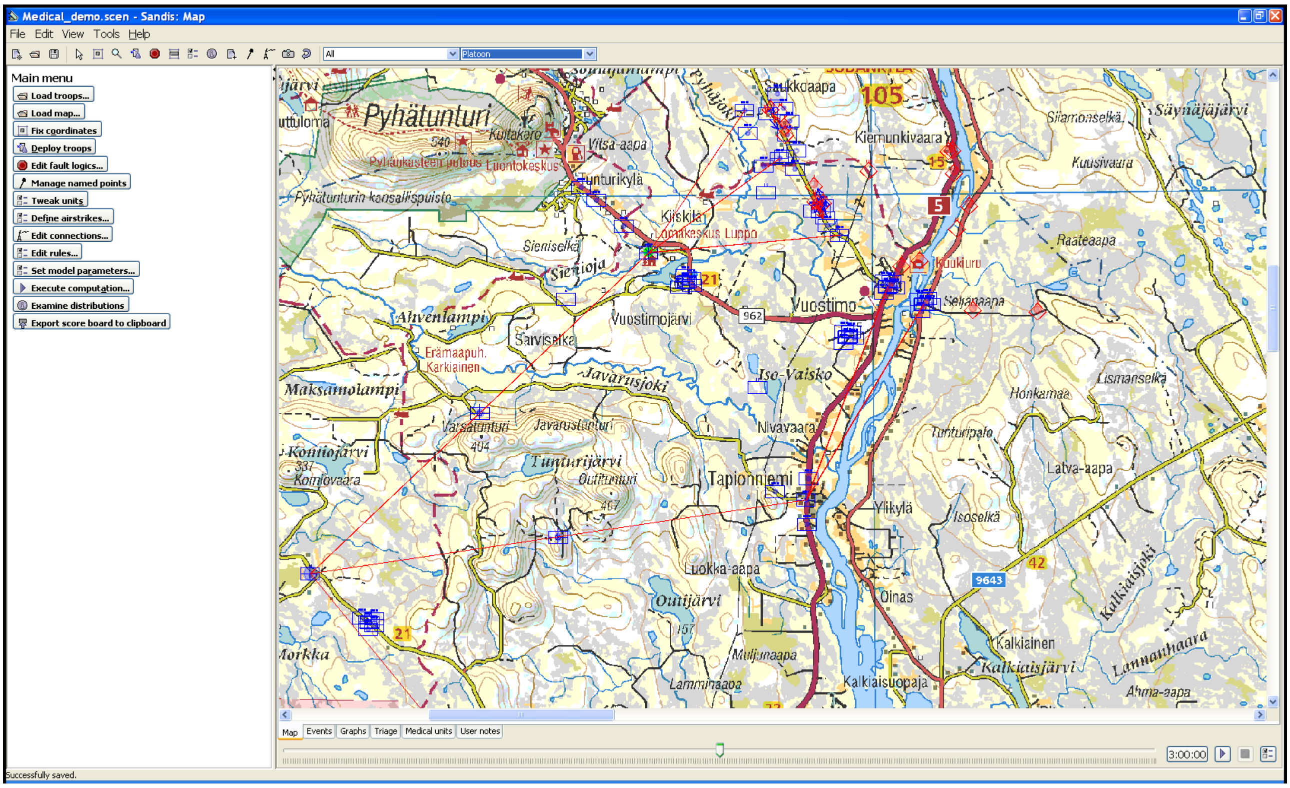
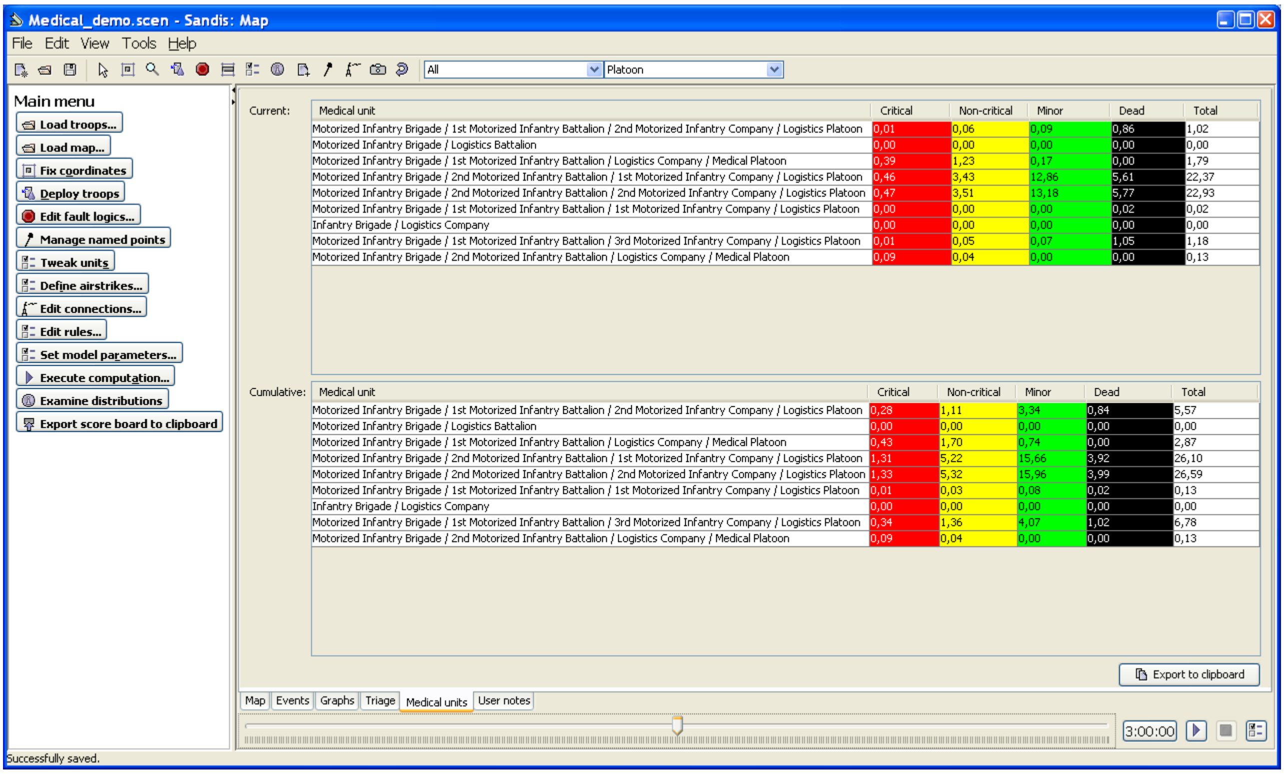


Figure 3. A fictitious example. A motorized brigade attacks an advancing mechanized infantry battalion. The evacuation connections are shown as red lines. The evacuation hospital is to the south, outside of the current map view.



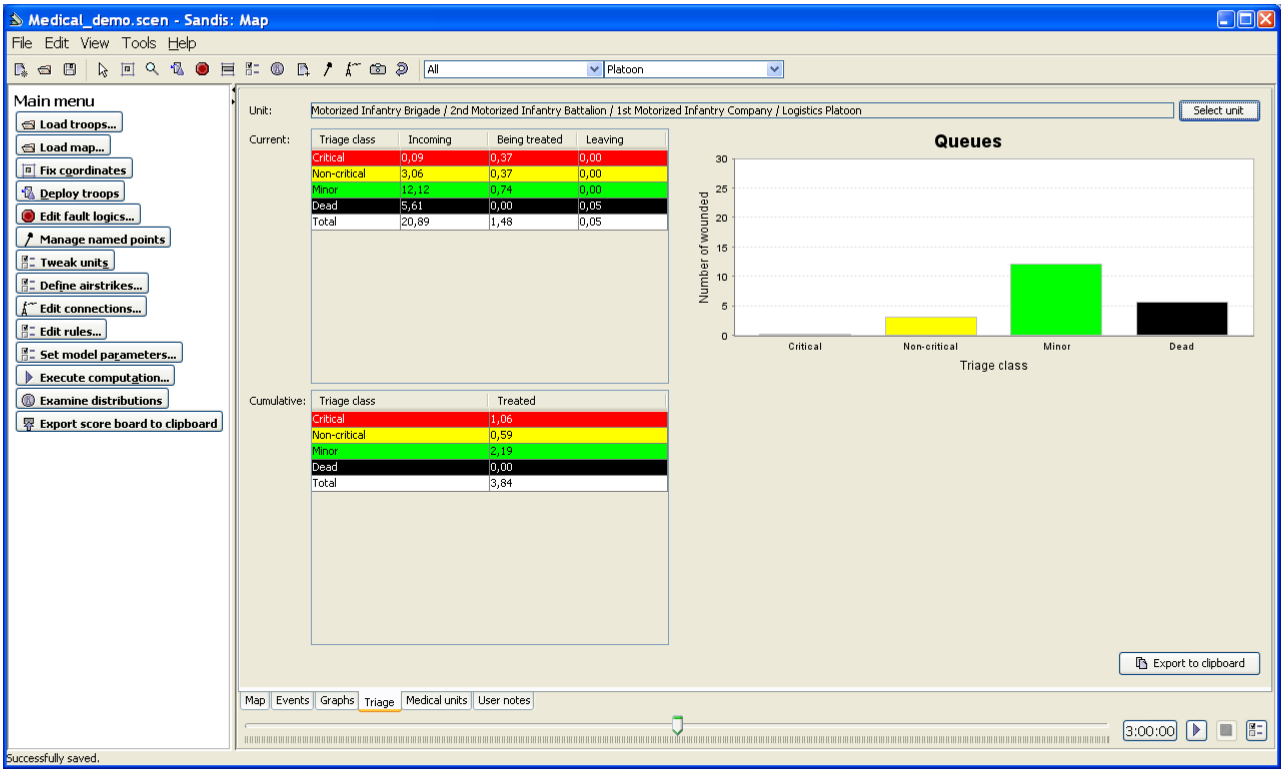
Current:

Medical unit	Critical	Non-critical	Minor	Dead	Total
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 2nd Motorized Infantry Company / Logistics Platoon	0,01	0,06	0,09	0,86	1,02
Motorized Infantry Brigade / Logistics Battalion	0,00	0,00	0,00	0,00	0,00
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / Logistics Company / Medical Platoon	0,39	1,23	0,17	0,00	1,79
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / 1st Motorized Infantry Company / Logistics Platoon	0,46	3,43	12,86	5,61	22,37
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / 2nd Motorized Infantry Company / Logistics Platoon	0,47	3,51	13,18	5,77	22,93
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 1st Motorized Infantry Company / Logistics Platoon	0,00	0,00	0,00	0,02	0,02
Infantry Brigade / Logistics Company	0,00	0,00	0,00	0,00	0,00
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 3rd Motorized Infantry Company / Logistics Platoon	0,01	0,05	0,07	1,05	1,18
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / Logistics Company / Medical Platoon	0,09	0,04	0,00	0,00	0,13

Cumulative:

Medical unit	Critical	Non-critical	Minor	Dead	Total
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 2nd Motorized Infantry Company / Logistics Platoon	0,28	1,11	3,34	0,84	5,57
Motorized Infantry Brigade / Logistics Battalion	0,00	0,00	0,00	0,00	0,00
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / Logistics Company / Medical Platoon	0,43	1,70	0,74	0,00	2,87
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / 1st Motorized Infantry Company / Logistics Platoon	1,31	5,22	15,66	3,92	26,10
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / 2nd Motorized Infantry Company / Logistics Platoon	1,33	5,32	15,96	3,99	26,59
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 1st Motorized Infantry Company / Logistics Platoon	0,01	0,03	0,08	0,02	0,13
Infantry Brigade / Logistics Company	0,00	0,00	0,00	0,00	0,00
Motorized Infantry Brigade / 1st Motorized Infantry Battalion / 3rd Motorized Infantry Company / Logistics Platoon	0,34	1,36	4,07	1,02	6,78
Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / Logistics Company / Medical Platoon	0,09	0,04	0,00	0,00	0,13

Figure 4. Overview of all medical units in the scenario. The upper table shows the situation at each medical unit at a given moment. Each column contains the number of wounded waiting for treatment and being treated. The lower table shows the corresponding cumulative numbers.



Unit: Motorized Infantry Brigade / 2nd Motorized Infantry Battalion / 1st Motorized Infantry Company / Logistics Platoon

Current:

Triage class	Incoming	Being treated	Leaving
Critical	0,09	0,37	0,00
Non-critical	3,06	0,37	0,00
Minor	12,12	0,74	0,00
Dead	5,61	0,00	0,05
Total	20,89	1,48	0,05

Cumulative:

Triage class	Treated
Critical	1,06
Non-critical	0,59
Minor	2,19
Dead	0,00
Total	3,84

Figure 5. Simulated situation at a company first aid station about one and a half an hour after the company has been hit by an air strike. Some of the critically injured have already been evacuated, while patients with non-critical and minor injuries are still waiting for treatment. The upper table shows the number of patients waiting for treatment, being treated and waiting for transport to the next facility. The lower table shows the cumulative number of treated patients. The bar visualizes the number of patients waiting for treatment.

4. Conclusions and future work

The modelling and implementation work has resulted in a software tool that can be used both to evaluate how well organized medical treatment affects the combat ability of troops as well as to evaluate the evacuation of wounded in order to evaluate and study the action. The results can be used in education, optimization of procurement and as support for operative planning.

The effective use of the model necessitates finding accurate parameter values. This requires field tests and consultation with medical experts.

Furthermore, the user interface and model development require further work.

Acknowledgements

The authors wish to thank Kosti Jokinen and Risto Bruun for software testing and calculating the test scenario.

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Publication V

Esa Lappi, Olli Pottonen, Sami Mäki, Kosti Jokinen, Olli-Pentti Saira, Bernt Åkesson and Marko Vulli. Simulating Indirect Fire – A Numerical Model and Validation through Field Tests. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

In e-proceedings under subdirectory “Session 1B”.

Simulating Indirect Fire - A Numerical Model and Validation through Field Tests

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Abstract

A numerical model for fragmenting ammunition has been presented previously [2]. This model has been extended to include direct hits and shockwave damage and it has been implemented in operational analysis software Sandis [1]. The kill probability is calculated using adaptive integration around the target unit, where the integration range from the target to the maximum distance is determined by the armor thickness and blast resistance of the target. Each fragment grenade produces fragment fans containing a specific number of fragments following a given mass distribution.

The model can be validated using field experiments by, for example, preparing a 100 m x 100 m target area containing cardboard and metal cylinders. The cardboard cylinders are used to calculate the number of fragments and the metal cylinders are used to calculate the number of effective fragments. There was a good correspondence between the model predictions and actual field tests.

1. Introduction

The simulation of indirect fire in Sandis is based on the model proposed by Heininen [2]. This report describes the details of applying the model in practice. More information about Sandis can be found in [1].

2. Calculating the mass of an effective fragment

The perforation capability of a fragment is, according to Rilbe's Formula [2],

$$g = qvm^{\frac{1}{3}}, \tag{1}$$

where q is a coefficient depending on materials of the fragment and the target (39 x 10^{-6} skg$^{1/3}$ for steel hitting steel), v the velocity of the fragment and m its mass.

The velocity at distance s is [2]

$$v(s) = (v_0 + v_2)\exp\left(\frac{-1}{c_1}\left(\frac{m_{ref}}{m}\right)^{\frac{1}{3}} s\right) - v_2, \tag{2}$$

where v_0 is the initial velocity, v_2 and c_1 constants describing the deceleration (c_1 = 17,51m, v_2 = 17m/s by default) and m_{ref} the mass of the reference particle (m_{ref} = 0.4g).

An increase in mass increases the perforation capability of a fragment directly, as seen in formula (1), and indirectly by increasing the velocity according to formula (2). We want to find the smallest possible mass for an effective fragment, i.e. one with enough perforation capability to damage the target. Unfortunately the result can't be expressed in closed form, so we have to resort to numeric calculation.

Let q, s and all constants be given. Let $x = m^{1/3}$. The perforation capability of a fragment is

$$g = qv(s)m^{\frac{1}{3}} = q\left((v_0 + v_2)\exp\left(-\frac{1}{c_1}\left(\frac{m_{ref}}{m}\right)^{\frac{1}{3}} s\right) - v_2\right)m^{\frac{1}{3}} \tag{3}$$

so we define

$$f(x) \ = \ q\left((v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right) - v_2\right)x, \tag{4}$$

where $\gamma = c_1^{-1}\, m_{ref}^{1/3}\, s > 0$, and we want to solve the equation $f(x) = y$, where y is the required perforation capability. A natural limit for f's domain is gained by requiring x to be large enough that the fragment's velocity isn't negative, meaning

$$(v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right) - v_2 \geq 0. \tag{5}$$

Thus f is defined in $\{x \in \Re \mid x \geq \gamma / \ln((v_0 + v_2)/v_2)\}$, and $f(x) \geq 0$ in the whole domain.

By differentiating we gain

$$f'(x) = q\left((v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right) - v_2\right) + q(v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right)\frac{\gamma}{x^2}x \tag{6}$$

$$= q(v_0 + v_2)\left(\exp\left(-\frac{\gamma}{x}\right)\left(1 + \frac{\gamma}{x}\right)\right) - qv_2 \tag{7}$$

Differentiating further we gain

$$f''(x) = q(v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right)\frac{\gamma}{x^2}\left(1+\frac{\gamma}{x}\right) + q(v_0 + v_2)\exp\left|-\frac{\gamma}{x}\right|\left(-\frac{\gamma}{x^2}\right) \tag{8}$$

$$= q(v_0 + v_2)\exp\left(-\frac{\gamma}{x}\right)\frac{\gamma^2}{x^3} > 0 \tag{9}$$

Because $f''(x) > 0$ in the whole domain and $f'(x)$ for the smallest value in domain, $f'(x) > 0$ in the whole domain. As f's first and second derivatives are both positive in the whole domain and f's smallest value is 0, for each $y \geq 0$ exists a unique solution which can be found with Newton's method:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}. \tag{10}$$

The initial value x_0 must belong to f's domain. One possible choice is the domain's smallest value, $\gamma/\ln((v_0 + v_2)/v_2)$.

3. Calculating the grenade's effective distance

We want to find the largest distance where the grenade's fragments are still effective.

The mass distribution for naturally fragmenting grenade's fragments follows Mott's distribution [2]:

$$N_m = N_0 \exp\left(-\sqrt{\frac{2m}{m_{avg}}}\right), \tag{11}$$

where N_m is the number of fragments with mass at least m, and m_{avg} the average mass of fragments.

Continuing with Mott's distribution, the greatest mass for fragments is gained from the condition $N_{m\_\max} = 1$[1], meaning

$$m_{\max} = \frac{1}{2} m_{avg} (\ln(N_0))^2. \tag{12}$$

The fragment with the greatest mass also has the greatest effective distance. A fragment is effective at a range s, if

$$g = q\left((v_0 + v_2)\exp\left(-\frac{1}{c_1}\left(\frac{m_{ref}}{m}\right)^{\frac{1}{3}} s\right) - v_2\right) m^{\frac{1}{3}} \geq g_{\min}, \tag{13}$$

where $g_{\min}$ is the smallest perforation capability required for a fragment to be effective. Thus the greatest distance where the fragments from a grenade can be effective is gained from equation

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[1] Here we consider the mass distributions of fragments to be deterministic, even though it might be more natural to consider the Mott's function as a probability distribution. It's easier here though to interpret the mass distribution as deterministic, which should give us an approximation good enough.

$$q\left(\left(v_0+v_2\right)\exp\left(-\frac{1}{c_1}\left(\frac{m_{ref}}{m_{\max}}\right)^{\frac{1}{3}}s\right)-v_2\right)m_{\max}^{\frac{1}{3}}=g_{\min} \tag{14}$$

and the largest distance is

$$s=c\left(\frac{m_{\max}}{m_{ref}}\right)^{\frac{1}{3}}\ln\left(\frac{v_0+v_2}{\dfrac{g}{q m_{\max}^{\frac{1}{3}}}+v_2}\right) \tag{15}$$

4. An overview of the method and miscellaneous improvements

Several formulas in the previous chapters are for fragments specifically. Before going further, it should be noted that while these work for most ammunition with only different constants, the formulas for fragment deceleration and mass distribution, for example, can easily be replaced.

In the indirect fire model in Sandis, the locations of the targets and grenade impact points both have probability distributions. We integrate over both distributions. If the distance between the grenade and the target is greater than the largest effective distance given by formula (15), the grenade doesn't cause any damage. Otherwise we calculate the smallest mass an effective fragment can have as described in section 2, and then with Mott's distribution the number of effective fragments. Once we know the number of fragments, the area they are spread in and the area of the target, calculating the probability of destroying the target is straightforward (see Figure 1).

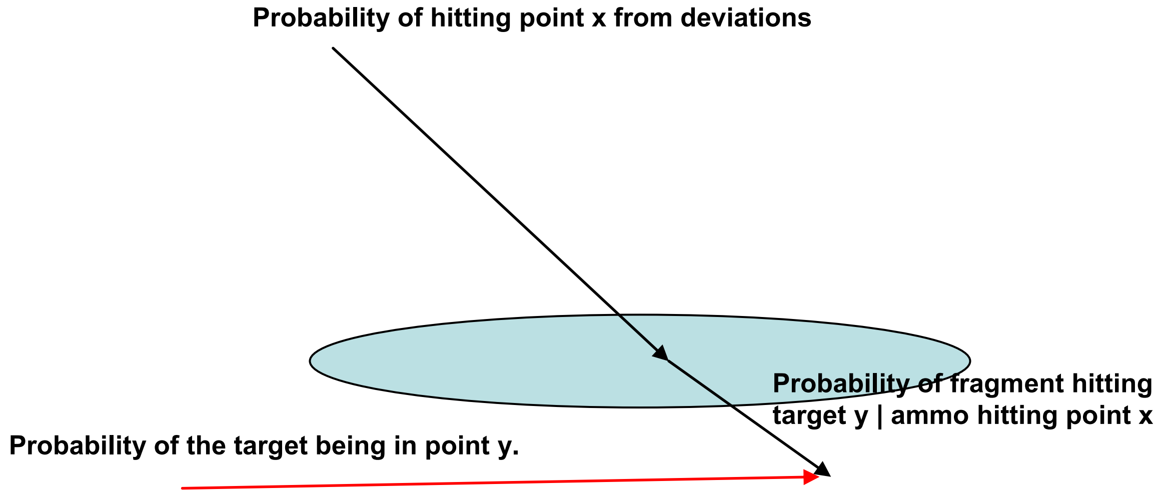


Figure 1. The basics of hit probability calculation

While all of our distributions are continuous in theory, the numeric calculations are discrete by nature. Instead of trying to divide the whole area into sufficiently small steps, the units are modelled with a limited number of calculation points – seven in the current model, the one in centre having larger weight than the others (see Figure 2). Now we can solve the problem by integrating cyclically around these points.

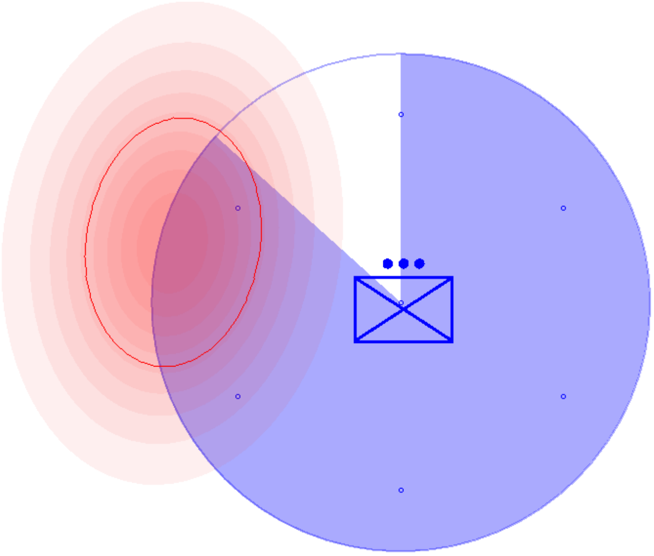


Figure 2. A Sandis screenshot from a simple example with a platoon being targeted, calculation points set visible

It doesn't matter much which numeric integration method is used, but incorporating adaptive integration is essential to get accurate results around points where calculation really matters, without wasting time in regions where no damage is done. In short, adaptive integration means splitting the integrand recursively until the pieces are small enough to have both absolute and relative errors stay within a satisfactory margin. This results in a sparse division in regions where the function is nearly constant and vice versa (see Figure 3).

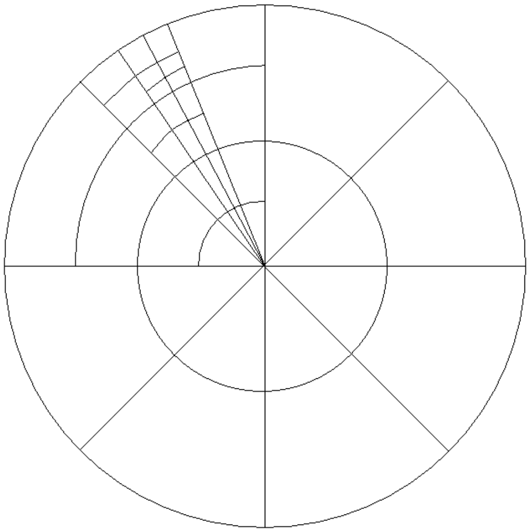


Figure 3. Splitting the integrand into sectors

For each calculation point, we split the area into a few sectors. Finally, the calculation is carried out by integrating over those sectors and recursively splitting them into smaller ones until the error has settled below the desired margin.

This solution to the problem has been found successful, but it is not the only one by any means. One example of an alternative approach is to use discrete locations for the targets, such as a rectangular or hexagonal grid, and a loss probability for the targets inside the polygon on the condition that the polygon is hit. [5]

4.1 Direct hits and effects of the shockwave

In addition to fragments, Sandis also calculates the probabilities for direct hits and getting damaged by the shockwave. Here we simply calculate the probability of grenades hitting within a certain radius from the target. For direct hits we get it directly from the target's area. For the shockwave the radius depends on the explosive material in the grenade and the target's pressure tolerance according to data presented in [3, Figure 26-9, p. 26-18]. From the chart, linear regression gives us

$$sd = k\frac{m^{\frac{1}{3}}}{\sqrt{p}}, \tag{16}$$

where *sd* is the largest distance with lethal pressure, *m* the explosive mass in the grenade, *p* sufficient pressure to kill the target, and $k = 32.87$ the determined slope.

Usually these effects are both negligible but, for example, against heavily armoured targets they might mean the difference between zero and nonzero kill probabilities.

4.2 The distribution of troops within a unit

The error caused by the use of calculation points instead of simulating a continuous distribution depends on the area occupied by the target unit relative to the spread of the strike. In practice this does not usually matter, but it becomes a problem if we have units covering large areas, like a defending platoon spread within 20 hectares.

This can be counteracted to a certain degree by carrying out the calculations separately for each point, as if a certain fraction of the unit's strength actually resided at that point. This way bombing just a fraction of the unit's area can only cause as much damage as there are troops in the target area. If this strength distribution changes due to losses, it starts to slowly converge towards the initial state.

So far this model is only used by the artillery model, but work to extend it to the direct fire model, where it would also affect the unit's firepower, is in progress. Another planned improvement is making the number of calculation points scale with the unit's area, which would eliminate the previously mentioned problem.

5. Validation

Several measurements have been performed to validate this model, some of which are discussed in detail in paper [4]. A part of the experiment was recreated in Sandis, which produced very similar results. A comparison between observed and simulated results is presented here. During the test the casualty rate was determined to be 35.4%, while Sandis's result was 37% (see Figure 6). If the probability of hit is 35% with 100 targets, the standard deviation $\sigma = (npq)^{1/2} \approx 5$, so 35±5% is the ideal accuracy for the hit probability in a single test.

The field test recreated in Sandis is presented in Figure 4. The detailed numeric data from the firing is classified, so only a colour-coded table is presented here (Figure 5).

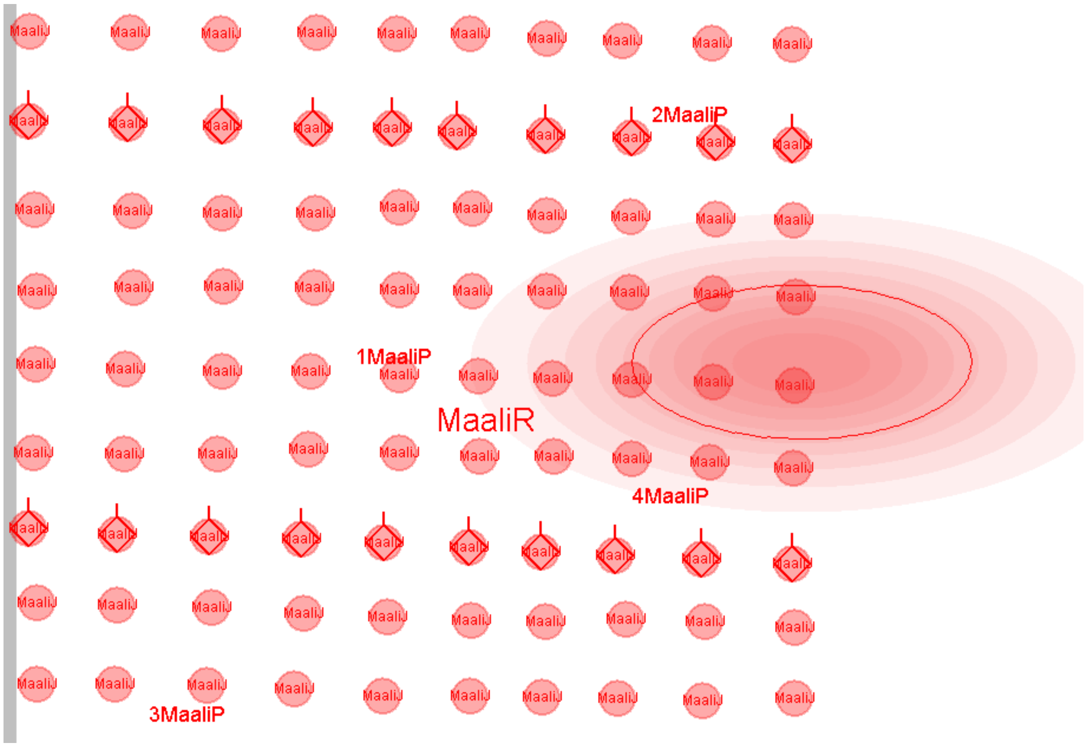


Figure 4. The setup recreated as a Sandis scenario. The center point and deviation of the grenade impacts were determined from the notes of the original test.

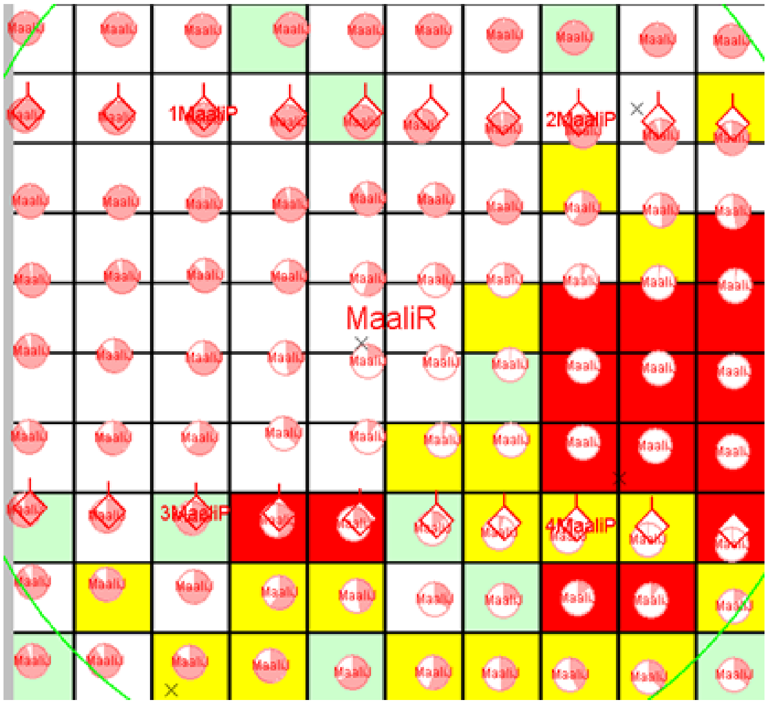
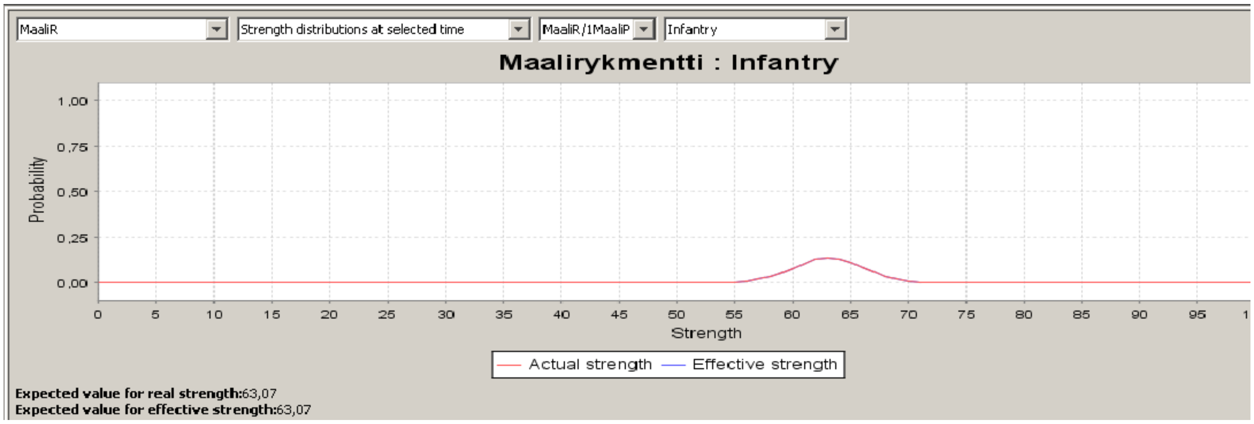


Figure 5. Overlay of the original notes and Sandis simulation results. Pie charts represent the probability of hit calculated by Sandis. The colours for each square represent the number of fragment hits recorded. Red corresponds to a large number of fragment hits, yellow an intermediate number and blue a low number. In the white squares there were no hits.



Expected value for real strength:63,07
Expected value for effective strength:63,07

Figure 6. The resulting strength distribution in Sandis.

Acknowledgements

The authors wish to thank Kari Papinniemi for participation in the field tests. The authors also wish to thank Risto Bruun for suggestions and improvements to the manuscript.

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Publication VI

Esa Lappi and Olli Pottonen. Combat parameter estimation in Sandis OA software. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

Combat parameter estimation in Sandis OA-software

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Abstract

We introduce a stochastic combat model and present a method of calculating effectiveness parameters for different weapons in a way compatible with the model. These calculations are performed by using some old test results as initial data.

Keywords: stochastic combat model, parameter estimation

1 Introduction

Sandis is a operational analysis software tool with a probability distribution based brigade level combat model. It estimates battle loss distributions and operation success probabilities. In this work we present a method for calculating parameters for the combat model used in Sandis.

The parameters in question describe the effectiveness of fire. For example, in the Lanchester equations (see e. g. [4])

$$\frac{dB}{dt} = -\lambda_1 R \tag{1}$$

$$\frac{dR}{dt} = -\lambda_2 B \tag{2}$$

λ_1 and λ_2 are analogous parameters. The values of these parameters depend on several factors such as shooting skill of troops, weapons used, terrain and weather conditions. We shall now concentrate on the dependence of the parameters on weapons.

Rest of this paper is organized as follows. Section 2 describes the capabilities of Sandis in greater detail and briefly introduces the combat model. In Section 3, the relevant parameters are calculated. Section 4 considers possible further research on the subject.

2 The Combat Model

The Sandis application calculates probability distribution for the outcome of a brigade level combat given by the user. The user needs to enter the strengths and armament as well as missions and locations of companies. No smaller or larger entities than companies may be directly manipulated. Sandis calculates the success probability of the overall mission as well as probability distributions for the strength of each platoon.

To further illustrate the capabilities of Sandis, let us consider a battle in which a blue company is repeatedly attacked by red forces. The expected strength of the blue company is depicted in Figure 1. The figure illustrates both nominal strength and actual strength. The actual strength is obtained by deducing from the nominal strength the soldiers who are assisting their wounded comrades [3].

Figure 1: Expected strength

However, the expected strength alone does not suffice to describe the outcome. Additional insight is provided by Figures 2, 3 and 4, which depict the probability distributions of nominal and actual strength of the blue company after one, two and three attacks, respectively.

In figure 5 the development of expected strength of blue forces and their probability of being defeated in another combat are illustrated.

Although companies are the only entities visible to the user, the model calculates probability distributions of the strengths of platoons. Platoons are not divided to any smaller groups. Thus, we need a way to calculate casualty distributions for firefights between platoons. Rest of this section describes the model used for this task.

Assume that a red fighter has the probability p of hitting a blue fighter with a single aimed shot. In this case we say that p is the *basic hit probability* of the red fighter. If we assume that different shots are independent, the probability that the blue fighter is wounded by at least one of n shots is

$$1-(1-p)^n, \tag{3}$$

regardless of whether the n shots were fired by one or several red fighters having equal skill and weapons.

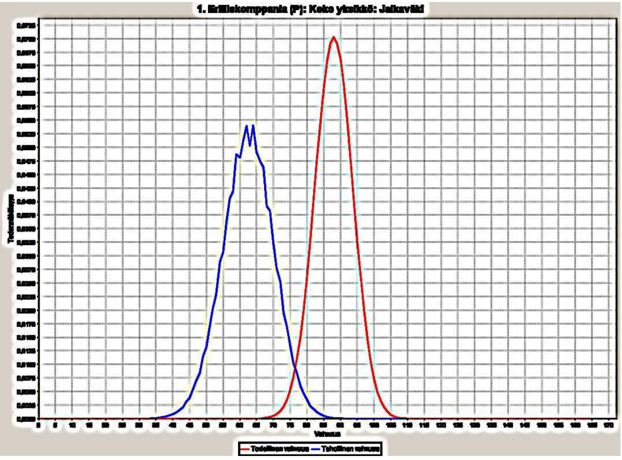

Figure 2: Probability distribution of blue strength after the first attack

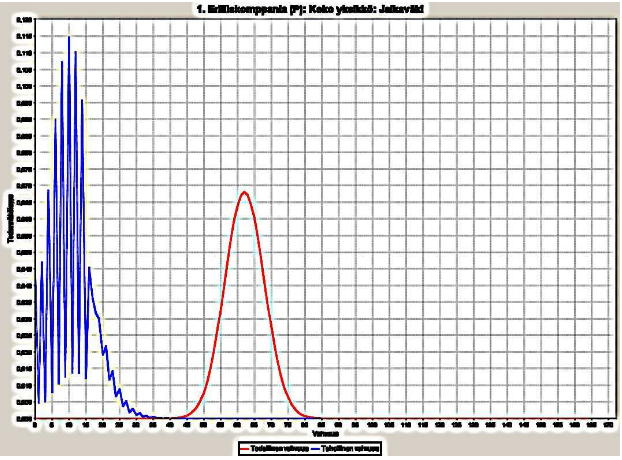

Figure 3: Probability distribution of blue strength after the second attack

If there are total m blue fighters, on average n/m shots are fired at each of them. Thus we argue that each of the blue fighters has probability

$$1 - (1 - p)^{n/m} \tag{4}$$

of getting hit. For simplicity, we assume that the events of different blue fighters getting hit are independent.

The model easily extends to the case in which red fighters have different kinds of weapons. If $n_1, \ldots, n_k$ shots are fired with weapons having the basic hit probabilities $p_1, \ldots, p_k$, the total probability of any blue fighter getting hit is

$$1 - (1 - p_1)^{n_1/m} \cdots (1 - p_k)^{n_k/m}. \tag{5}$$

Above only point fire was considered. If the shots are not well aimed, i. e., in a case of area fire, the probability of a single blue fighter getting hit does not

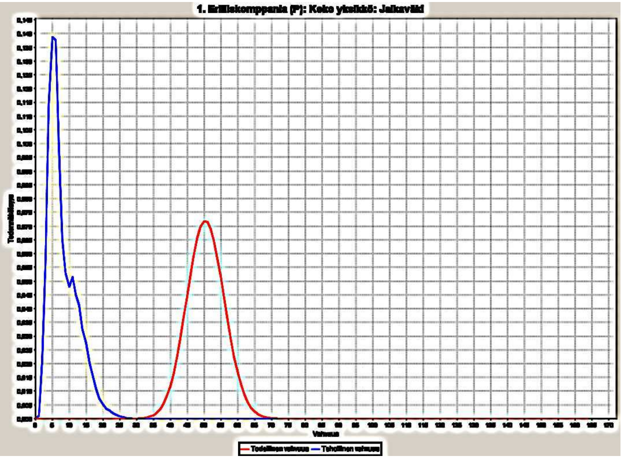

Figure 4: Probability distribution of blue strength after the third attack

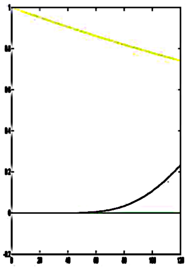

Figure 5: Expected strength and probability of being defeated

depend on the number of blue fighters and the the total probability of a blue fighter getting hit is

$$1-(1-p_1)^{n_1}\cdots(1-p_k)^{n_k}. \tag{6}$$

Note that the basic hit probabilities p_i depend on circumstances such as shooting distance and whether the shots are aimed or not.

3 Calculating parameters

Since unclassified reports concerning the effect of infantry fire are few and far between, the calculations on this paper are based on a more than 50 years old report by Finnish Defence Forces [1]. At that time the primary weapons of Finnish infantry were submachine guns, rapid-fire rifles, (non-automatic) rifles and semi-automatic rifles.

On field tests a platoon (36 men armed as in Table 2) inflicted 45% casualties during one minute of shooting to dummies at a distance of 100 m [1, p. 23]. On distances of 200m and 300m the casualties were 14% and 6%, respectively. The

Table 1: Infantry weapons [1, p. 23]

Weapon	Firing speed (shots per minute)
Submachine gun	100
Rapid-fire rifle	60
Rifle	8
Semiautomatic rifle	20

Table 2: Armament of an infantry platoon [1, p. 23]

Weapon	Count
Submachine gun	20
Rapid-fire rifle	4
Rifle	8
Semiautomatic rifle	4

targets were located in a forest of medium density but open ground lay between shooters and targets. The targets were lying on an area of $100m \times 100m$ and presumably there were 36 of them.

Based on the field tests, we wish to calculate the basic hit probabilities for different weapons, but additional information is needed for this task. Fortunately, this information can be found in the same report and is included in Table 3.

Table 3: Relative effectiveness of infantry weapons [1, p. 8]

Weapon	0m	50m	100m	200m	300m	400m	500m
Submachine gun	148	140	67	15	3	0	0
Rapid-fire rifle	109	105	50	15	12	10	9
Rifle	18	18	13	8	5	3	3
Semiautomatic rifle	33	33	26	10	8	7	7
Light machine gun	106	105	85	45	24	20	19

Assume that one fighter armed with a weapon of relative effectiveness of 1 has the probability p_0 of eliminating an enemy during a minute fight. When enemies are at distance of 100m, the relative effectiveness of a platoon is 1748 (this is easily computed from Tables 2 and 3). Thus a platoon confronting m enemies eliminates on average the fraction

$$1-(1-p_0)^{1748/m} \tag{7}$$

of them during the minute fight. Since we already know that the damages inflected on a enemy platoon are 45%, we have

$$1-(1-p_0)^{1748/36} = 0.45, \tag{8}$$

which implies

$$p_0 \approx 0.0122. \tag{9}$$

For a weapon with relative effectiveness of x and fire speed n shots per minute, the probability that a single shot eliminates a single enemy is

$$1 - (1 - p_0)^{x/n}. \tag{10}$$

By using this formula, we get the parameter values for Table 4.

Table 4: Basic hit probabilities of different infantry weapons

Weapon	0m	50m	100m	200m	300m	400m	500m
Submachine gun	1.81%	1.70%	0.82%	0.18%	0.04%	0	0
Rapid-fire rifle	2.21%	2.13%	1.02%	0.31%	0.25%	0.20%	0.18%
Rifle	2.73%	2.73%	1.98%	1.22%	0.77%	0.46%	0.46%
Semiautomatic rifle	2.01%	2.01%	1.59%	0.61%	0.49%	0.43%	0.43%
Light machine gun	0.43%	0.43%	0.35%	0.18%	0.10%	0.08%	0.08%

As a sort of verification we calculated the casualties which a platoon inflicts in a minute on an enemy platoon at distances of 200m and 300m based on the data in Table 4. The results were 14.7% and 6.0%, which are in agreement of the original test results.

4 Conclusions

We have shown a rather simple method of calculating the necessary parameters with few additional assumptions. It should be noted that the parameters are calculated in such a way that they yield results conforming to input data in firefights between platoons, which are of interest, but may not yield accurate results in firefights of much larger or smaller scale.

Unfortunately, we had to resort to old test results which did not include modern weapons such as assault rifle. In order to obtain more useful results, new tests are required.

Another problem is the assumption that all fire is point fire when in fact a combination of point and area fire would be better model. Unfortunately, proportions of the combination are unknown. Also this problem could be solved by performing new tests in which the number of targets vary. Simply varying the number of shooters does not suffice, since the formulae 5 and 6 have the same functional form as functions of n_k. To further illustrate this point and the difference between point fire and area fire in general, let us consider the probability that a single target gets hit in different cases. In each case the probabilities are calculated based on the fact that during one minute a platoon eliminates on average 45% of an enemy platoon.

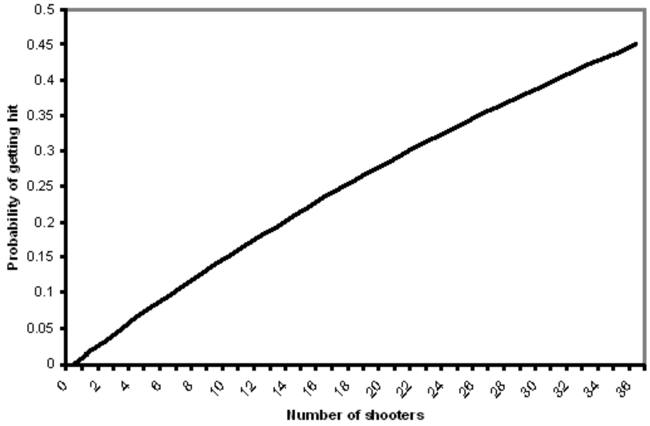

Figure 6: The probability of getting hit when the number of targets fixed

If the number of targets is fixed but the number of shooters vary, the point fire and area fire models predict equal hit probability as depicted in Figure 6.

If the number of shooters is fixed and the number of targets vary, the probability of getting hit by area fire remain fixed, but the probability of getting hit by point fire increases as the number of shooters decrease as depicted in Figure 7. However, the expected number of casualties tends to increase when the number of targets increase. This is only logical: when several shooters shoot an a single target, it is probable that the single target gets hit, i. e., that 100% of the targets get hit. Should there be several targets, probably not all of them get hit, but more than one do. In this case the relative casualties are lower but absolute casualties higher.

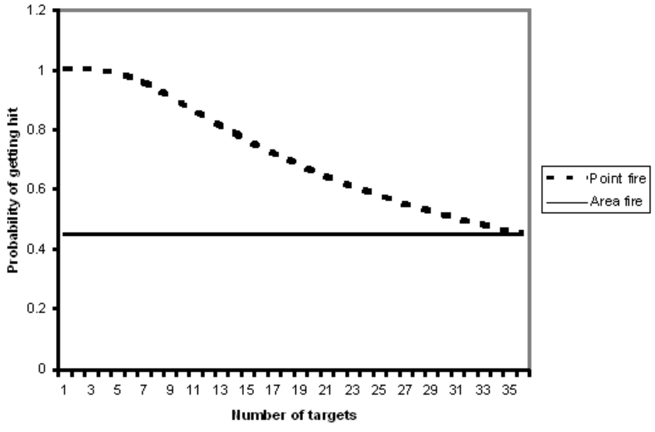

Figure 7: The probability of getting hit when the number of shooters is fixed

If the numbers of targets and shooters are equal, the probability of getting hit by point fire remains fixed, for every shooter has a distinct target and equal hit probability. However in the case of area fire the probability of getting hit increases as the number of targets increase, see Figure 8.

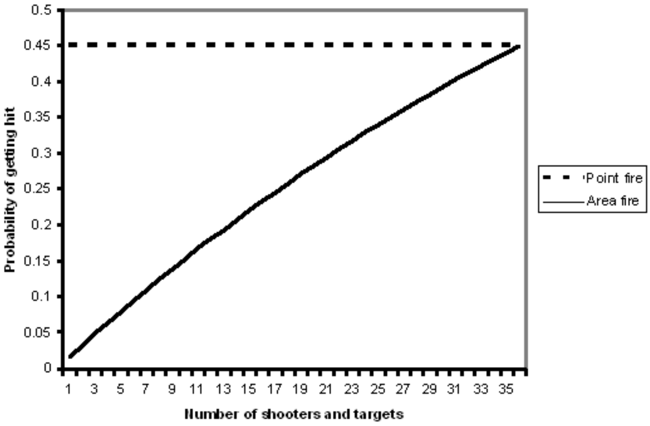

Figure 8: The probability of getting hit when the number of targets equals to the number of shooters

As a final remark we conclude that new test shootings are a good chance to validate the model. Thus the number of shooters as well as number of targets should be varied.

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VII

Field Test for Parameter Estimation of Small Arms Fire

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Abstract

An infantry squad firing at another squad was tested with conscripts. The primary objective of the test was to gather parameter data for Sandis OA –software. The second objective was to compare results from "TASI" combat simulators and real ammunition in winter conditions.

Seven squads shot same test field with five target dummies placed in the firing zone. The average distance from the shooters was about 150m. The dummies were at positions, where they could have been shooting at the squad, but at the same time were using the cover of the terrain.

The TASI –simulators gave similar results as the real ammunition in winter conditions and the results were about the same as data from [1] with recalculated values from [3].

1. Introduction

The Finnish defense forces have a need for cost effectiveness analysis and operational analysis research methods. PVTT, Army Academy and the Jaeger Brigade executed a research test firing as a joint project. The research firing was carried out concurrently as a part of a Jaeger Brigade conscripts live firing field exercise.

We conducted a routine squad defensive firing drill in a research setting. Targets were human dummies ("Anne-nukke"). Firing distance was approximately 150 meters. The experiment was carried out as part of conscript training. Hence an infantry defensive firing drill was combined with an experimental research firing.

The research project had multiple objectives:

1) to gather data on the effectiveness of infantry light arms fire in winter conditions
2) to compare results from experimental test firing carried out in the 1950's [1], which are the source data for the parameters defining the effectiveness of light arms fire in the SANDIS-program [2] against new, contemporary data [3]

3) to compare the results of live firing with results of combatant simulator (TASI) firing.
4) to obtain probabilities of casualties induced by infantry fire in different conditions. These are needed for the Sandis software.

Data based on research in winter conditions is not available. Hence, both the reducing effect of snow on light arms fire and the effect of snow on the corresponding simulator results were speculative. Therefore, the tests carried out in winter conditions produced basic data required for the planning of further research.

The estimates publicized on the efficacy of assault rifle fire were contradictory. According to the textbook “Todennäköisyys- ja ampumaopin perusteet” 1984 [4 p. 175] a single shot probability of a hit was stated as 63.3%. The value is obviously inconsistent with probabilities (1-2%) provided by Keinonen [1]. Since the textbook [4] did not present a description of the test setting, on which the estimate of the effect of fire was based, further research was crucial.

There is simulator data for research purposes from various exercises. However, the usefulness and credibility of the data is not clear. A small-scale experimental firing to assess the quality of the available simulator data is needed in order to compare the results of simulator fire with the results of live ammunition fire.

The firing experiment supports the Army Academy to improve the TASI simulator and develop the next generation of simulators.

2. Materials and methods

2.1 Description of the firing exercise

The research was carried out at the Kyläjärvi firing area during the Jaeger Brigade conscripts’ live firing exercise 26.-30.3. 2007. Four squads from an anti-tank company fired at 28.3.2007, and three squads of a platoon from an infantry company fired at 29.3.2007. The targets were plastic human dummies (“Anne-nukke”). In front of some of the dummies were small electric flash-bangs. In the TASI test firing the dummies wore combatant simulator laser indicator vests and head gear. The test firing took place in the Kyläjärvi shooting range, in Akkalanselkä. The weather was sunny and the temperature varied between +2°C and +10°C.

For the firing, a squad took positions in foxholes, keeping the terrain ahead under surveillance. They had orders to open fire immediately if the enemy opens fire. The opening of fire by the enemy was demonstrated by detonating the flash-bangs in front of some of the target dummies.

2.2. Preparations and target elements

Before the firing Senior Lieutenant Vulli checked the aiming of the TASI weapons at about 40 meter distance. Checking took place in the surrounding area of Kyläjärvi Johtola. An aiming check board was used and the beacons, 30 cm by 30 cm, were tested. Batteries for the vests were placed in and checked in the beginning of both firing days.

The TASI weapons used in the firing were numbered and placed in the shelter position in such manner that each individual weapon always fired from the same foxhole. TASI weapons were issued in the beginning of each experimental firing, and afterward gathered for the next firing. An inspection performed after the firings revealed that only one weapon with a laser emitter (number 5) had lost aim during firing.

The firing test took place at the top of Hill Akkalanselkä (N 67° 21’47.9’’, E 26° 24’ 29.1’’). The direction of fire was westwards.

Figure 1. Hill Akkalanselkä and the direction of fire. The point of the arrow points at a vehicle track, which is one of the “ditches” referred to later in the report

We positioned the dummies in shallow ditches created by vehicles in the following way: a member of the research team ducked down and searched for a fighting position where he could fire on the enemy in the foxholes. Next, the research team member was replaced by a dummy. Hence the dummies emulate a stationary enemy force lying on the ground, firing at the defenders. A firing position selected by a trained soldier and emulated by a human dummy provides a more realistic target than the traditional piece of cardboard placed in the firing area. Hence spotting the dummies was not easy. The dummies were covered with newspaper and the heads were covered with Pirkka-brand garbage bags of light yellow color. The newspaper represented a snow camouflage uniform. It also made recording hits and quickly fixing the holes possible.

Dummies were numbered from one to five. The closest dummy on the left had number 1, the closest dummy in the middle (in a ditch concealed by a bush) had number 2, the closest dummy on the right in a ditch had number 3 and the dummy about five meters behind dummy 3, laying in the shadow of a tree stump, had number 4. Dummy number 5 was ten meters further, covering behind a tree stub.

The positioned dummies can be seen in Figures 2-7.

Figure 2. Dummy number 1 wearing TASI gear.

Figure 3. Dummy number 2.

Figure 4. Dummy number 3 at the end of a ditch in the shadow of a bush.

Figure 5. Dummy number 4 in the shadow of a stump with roots, feet in a snowmobile track.

Figure 6. Dummy number 5 in the cover of a tree stump.

Figure 7. Dummy targets 1-4 as seen from behind.

The dummy targets represented ducked enemies who were using the cover of the terrain to present as small a target as possible to the direction of the defending force. Figures 8 and 9 show the dummies from the defenders' point of view.

Figure 8. Target dummies as seen from the front. Arrows pointing upwards reveal target dummies 1, 2 and 3, from left to right. The horizontal arrow on the right indicates the position of dummy number 4. The arrow downwards is pointing at dummy 5.

Figure 9. View from behind a foxhole, distance to target dummies 150m

The dummies were fired upon from foxholes on top of a hill. Every dummy was not visible from every defender's position. However, from each position, at least one dummy with location indicated by a flash-bang could be spotted.

Figure 10. Foxholes as seen from the firing zone.

2.3. Description of the test firing

Shooting was carried out as follows:

15 second firing

Two magazines we filled: one with 10 tracers and another with 30 regular rounds. Next the squad leader gave standard defense orders. Each fighter was escorted to his/her foxhole and given an order defining the firing sector and (most relevantly for the study) rules for opening fire: open fire either if the enemy approaches over a defined line or fire back if the enemy opens fire first.

60 second firing

The second (the 60s firing) started at the shelter position as the squad leader ordered “***Asemaan*!”** (“Battle positions!”)

When either the squad leader had guided the fighters to their fighting positions (the 15s firing) or the squad had run to take their positions (60s firing), the firing supervisor gave the following orders:

Orders with live ammunition

a) The 15s test firing, continued as a normal defensive firing drill

“***valojuovalipas kiinnitä*!” -** (insert the magazine with tracers!)

“***lataa*!”** – (load!)

“***tähystä***!” – (scan your sector!)

The small electric flash-bangs were detonated

15 s of firing

“***lipas***!” (replace magazine + cock the rifle)

This order ended the test firing at the dummies.

The drill continued as normal defense exercise: the fighters replaced the tracer magazine with the magazine with 30 regular rounds.

Next, mobile targets rose up time after time until all rounds had been shot.

“***tuli seis!”*** (cease fire!)

The tracer magazines were collected in order to count the number of rounds fired at the dummies.

b) 60s of firing:

“***asemaan****!”* – (take positions!)

“***lipas kiinnitä****!”* – (insert magazine!)

“***lataa!”*** – (load!)

“***tähystä****!”* – (scan your sector!)

Flash-bangs were detonated,

60s of firing

“***tuli seis****!”* (cease fire!)

Orders when shooting with TASI simulators

a) 15s firing
   - “***lipas kiinnitä****!” –* (insert magazine!)
   - “***lataa****!” –* (load!)
   - “***tähystä****!” –* (scan your sector!)
     - Flash bangs were detonated
     - 15s of firing
   - “***tuli seis****!”* (cease fire!)

b) 60s firing:
   - “**lipas kiinnitä**!” (insert magazine!)
   - “**lataa!”** (load!)
   - “**tähystä**!” (scan your sector!)
     - Flash bangs were detonated
     - 15s of firing
   - “**tuli seis!”** (cease fire!)

When the TASI combatant simulator system was used the magazines were filled with 10 blanks for the 15 seconds firing and with 30 blanks for the 60 seconds firing.

The results of each firing test as well as any special conditions, such as non-exploded flash-bangs and reusing them are included in the results file of Appendix 1.

2.4 Documenting the data

After the test firing we counted the number of unused rounds in each fighter’s magazines, and calculated the total number of shots fired. When the weapons had been checked for safety, the research team got permission to enter the firing zone.

After the weapons had been checked and rounds counted the research examined the dummies and then fixed the bullet holes.

After shooting with live rounds we counted and documented four different kinds of hits: hits in the arms, head, legs and torso. Vulli, Lappi and Papinniemi examined the dummies and Mäki recorded the hits on a form presented in Appendix 2.

Senior Lieutenant Vulli read the hits recorded in the TASI simulators. For that task no other research personnel were needed. After each experiment firing the results of the TASI firing test were recorded using a dedicated data recording device into a Panasonic notebook computer using the data recording program AAR. A file containing the results was saved as a separate file for each individual vest.

Some of the hits were apparent and easily detected. However, others were only small holes. Often the exit hole was larger than the entry hole. For every hit the trajectory of the bullet inside the dummy was examined. The same bullet may have first touched the head slightly and then entered the torso. Such hits were counted as head injuries, even though they also made a hole in the body.

Figure 11. A hit in the arm.

Figure 12. A headshot.

3. Results

The results are combined in an Excel sheet in Appendix 1. The most relevant results for each dummy are presented in table 1. "Indicated" ("ilmaistu") means that a flash bang was detonated in front of the dummy when the firing started.

		Maalit									
		1	2	3	4	5	Yht	15s	60s	tasi	kovat
Indicated, not hit	Ilmaistu, ei tuhottu	13	0	10	14	0	37	22	15	17	20
Indicated, hit	Ilmaistu, tuhottu	8	0	12	8	0	28	13	15	12	16
Not indicated, not hit	Ei ilmaistu, ei tuhottu	7	26	5	3	27	68	33	35	38	30
Not indicated, hit	Ei ilmaistu, tuhottu	0	2	1	3	1	7	2	5	3	4
P(hit) if indicated	Tuhoamis% kun ilmaistu	38.10%	ei	54.55%	36.36%	ei	43.08%	37.14%	50.00%	41.38%	44.44%
P(hit) if not indicated	Tuhoamis% ei ilmaistu	0.00%	7.14%	16.67%	50.00%	3.57%	9.33%	5.71%	12.50%	7.32%	11.76%

Table 1. Probability of destruction (hit) for each individual dummy.

According to the data, the probability of a casualty outcome for an enemy fighter who is firing is about fourfold compared to that of a fighter not firing. If a fighter is actively taking cover, the casualty probability can be assumed to be even smaller.

Another significant parameter value for the Sandis direct fire model is the hit (elimination) probability of a single shot. For the complete data the probability of an effective hit is 1.05%. If the last five test firing sets with less flash-bangs are omitted, the results are approximately the same for both dummies wearing TASI simulators and for live ammunition.

The results - namely the single shot hit probability - of the anti-tank company were 1.13% for the TASI dummies (shot first) and 1.17% for dummies shot with live rounds after that. There was a shortage of electric flash-bangs with the infantry company, so their results are not quite comparable. The hit probability for infantry company fire was 1.12% for the live rounds shot first. However, for the TASI dummies, which where fired last, the shortage of indicator flash-bangs decreased the average single shot hit probability: it was only 0.68%.

As an extra observation, by observing the tracers and according to bullet marks on the snow it was concluded that the bullets missed the dummies mainly because of flying too high, over the targets. There were multiple marks in the snow behind the dummies, but only few in front of them.

In addition, fire was concentrated at the stump with protruding roots, not at the dummy fighter 4 in the shadow of the stump.

Figure 13. The fire that hit the stump with protruding roots, not the dummy fighter in the shadow of the stump.

4. Conclusions

Because of the small size of the experimental data, the results can only be considered preliminary. However, according to the data obtained, TASI simulator results are of the same magnitude as the results obtained using live ammunition. Therefore, simulators seem applicable in winter conditions for both applied fire practice and battle emulating firing exercises. Hence more versatile exercises can be developed, since shooting with simulators doesn't require extended safety zones and complicated safety arrangements.

The presented test firing had a small data set and studied only two platoons in winter conditions. Hence, further research is required to increase the amount of the data and to allow taking diverse terrain conditions under consideration. In that case, variables should include different firing distances, different environments, the number of shooters, the number of targets, and a variety of weapons, e.g. the light machine gun which in this experiment wasn't analyzed at all.

In addition, there is a further need for cost-effectiveness analysis for simulator use. Results from Sandis calculations and field experiments can be combined for such analysis.

The results of this research are of the same magnitude as the results of the research by Keinonen [1]. Based on the results presented in [1], Lappi and Pottonen [3] calculated the hit probabilities of single shots for different weapons for Sandis. The hit probability obtained for a semi-automatic rifle was 1.59% for a distance "over 100m", and 0.61% for a distance "over 200m". In both cases the targets were placed on an area covering 1 hectare (= 100m x 100m = 10 000m^2).

Most likely the distance "100m" refers to the distance to the closest targets. In that case the 100m result corresponds to our results presented here, since the medium distance to a target is 150m. If, however, the distance stated in [1] refers to the centre of the one hectare target area, then 150m on our results matches the experimental result in [1] since linear extrapolation of the probability gives us 1.1%, which matches the presented research test firing exactly.

Parallel further research on more detailed level (various distances, diverse positioning, different terrain, different seasons and weather, a different number of shooters and targets) is also needed in order to improve the parameters used in the Sandis software. In any case, we can conclude that using the public data from the 1950's as the first estimate of infantry fire for the Sandis operational analysis software was obviously a functional solution.

Acknowledgments

Many organizations have contributed to the creation of this research report. The Jaeger Brigade provided the facilities and training ground for shooting in winter conditions. The Brigade also provided the needed weapons, the soldiers performing the actual shooting, required supervision and organization for the firing tests as well as the working facilities for the research team.

Army Academy provided the expertise required for using the combatant simulator system (TASI). PVTT (Technical Research Center of the Defense Forces) provided the mathematical modeling expertise.

We would like to state our personal gratitude for the staff of the Jaeger Brigade. In addition we want to express our special thanks to director, Captain Sipponen and to Senior Lieutenant Mähönen and Senior Lieutenant Haavisto, who were organizing and who supervised the firing on the field. We also wish to thank Kari Papinniemi and Sami Mäki, who participated in the field tests.

The authors also wish to thank Risto Bruun, Kosti Jokinen, Riku Lappi and Bernt Åkesson for suggestions and improvements to the manuscript.

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Appendices

Appendix 1 Results

Ammunnan numero			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ryhmän numero			1	1	2	2	3	3	4	4	1	1	2	2	3	3	4	4
Päivä/Yöammunta			P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Ampumapäivä			28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07	28.3.07
Ampuma-aika			13:20	13:35	13:50	14:00	14:15	14:25	14:40	14:50	15:10		15:45	16:00	16:15	16:25	16:40	16:55
TASI/Kova			T	T	T	T	T	T	T	T	K	K	K	K	K	K	K	K
15s/1min/muu aika			15s	1m	15s	1m	15s	1m	15s	1m	15s	1m	15s	1m	15s	1m	15s	1m
Osumat maaleihin	1	Pää	1	1			1		1				3					
		Vartalo																
		Käsi																
		Jalka																
		Tuhottu	1	1	0	0	1	0	1	0	0	0	1	0	0	0	0	0
		Ilmaisin	X	X		X	X	X	X		X	X	X	X	X	X	X	X
	2	Pää			1													
		Vartalo																
		Käsi																
		Jalka																
		Tuhottu	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Ilmaisin																
	3	Pää	1	1				1				3				1	1	
		Vartalo																
		Käsi										1			1			1
		Jalka																
		Tuhottu	1	1	0	0	0	1	0	0	0	1	0	0	1	1	1	1
		Ilmaisin	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
	4	Pää		1								4			1		1	2
		Vartalo										1		1				
		Käsi									1	1						1
		Jalka																
		Tuhottu	0	1	0	0	0	0	0	0	1	1	0	1	1	0	1	1
		Ilmaisin	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
	5	Pää						1										
		Vartalo																
		Käsi																
		Jalka																
		Tuhottu	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		Ilmaisin																
Osumia yht.		Pää	2	3	1	0	1	2	1	0	0	7	3	0	1	1	2	2
		Vartalo	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
		Käsi	0	0	0	0	0	0	0	0	1	2	0	0	1	0	0	2
		Jalka	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Laukauksia		1	2	18	0	25	8	30	10	30	10	30	2	30	10	30	10	30
		2	1	29	0	16	7	30	10	30	10	26	5	30	10	30	4	30
		3	4	27	0	11	10	30	10	30	10	30	4	30	10	30	10	30
		4	2	30	0	30	2	30	10	30	10	30	4	30	10	29	10	30
		5	10	30	3	13	3	30	6	30	10	30	5	26	10	30	8	27
		6	8	30	1	30	10	30	9	30	9	30	8	30	10	30	10	30
		7	10	30	0	30	0	30			10	30	9	30	10	28		
		8																
Laukauksia yht.			37	194	4	155	40	210	55	180	69	206	37	206	70	207	52	177
Osuma%		P	5.41%	1.55%	25.00%	0.00%	2.50%	0.95%	1.82%	0.00%	0.00%	3.40%	8.11%	0.00%	1.43%	0.48%	3.85%	1.13%
		V	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.49%	0.00%	0.49%	0.00%	0.00%	0.00%	0.00%
		K	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.45%	0.97%	0.00%	0.00%	1.43%	0.00%	0.00%	1.13%
		J	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Tuhotut			2	3	1	0	1	2	1	0	1	2	1	1	2	1	2	2
Kokonaisosuma%			5.41%	1.55%	25.00%	0.00%	2.50%	0.95%	1.82%	0.00%	1.45%	4.85%	8.11%	0.49%	2.86%	0.48%	3.85%	2.26%
Tuhottuja/laukaus			5.41%	1.55%	25.00%	0.00%	2.50%	0.95%	1.82%	0.00%	1.45%	0.97%	2.70%	0.49%	2.86%	0.48%	3.85%	1.13%

Final results

17	18	19	20	21	22	23	24	25	26	27	28	Kaikki yht.
5	5	6	6	7	7	5	5	6	6	7	7	
P	P	P	P	P	P	P	P	P	P	P	P	
29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	29.3.07	
8:30	8:45	9:00	9:15	9:40	9:50	10:05	10:20	10:35	10:45	10:55	11:05	
K	K	K	K	K	K	T	T	T	T	T	T	
15s	1m	15s	1m	15s	1m	15s	1m	15s	1m	15s	1m	
		1				1						9
												0
			1									1
												0
0	0	1	1	0	0	1	0	0	0	0	0	8
X		X	X		X	X		X		X		
					6							7
					2							2
												0
												0
0	0	0	0	0	1	0	0	0	0	0	0	2
							1		1		1	11
			1									1
					1							4
												0
0	0	0	1	0	1	0	1	0	1	0	1	13
X	X		X	X			X		X		X	
	2		3	2		1						17
	1		1	1								5
												3
												0
0	1	0	1	1	0	1	0	0	0	0	0	11
X	X	X			X	X		X		X		
												1
												0
												0
												0
0	0	0	0	0	0	0	0	0	0	0	0	1
0	2	1	3	2	6	2	1	0	1	0	1	45
0	1	0	2	1	2	0	0	0	0	0	0	8
0	0	0	1	0	1	0	0	0	0	0	0	8
0	0	0	0	0	0	0	0	0	0	0	0	0
10	30	10	14	10	23	7	30	10	30	6	30	17.32143
10	30	5	12	10	28	10	30	10	14	9	30	16.64286
9	30	10	18	10	23	10	30	6	30	10	30	17.57143
8	25	10	21	10	30	3	26	5	20	10	30	17.32143
7	11	10	30	10	30	6	30	9	30	10	30	17.28571
10	30	10	19	10	30	10	30	10	30	4	30	18.85714
10	27	8	27	10	30	3	30	5	30	8	0	16.875
64	183	63	141	70	194	49	206	55	184	57	180	3345
0.00%	1.09%	1.59%	2.13%	2.86%	3.09%	4.08%	0.49%	0.00%	0.54%	0.00%	0.56%	1.35%
0.00%	0.55%	0.00%	1.42%	1.43%	1.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.24%
0.00%	0.00%	0.00%	0.71%	0.00%	0.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.24%
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0	1	1	3	1	2	2	1	0	1	0	1	35
0.00%	1.64%	1.59%	4.26%	4.29%	4.64%	4.08%	0.49%	0.00%	0.54%	0.00%	0.56%	1.82%
0.00%	0.55%	1.59%	2.13%	1.43%	1.03%	4.08%	0.49%	0.00%	0.54%	0.00%	0.56%	1.05%

						49	206	55	184	57	180	1606
						2	1	0	1	0	1	15
						4.08%	0.49%	0.00%	0.54%	0.00%	0.56%	0.93%
						2	1	0	1	0	1	15
						4.08%	0.49%	0.00%	0.54%	0.00%	0.56%	0.93%

64	183	63	141	70	194							1739
0	3	1	6	3	9							46
0.00%	1.64%	1.59%	4.26%	4.29%	4.64%							2.65%

Appendix 2 Data collection form

(Prepared by corporal Sami Mäki)

Ammunnan tiedot
TASI ☐
Kovat ☐

Päivä ☐
Yö ☐

15 s ☐
1 min ☐
Muu ☐

Ammunnan numero:
Ampuva ryhmä (nimi ja numero):
Ampujien määrä:
Ammunta-aika:
Ammuntapäivä:

OSUMAT

MAALIT

	Pää	Vartalo	Jalka	Käsi	Ilmaisin
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

Laukauksia yhteensä:

Ammutut laukaukset

Ase	Laukauksia
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	

Lisähuomautuksia ammunnasta:

Publication VIII

Esa Lappi, Kari Stenius and Marko Vulli. Field Tests for Finding the Injury Profile from Mortar Fire. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

In e-proceedings under subdirectory “Session 2B”.

Field Tests for Finding the Injury Profile from Mortar Fire

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Abstract

Field tests were performed to find the firepower of mortar units and injury profiles from mortar fire. The injury profiles provide information for preparations for medical action on the battle field and parameters for simulators.

In five tests ten lying dummies were randomly placed in a 100 m x 100 m target square and in three tests only five dummies were used. After each firing the dummies were examined and the locations of the injuries and fragment sizes were determined. The dummies were categorized into five classes based on their injuries: no hit, light, moderate, severe and dead or dying. The impact point of each grenade was marked and the coordinates were recorded.

The locations of the fragment hits and the injury class as a function of the distance to the nearest impact point were studied. The hit location distribution was similar to data from Operation Iraqi Freedom, but the number of lightly wounded was smaller in the tests.

1. Introduction

The aim of the measurements was to determine the effectiveness of mortar fire and consequential injures on a dummy target unit. The dummy unit was representing a person lying on the ground taking cover.

The results will be used in different fields. Combat training simulators as well as military operational analysis tools like Sandis [1] need parameter data like fragment hit probabilities. Evacuation models and medical training also require parameters. Injury profiles provide additional information to predict the procedures and activities required to treat and evacuate the wounded. The new data will make future programs simulating tactical field medicine more useful and realistic.

2. Materials and methods

The experiments were carried out in the Rovajärvi firing range during field firing exercises on November 19th - 30th, 2007 (winter conditions) and on May 19th - 30th, 2008 (summer conditions)

Three one hectare (100m x 100m) fields of target units were constructed for both winter and summer conditions. Each had 100 cardboard cylinders as targets.

In addition, in November there were 10 human figure dummies ("Anne first aid dummy") and 10 metal cylinders made of 1mm aluminium plate in one of the fields. In May there were two fields with additional targets in addition to the paper cylinders: one field with 10 metal cylinders and 10 Anne-dummies, and another with 10 metal cylinders and 5 Anne-dummies. Metal cylinders are used to obtain the ratio between high energy fragments and low energy fragments. Anne dummies are used for injury profile and hit probability studies between cylinders and dummies.

The firing took place in Outovaara in the Sarriojärvi firing area.

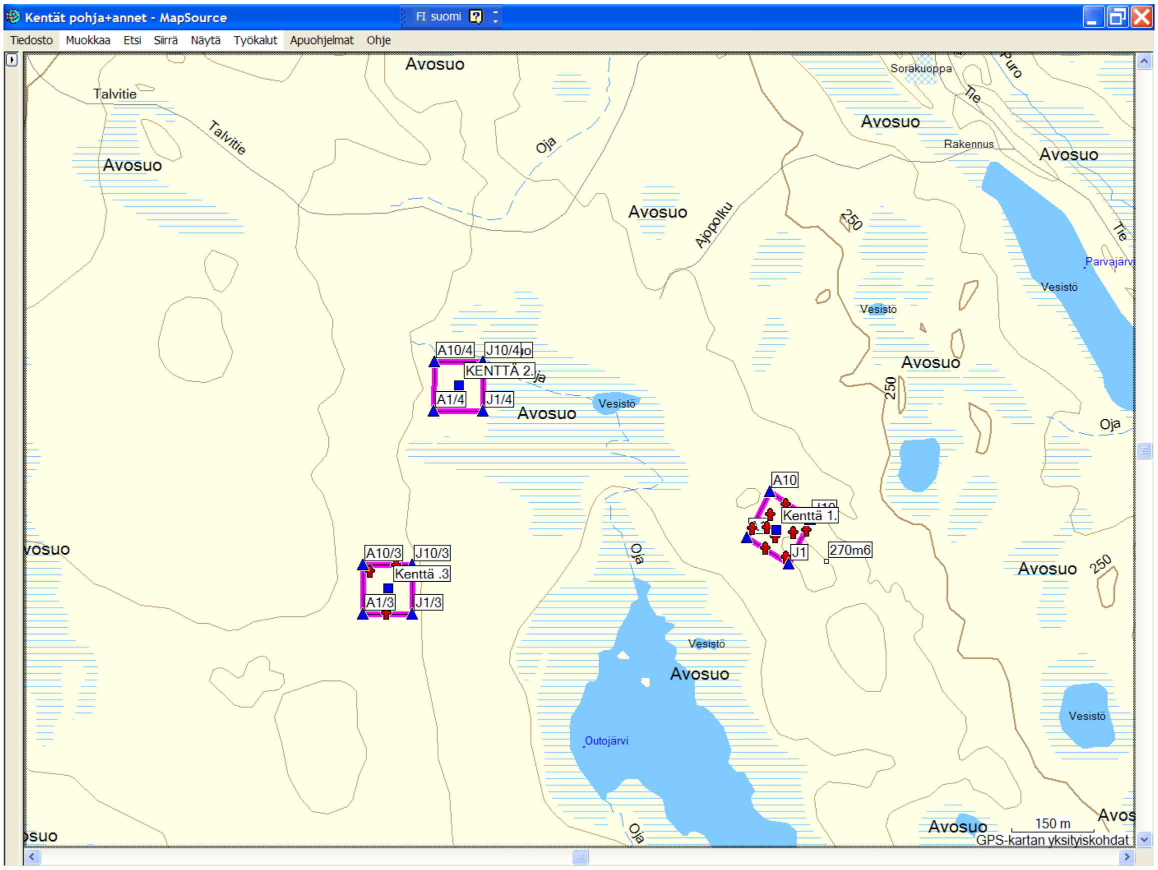

Figure 1. A map presenting the firing area and the target fields.

2.1 Preparations and target units

In order to locate the fragment hits the Anne-dummies were wrapped in newspapers and masking tape and the heads of the dummies were covered with blue plastic bags. Hence the “mummified” figures appear different from real people, regardless of viewing distance.

The dummies and the metal cylinders were placed in same fields. The ratio of the number of fragment hits on the dummies and the cylinders was used to evaluate the validity of using a cylinder to represent a human body. The ratio of the number of hits on the metal cylinders and the cardboard cylinders was used to estimate the penetrating power of the fragments. The combination of the fragment hit profile on the dummies and the fragment penetrating power on dummies was used to estimate the severity of injuries caused by mortar fire. The dummies were positioned laying flat on the ground, each one beside a metal cylinder, as shown in Figure 2.

Figure 2. The targets mimicked combatants laying on the ground to take cover.

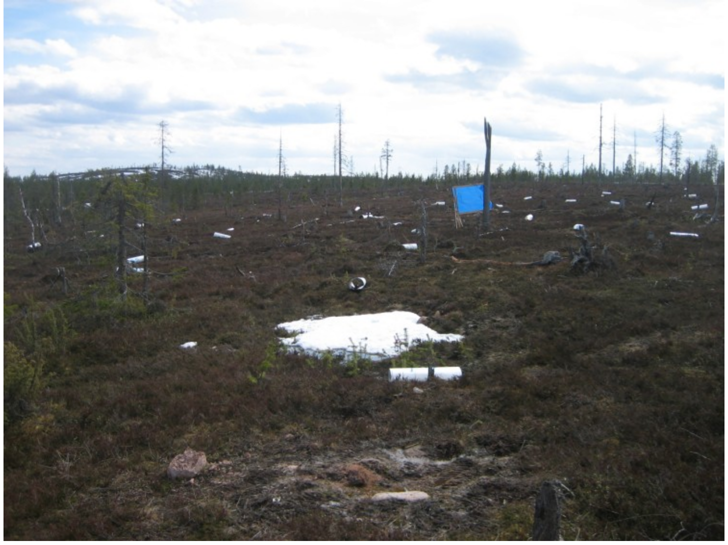

Figure 3. There was a large blue plastic film in the centre of the target field for the artillery observers.

Figure 4. Target units were positioned in lines. The distance between adjacent target dummies was 10 meters.

2.2 Recording the data

After the shelling the fragment hits in each cylinder were counted. Fragment hits in the human figure dummies were recorded and classified as hits in the arms, head, legs or torso. After each bombardment the target objects were inspected and each fragment hit was marked with a marker pen and, if needed, covered with masking tape. Fragment hits on the Anne-dummies were classified according to estimated injury severity and rated in triage classes 1-4.

Figures 5 and 6. Hits were marked and counted.

Figure 7. An explosion in a tree above the target unit.

Figure 8. An explosion next to a cylinder.

Figure 9. Injures were classified according to severity.

Figure 10. Nearby hits cut down branches from trees on the targets.

2.3 Medical measurement methods

The human figure dummies made it possible to take anatomy into account in the evaluation of injuries caused by fragment hits in different parts of the body. For each fragment hit, the size of the fragment and the trajectory of the fragment from the point of explosion were estimated and the point of hit was marked on the human figure dummy. Penetrating hits in the chest, in head and in the abdominal cavity were rated as class (1) or as class (4) injuries. The classification was done on the spot. Hence the distance from the point of explosion and energy of the explosion could be taken into account. The number of fragment hits was also taken into consideration when classifying the wounded. A single fragment penetrating an anatomically critical part of the body could result in classifying the dummy as a patient in class (4) (fatally wounded or dead). A metal cylinder placed next to the dummy was used to show the penetrating energy of the fragments at the spot.

3. Medical test results

3.1 Location and distribution of injuries

In the experiment fragment hits and injuries of 65 Anne-dummies were evaluated. There were a total of 338 fragment hits in the dummies and they were distributed between different body parts as shown in the following figures.

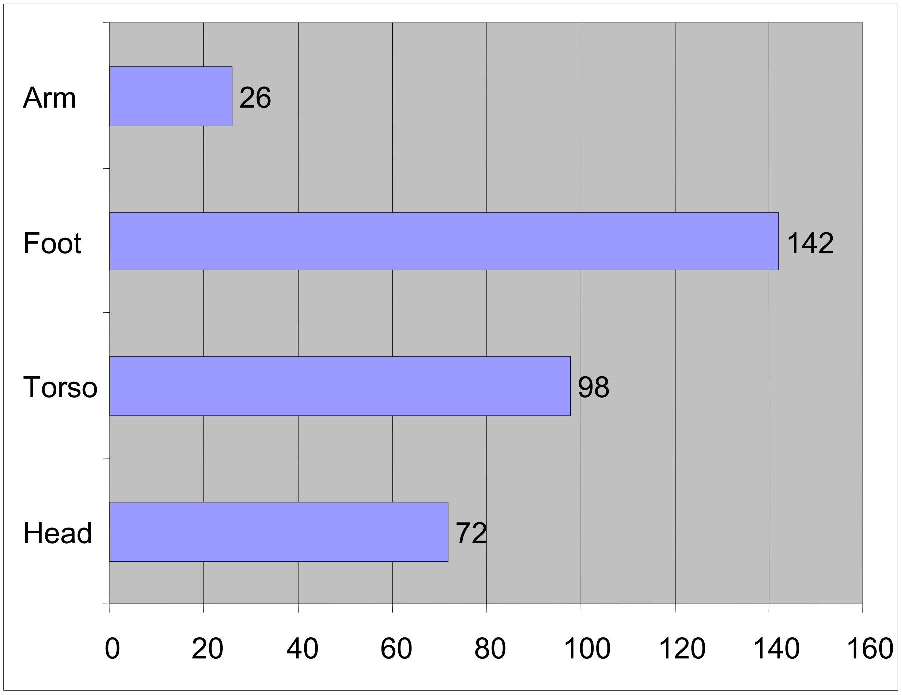

Figure 11. Fragment hit distribution (number of hits).

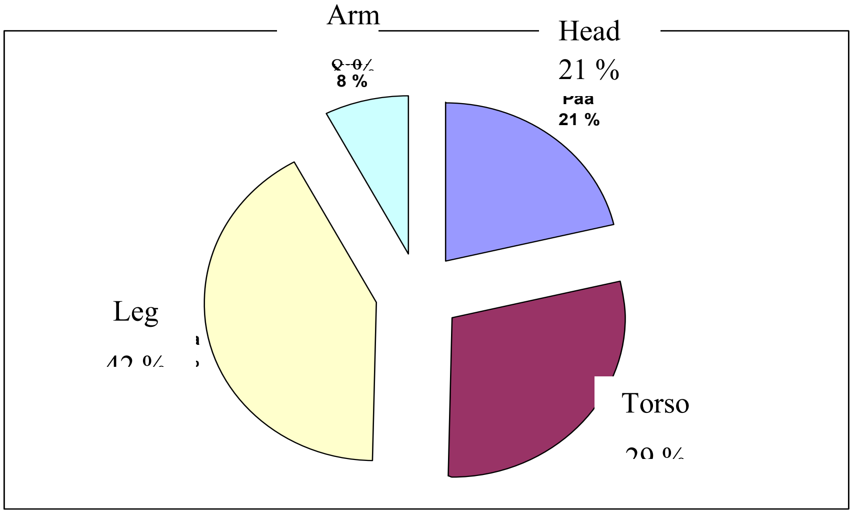

Figure 12. Fragment hit distribution (percentages).

The Anne human figure dummies performed well as target units. They made it possible to make a reliable estimate of the injury severity class of the wounded. They also provided reliable data on the location of the injuries. Results of the tests turned out to be in line with results from reference literature.

3.2 The relationship between the distance from the point of explosion and the nature of the injuries

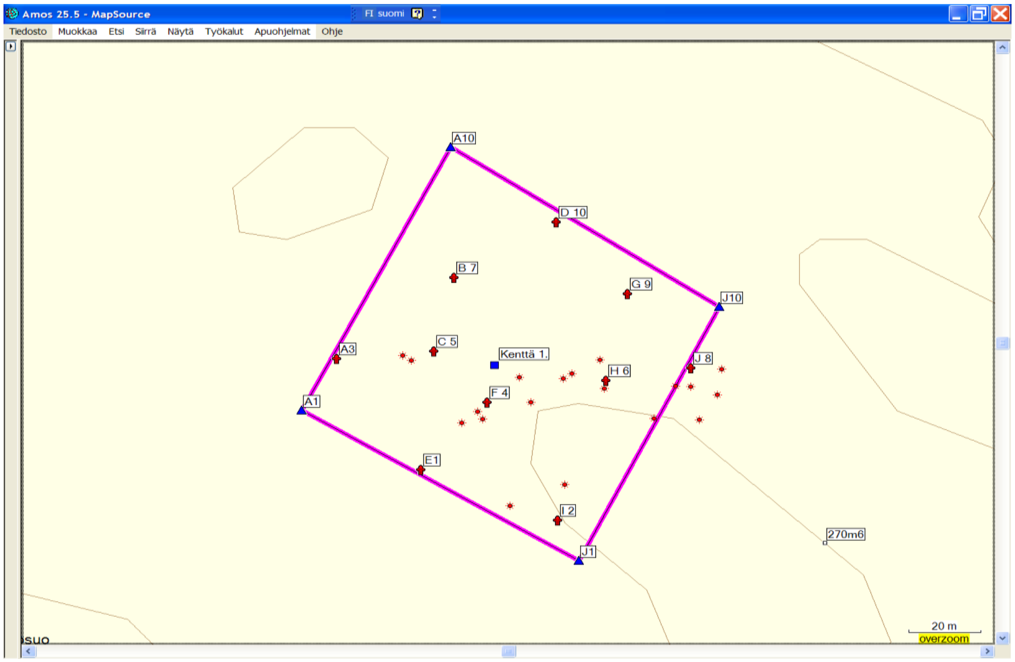

Figure 13. The positions of the Anne dummies in the target field and the impact points of the shells.

Triage classes used in the experiment

1. Urgent **Red**
2. Relatively Urgent **Yellow**
3. Can wait. No serious injuries **Green**
4. Lethally injured, Dying or Dead **Purple**
5. No Injuries. (triage 0) **White**

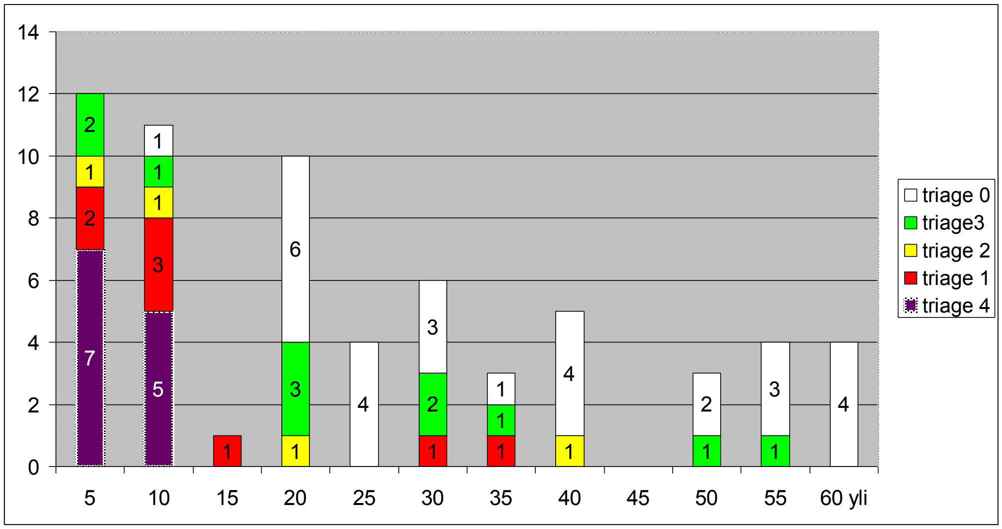

Figure 14. Quantity of victims in each injury urgency class relative to the distance (meters) from the point of explosion.

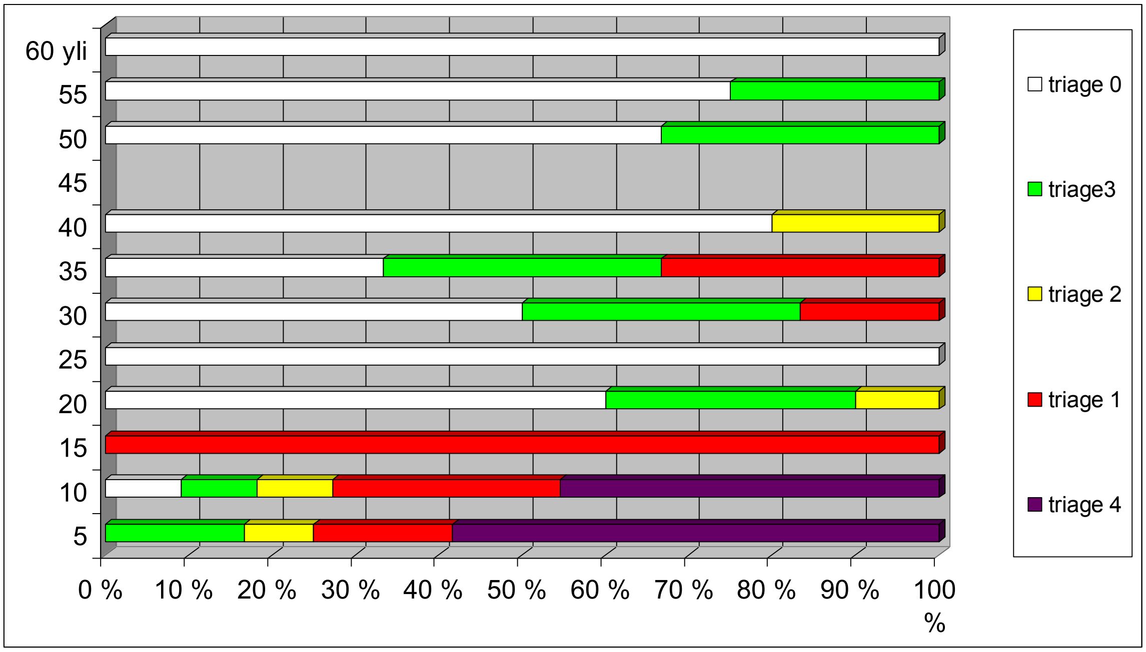

Figure 15. Urgency classes of the injuries as percentages at different distances (in meters) from the point of explosion.

At a 1-5 meter distance from an explosion no target figure remained uninjured. Dead or dying comprised 60% of them. At a 10-meter distance one target figure remained uninjured, the rest of the victims getting mainly severe injuries. This can be explained to some extent by the fact that in forest terrain trees and ground contours shield a person seeking cover on the ground. Severe injuries requiring urgent care were found at distances up to 35 meter from the explosion. The effect of stray fragments was illustrated by the fact that fragment hits were found up to the distance of 55-60 meters from the points of explosion (3 hits at 55m-60m).

3.3 Typical injuries

Piercing wounds from large fragments caused the most severe injuries regardless of which part of the body (limbs, torso, head) they hit. Target dummies near the point of the shell explosion had multiple injuries, i.e. they had fragment hits all over the body. An injury caused by a single fragment depended mainly on the part of the body the fragment hit.

Single hits in the limbs resulted mainly in a triage class 3 injury, provided that the loss of blood could be stopped immediately by first aid by the wounded himself or a fighter next to him/her.

Figure 16. A Penetrating injury in the chest. Instant death. (IV)

Figure 17. A Penetrating head injury. (IV)

Figure 18. Multiple fragment hits in the leg, no other injuries. (III)

Figure 19. Fingers pierced by a fragment.

Figure 20. A hit in the foot.

Figure 21. A superficial scratch on the chest. (III)

4. Conclusions

According to comparison with the Anne-dummies, the cardboard cylinders provide a fairly good approximation of human figures thrown on the ground to seek cover. In addition, the number of penetrating hits in the cardboard cylinders and metal cylinders were compared. The ratio demonstrated nicely the effective fraction of the projectiles hitting the cylinders.

The anatomic distribution and the severity of the injuries are to a large extent in line with corresponding numbers in the reference literature. A major part, 50%, was in the arms and legs. Hence stopping the bleeding as fast as possible would have been the primary first aid. With proper field dressing, using a pressure dressing and/or a tourniquet, many of the injuries could have been treated by a medic or a fighter next to the victim. Injuries caused by shell fragments either in the abdominal cavity or in the chest require fast evacuation to a dressing post and/or to a dressing station and immediate surgical procedures in order to halt the internal bleeding and sustain breathing.

The pressure effects of explosions cannot be demonstrated by this method. To estimate the pressure effects a different method should be developed. Model figures wearing a helmet and protective vests should also be tested in order to evaluate the effect of protective gear on the injury profiles.

The field medical analysis on this test setting provides data for the development of operational analysis - based simulation methods for field medicine (e.g. [1]).

The data set obtained from the measurements in these live firing tests was small. Only three types of terrain were studied. Hence further research is necessary in order to increase the amount of primary data and to enable analysis in different terrain conditions. Variables requiring further study include different distances from the point of shell explosion, different kinds of terrain, different mortar and artillery weapon systems and a set of different target troops using different protection methods and equipment.

Acknowledgements

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References

[1] Lappi E. "Sandis – Operational analysis software for comparative analysis", 2nd Nordic Military Operational Analysis Symposium, Stockholm, November 17-18, 2008.

Publication IX

Lauri Kangas and Esa Lappi. Probabilistic Risk Analysis in Combat Modeling. In Hämäläinen, Juhani (ed.) Lanchester and Beyond. A Workshop on Operational Analysis Methodology. PVTT Publications 11. ISBN 951-25-1707-8.

Probabilistic Risk Analysis in Combat Modeling

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Abstract

Probabilistic approaches are breaking ground in the assessments of military scenarios. Stochastic combat models give the probability distributions of the force strenghts. From this information it is possible to derive the probability of the unit being unoperational. Certain scenario is composed, among other things, of several units and the missions both sides have. Each mission determines a fault logic for the units included in the scenario. With probabilistic risk analysis methods combined with operability probabilities provided by a stochastic combat model we get fair good risk assessment of the situation. Additionally, we can outline the operability of forces as a whole and calculate the success of a certain mission that includes lots of forces.

Keywords: Combat modeling, probabilistic risk analysis (PRA), fault logics

1 Introduction

Military battle assessments have been important since wars started to take place. Finnish Defence Forces use many methods to evaluate a certain tactical situation, one of the most important being Quantified Judgement Method [1](QJM) -based analyses. These methods try to describe the potential damage a weapon system can affect. Basically, they score weapon systems and then compare the total scores of forces.

These kind of analyses omit some relevant issues that need to be considered, most importantly the probabilistic nature of war. This paper suggests that probabilistic approach to battle combined with probabilistic risk analysis provides tremendous benefits to the situation assessment. Stochastic combat modeling gives measures for randomnesses and uncertainties. Probabilistic risk analysis helps to see that the success constructs from the lower level performance and to identify the weak components of a system.

Stochastic combat modeling issues have recently been under research and probabilistic assessments have been made available [2], [3] in Finnish Defence

Forces Technical Research Center (PVTT). This research has led to the development of a operational analysis software tool, Sandis, created in PVTTEIOS.

The probabilistic risk analysis (PRA) provides methods to evaluate system success (and fault) probabilities. It has now been used in process engineering for few decades. PRA is both qualitative and quantitative analysis. It helps to assess the risks that a system includes and to measure them.

Both the stochastic combat modeling and probabilistic risk analysis are based on probabilistic approach. In this paper we demonstrate how these two can be combined in an entirely novel way that produces solid judgement of the situation.

2 Stochastic Combat Models

Combat models try to describe the events of a battle trough mathematical formulation. Deterministic combat models give a point estimate of result, in form or another - stochastic combat models take into account the "chaotic" and probabilistic nature of battle. In stochastic combat models, events are thought random, and this leads to probability distributions. Most intuitively, losses within a certain time interval can be thought as random variable, and then the force strenghts become random variables. Figure 1 demonstrates the idea of force strenght distribution (on right) and the faulting probability (on left).

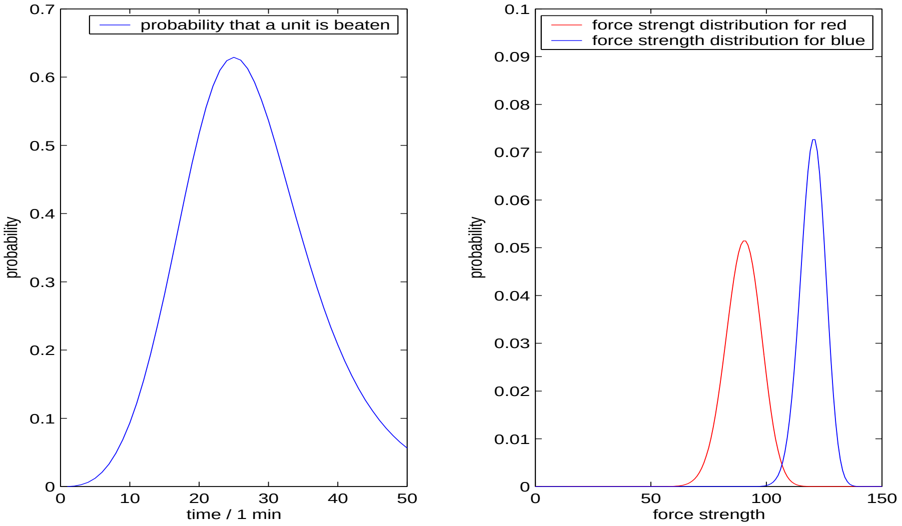

Figure 1: On left there is an example of a unit's faulting probability with respect to time. A unit can regain its operability because of reinforcements, first aid given etc. On right there is an example of force strenght distributions. Blue has at high probability bigger strenght than Red.

PVTTEIOS has been working with stochastic combat models for some time now and the research done has led to a development of a Sandis software. This software is based on a scenario based battle model designed lately [7], and it calculates the force strenght distributions for every company included in a scenario. It includes a model for first aid and evacuation of the wounded, described more closely by [5]. It also calculates the operability probabilities for each company. The mathematical methadology of this model is more described in [3] and the application possibilites of the software have been considered in [4].

3 Probabilistic Risk Analysis

3.1 Background

Probabilistic risk analysis has become a common engineering tool. The methods are taught in technical universities and the senior author has been working in the field for a decade before joining the military research center. This PRA-section is based on HUT teaching material by Dr. Urho Pulkkinen [9], Perry's Handbook of Chemical engineering [8] and practice used in Turvallisuusarviointi TA Oy (Safety Evaluation ltd).

Probabilistic risk analysis can be used, if the system and its functionality can be modeled and probabilities of success, failure or malfunction can be estimated for each modeled part. This can be done using statistics and observations. The statistics can be from systems or subsystems. For example the insurance companies have fire statistics, which showed 5% failure probabilities to automatic sprinkler systems. Thus we can use 95% probability for successful suppressing, if there are standardized sprinkler systems. On the other hand, we might know, that water pump failure probability, detection system failure probability, pipeline operability and calculate the failure probability of that special system form the parts. Also detection system can be divided to subsystems etc.

The probabilistic risk analysis can be devided into separable steps that are taken. There are various sets of steps in the literature that differ a bit of each other. Turvallisuusarviointi TA Oy (Safety Evaluation ltd.) uses the following steps based on [8]:

1. Define goal
2. Describe system
3. Identify risks and hazards or weak points
4. Estimate consequences and their probabilities

5. Model risk situations and name initial failures
6. Estimate probabilities of the initial failures
7. Calculate overall failure probabilities
8. Estimate the losses for failure situations.
9. Calculate expected values for further actions
10. Decisions and Future action.

3.2 Cut Sets

Cut set is such set of components that if every component in a cut set fail, the whole system fails. Following simple example explains the idea.

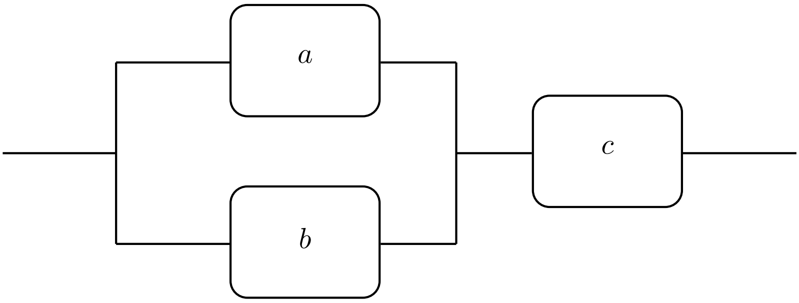

Figure 2: Simple system with components a, b and c.

For the system to work component c is essential and either component a or component b must work properly. Cut sets are $\{a, b, c\}$, $\{a, b\}$, $\{a, c\}$, $\{b, c\}$ and $\{c\}$.

Minimal cut set is a cut set, where one cannot take any component out of the cut set without the system become operational. Mathematically, a minimal cut set does not have a subset that is a cut set.

Thus, in example we examined, minimal cut sets are $\{a, b\}$ and $\{c\}$. If we want to calculate system failing probability, minimal cut sets are usually used in calculations. Let us denote the whole system by abc and the subsystem composed by a and b by ab (see figure 2).

For each minimal cut set the failing probability is a product of each components failing probability, in this example

$$P('ab \text{ fails}') = P('a \text{ fails}') * P('b \text{ fails}') \tag{1}$$

Now the failing probability of the whole system is

$$\begin{aligned} P('abc \text{ fails}') &= P('ab \text{ fails}' \text{ or } 'c \text{ fails}') \\ &= P('ab \text{ fails}') + P('c \text{ fails}') - P('ab \text{ fails}' \text{ and } 'c \text{ fails}') \end{aligned} \tag{2}$$

If failing probabilities are near zero for all components, we can neglet the term $-P('ab \text{ fails}')P('c \text{ fails}')$ as a second term object, and failing probability can be estimated to be the sum of cut sets failing probabilities.

Generally, if the operability of a system T can be modeled with fault logics and the set of all minimal cut sets $\{C_i\}_{i=1}^{n}$ is separable, that is $i \neq j \Rightarrow C_i \cap C_j = \emptyset$, the fault probability of the whole system is [9]

$$\begin{aligned} P('T \text{ fails}') &= P\Big(\bigcup_{k=1}^{n} 'C_k \text{ fails}'\Big) &(3) \\ &= \sum_{k_1} P('C_{k_1} \text{ fails}') - \sum_{k_1<k_2} P('C_{k_1} \text{ fails}' \cap 'C_{k_2} \text{ fails}') + \\ &\quad \sum_{k_1<k_2<k_3} P('C_{k_1} \text{ fails}' \cap 'C_{k_2} \text{ fails}' \cap 'C_{k_3} \text{ fails}) - \ldots &(4) \end{aligned}$$

The first term approximation of this equation is similarly the sum of the cut sets' probabilities, which is a good approximation if all the probabilities are near zero.

3.3 Fault Trees and Event Trees

If a success or failure can be modeled with separate events, event tree analysis can be used. A simple example of event tree below describes operation with two steps. If the first step succeeds in second step there are tree options: complete success, minor failure (a fails) or major failure (b fails). If the operation starts with a failure (for example artillery fails to support an attack) recovery operations might save the system (attacking tanks use direct fire to support advancing forces etc.), but if that fails, the operation ends with a disaster and system is lost. (Our forces loose the battle.)

The probabilities of each consequence are calculated as a product of all probabilities on the path from initial state to the consequence. When measure of the cost or the profit of each consequence is multiplied with the probabilities, we get expected values of each path and adding them together we get the expected value of the whole operation.

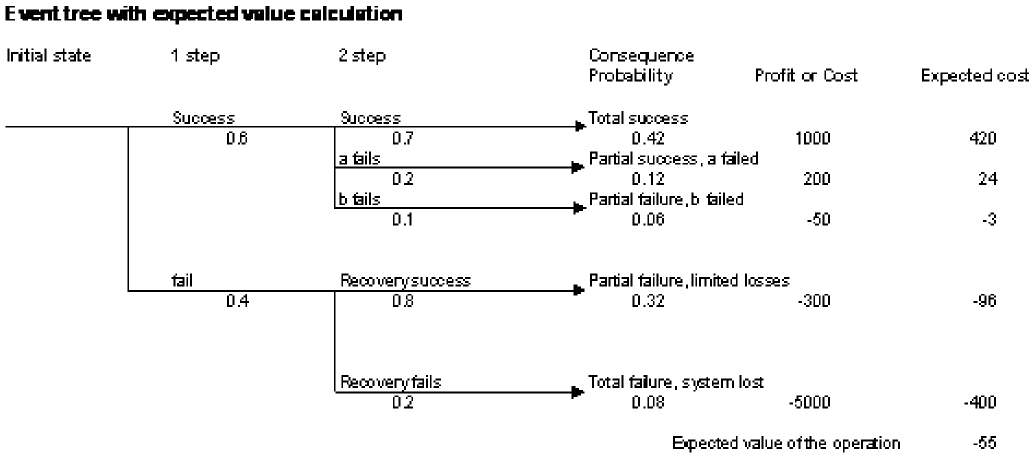

Figure 3: Event tree with expected value calculation.

Fault trees are used, when system success or fail is built from the components. The success (or failure) comes with and/or gates ending with top event. The fault tree is commonly used, and there are commercial software tools available for this kind of analysis. For example Finnish defense forces have ELMAS software from Tampere University of Tecnology and later Artekus Oy [6].

4 Fault logics and Use of Probabilistic Risk Analysis in Operational Analysis

We now introduce a more general fault logics port: a k/n -port. It means that for an ensemble of n components k must be operational for the whole ensemble to be operational. It can easily be seen that k/n -port actually includes the *and*-gate and *or*-gate. This kind of port is more convenient in military analyses, because we often define the fault logic in the k/n -form, e.g. "at least two of these units must keep their position".

Let us examine the following example (see figure 4): there are three roads to the attacker's target area, and there is a defending unit blocking each road and also a fourth unit defending the target area. Let us assume, that operation needs first breaking trough with any road and then taking the target area (e.g. paratroops could not keep the are without support and maintenance via the roads).

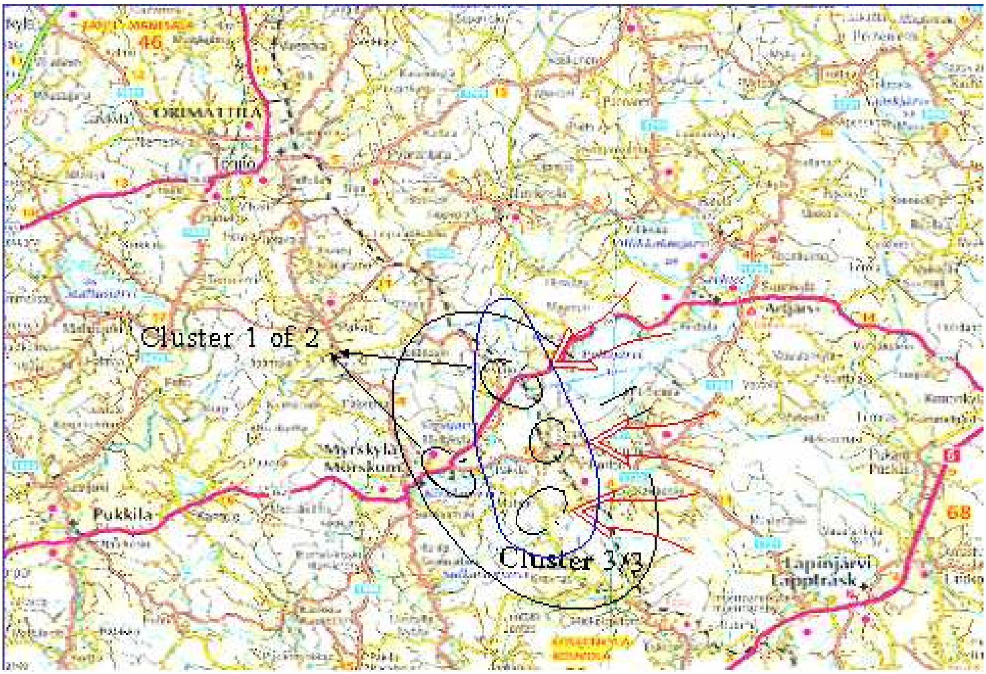

Figure 4: Analysis

In this imaginary situation the success logic for the units that defend the road is 3 of 3: every unit has to succeed in keeping its area. If these units form cluster no. 1, and the fourth unit forms cluster no. 2, the success logic for these two clusters is 1/2: at least other of the two has to succeed.

More generally, let us examine a scenario with the perspective of stepwise PRA, discussed in page 4. In military operational analysis, we have to define the goal of a mission, and to describe the scenario (steps 1 and 2). Thereafter, we have to identify what could go wrong, that is, which subtasks of a mission are at most risk to fail (step 3). Consequences of such events have to be estimated (step 4) and the failure of subtask has to be decomposed to initial failures (step 5). This means that we define a desired success logic for units involved. After that, we need to estimate the probabilites for certain units to fail (step 6) and furthermore to calculate the fault (or success) probability of the whole mission (step 7). Then we have to estimate what losses would a failure inflict (step 8) and to calculate the estimated values for possible actions (step 9). Finally, we can use this information to make our decision how to proceed.

If an operations analyst defines the scenario and the mission with fault logics conserning the units in the scenario and also defines the cost of the mission to fail (steps 1-5), the Sandis software will provide the units' faulting probabilites and the whole mission's faulting probability (steps 6-7) and also provides additional information about the losses (e.g. remaing forces' strenght distributions). After that the analyst can estimate the losses related to the failure and calculate the expected values for all possible actions (steps 8-9). Finally he can compare the alternative actions and conclude to some decision among them (step 10).

5 Conclusions

We have introduced what similarities stochastic combat modeling and probabilistic risk analysis have in the way they approach problems. We have shown that they are closely linked to each other and can be combined in a way that richens the analysis of a tactical scenario. Probabilistic risk analysis methods fit well in the area of military operations research, especially if stochastic combat models are used.

We have presented a way an operations analyst can use PRA-methods in scenario based analysis. With a given scenario, mission and fault or success logics of the units, the success probability of the whole mission can be calculated with the help of Sandis software.

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Publication X

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X

Network Warfare and Probabilistic Risk Analysis (PRA)

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Abstract

Probabilistic risk analysis can be used as a tool in military operation analysis. It has been implemented in the Sandis code developed and used by Finnish Defence Forces Technical Research Centre. (PVTT). In the probabilistic combat calculations, a probabilistic network warfare model can be implemented using methods by Sarvi et al. [9]

Key words

probabilistic risk analysis, combat models, network warfare.

1. Introduction

Probabilistic risk analysis (PRA) provides methods to evaluate system success probabilities. The communications and the reliability of the communication networks are essential for the military units to function effectively.

When considering our own forces, the stepwise methods of the PRA need only little modification in order to be used in Electronic Warfare (EW) and network analysis. The enemy action only affects the failure probabilities, not the structure of the system as a reliability problem.

When planning our own electronic warfare, the goal is to cause maximal harm to enemy operation. When a risk analysis model of the enemy is available, our own action can be selected to cause optimal damage with the best probability-consequence combination to fit our battle plan and other military action.

The methods to estimate the battle value of EW action have been discussed in papers [1], [2], [3] and the *Sandis* simulation software tool in [4]. The *Sandis* software has been developed in the Finnish Defence Forces Technical Research Centre (PVTT), and it uses state machines and Markovian combat modelling for battle loss analysis.

The software is being developed further, and the work in PVTT continues in order to include new weapon systems and features to *Sandis*. – For a description of *Sandis*, see e.g. [10].

For accurate operation success and battle loss calculation there is a need to estimate communication network availability.

2 Probabilistic risk analysis (PRA) used with *Sandis*

Probabilistic risk analysis is an established engineering tool. Its methods have been taught in Helsinki University of Technology for 20 years. The information is commonly available in textbooks, for example [5], [6], [7].

The use of the PRA methods for military solutions has been discussed by Kangas & Lappi [8]. In combat modelling, event tree type analysis can be used, as described in [8].

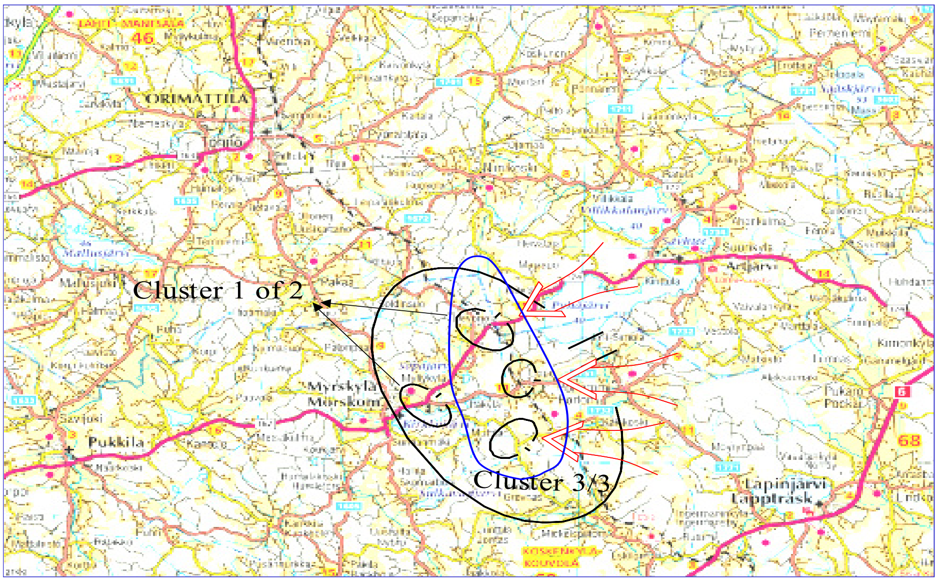


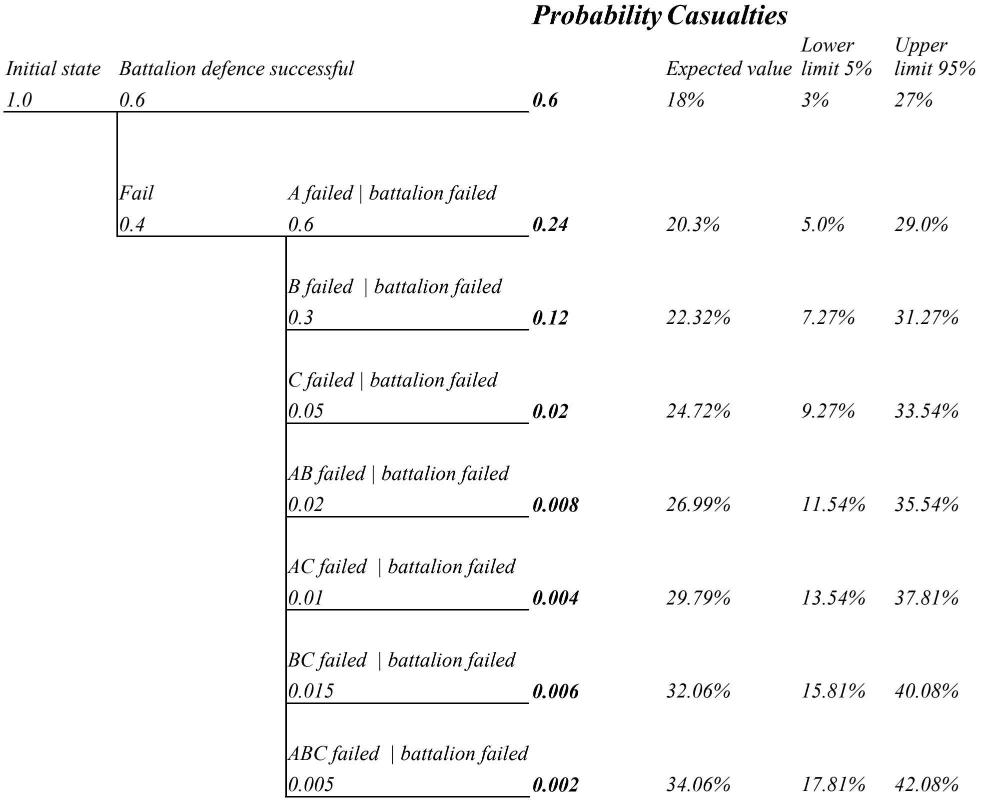
Figure 1. Defending battalion with a cluster with 3/3 fault logic

The future is estimated by using a number of alternative paths of events with a probability estimate for each of the paths. These different alternative future outcomes must be calculated separately using different combinations of beaten units from the branching point of the simulated scenario.

As an example, let us consider a defending cluster with 3/3 fault logic. The *Sandis* code gives failure probabilities for individual units (companies) and the resulting failure probability of a 3/3 unit cluster (a battalion) as a function of time. These values can be used for further analysis using event trees.

An example with dummy parameters is shown in figure 2. Eight Sandis simulations would be needed to get the initial probability values for this event tree.

Accurate analysis



Initial state	Battalion defence successful		Probability	Casualties: Expected value	Lower limit 5%	Upper limit 95%
1.0	0.6		**0.6**	18%	3%	27%
	Fail 0.4	A failed | battalion failed 0.6	**0.24**	20.3%	5.0%	29.0%
		B failed | battalion failed 0.3	**0.12**	22.32%	7.27%	31.27%
		C failed | battalion failed 0.05	**0.02**	24.72%	9.27%	33.54%
		AB failed | battalion failed 0.02	**0.008**	26.99%	11.54%	35.54%
		AC failed | battalion failed 0.01	**0.004**	29.79%	13.54%	37.81%
		BC failed | battalion failed 0.015	**0.006**	32.06%	15.81%	40.08%
		ABC failed | battalion failed 0.005	**0.002**	34.06%	17.81%	42.08%

Figure 2. Event tree of 3/3 battalion. (dummy values)

If all the scenarios are calculated, the simulation time and the work needed is growing with n^2. In scenario with two battalions the number of different combinations is $8^2 = 64$. Thus there is a need to simplify analysis. Figure 2 shows a simplified event tree, in which only two Sandis simulations are necessary for one cluster and $2^2 = 4$ for two clusters.

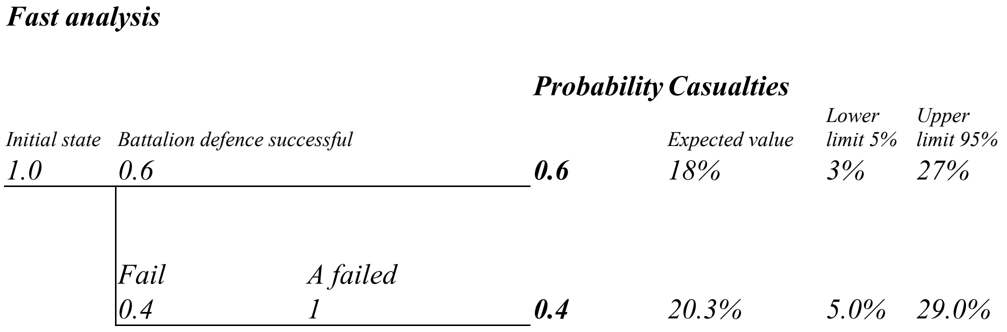


Figure 3. Fast analysis version of 3/3 cluster analysis (dummy values)

In this example, the probabilities of all event paths which result in failure are collapsed into the one which the greatest likelihood of failure. There are other options to simplify the analysis, e.g. choosing the worst case.

When certain units are selected to be beaten or not beaten in scenario based analysis, the Sandis strength distributions need to be adjusted before further calculations. Two alternative strength distributions are calculated as conditional probabilities.

(1a) $P(\,strength\ n \mid beaten) = P(strength\ n) \,/\, P(beaten)$,

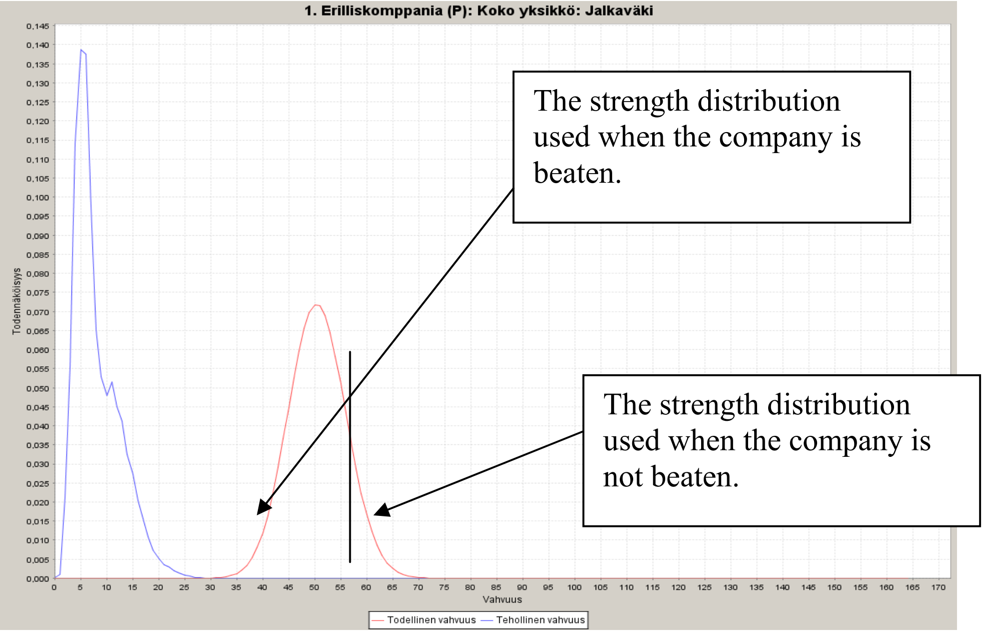
if the unit is beaten with strength n and else

(1b) $P(strength\ n \mid beaten) = 0.$

Because the sum of first states is not in general equal of the probability of being beaten, in code the probability of being beaten in distribution calculations will be changed to the sum of the first m states, where m is the smallest value for which the condition

$$\sum_{i=0}^{m} p(i) \geq P(beaten) \qquad (2)$$

holds. The same method is used from the original strength towards zero when calculating the conditional probability of the unit been not beaten in the other branch of the event tree.



The strength distribution used when the company is beaten.

The strength distribution used when the company is not beaten.

Figure 4. Probability distribution from *Sandis*

For example, we can have two branches of event tree with different weather, new set of weapon systems available or not, use of electronic warfare (EW), air attacks, special ammunition etc. These distributions calculated by *Sandis* can be used in probabilistic analysis and cost effectiveness calculations.

3. Network warfare

The communication systems are part of the military machinery. If we want a realistic battle loss and outcome analysis, we need the communication network analysis as one part of the process.

In the ongoing analysis in PVTT, unit states include communication state probabilities. In many cases the result of the battle depends on the ability of unit A (for example artillery) to support unit B (for example attacking infantry). Thus one of the features to be included in the *Sandis* software is communication network analysis.

A traditional communication system is based on direct radio links between A and B. If unit A can receive messages from B, A can support B.

In these cases the cut sets for communication are easily solved, thus number of possible radio links is limited to 1–5. A simple example is given in figure 5.

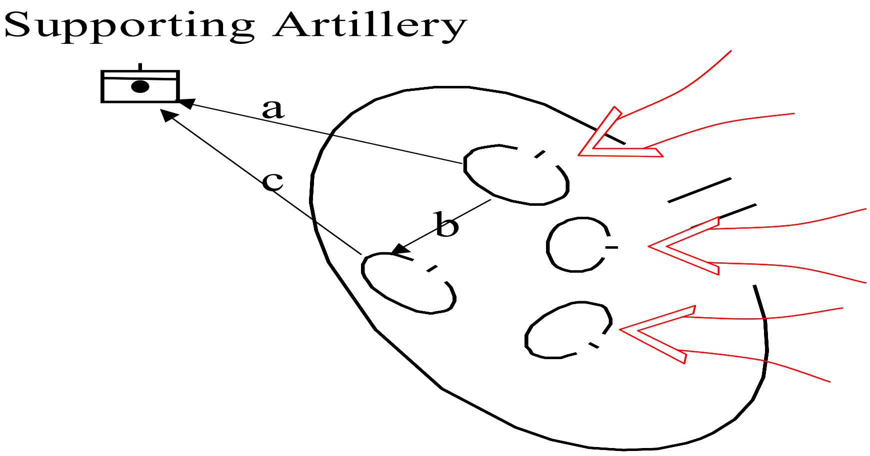


Figure 5 A simplified example of a military network

An artillery unit supports a defending battalion. The communication links available to a defending company by which they can reach the artillery are a direct link using the artillery network frequency, and a relay through battalion headquarters with another radio network and frequency.

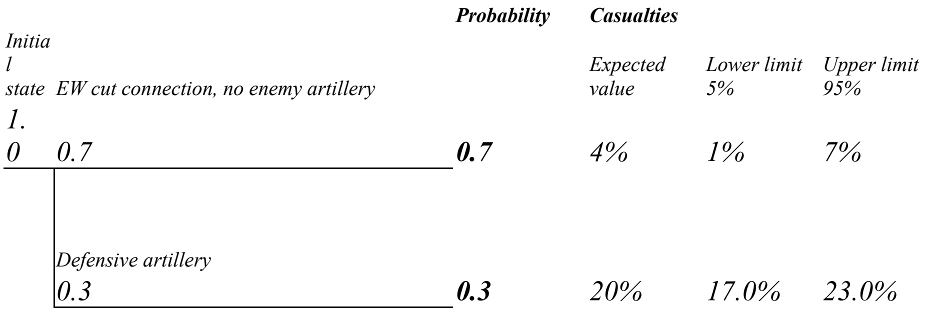
The cut sets for the communication are {a,b} and {a,c}. To find the probability of successful communication, we need to calculate the probabilities of the individual links working and combine them.

If an automatic network system is working, unit A can reach unit B using different paths. The neighbouring companies and other units (not shown) can relay messages. Thus the network has lots of paths from the infantry to artillery. In real cases the number of nodes can be 20, and one node can relay data between 4 or 5 nodes. As the number of paths increases, the cut set analysis becomes impractical.

If we need an overall picture of the network and its availability, we should simulate all communications and traffic in the network using specific tools for network analysis. This is possible within peacetime time constraints. It may be possible for operation analysis with lots of scenarios or EW operational planning in the field in the future as computers will be faster.

As a result a faster method must be found. One way of analysis is to use average failure probabilities of the network and use of them in a simplified simulation. The parameters can be obtained from field exercises or simulated data. These average values can be used in Monte Carlo simulation and thus a probability of link A-B working can be obtained from this simulation data.

EW event tree.



Initial state	*EW cut connection, no enemy artillery*	***Probability***	***Casualties*** *Expected value*	*Lower limit 5%*	*Upper limit 95%*
1.0	*0.7*	***0.7***	*4%*	*1%*	*7%*
	Defensive artillery *0.3*	***0.3***	*20%*	*17.0%*	*23.0%*

Figure 6. Event tree with EW as diverging point. The enemy cannot use its artillery, if EW cuts the communication network with probability p = 0.7.Two separate *Sandis* simulations are needed for the analysis.

This kind of simulation has been tested by project [9], in which Sarvi, Saloheimo, Niemi & Heimo analysed a theoretical network of a brigade with dummy parameters. The project work showed that Monte Carlo type of network simulation could be used for network analysis. The Monte Carlo simulation time using *Matlab* was reasonable and the EW network calculations can be used in analysis with for example 30 minutes time stepping while the combat losses are calculated with 1 minute time steps. Also event stepping is possible for further use. For example, when a new unit enters or leaves the combat zone, network probability is recalculated.

The way of using PRA with probability information of network working probability can be used in two different ways. First method is expected value based, the second event based. When network dependent weapon systems are used, the probability of communication available makes two different cases: dependent system can be used or not. In expect-value calculations the combat losses of network dependent weapon systems are directly multiplied with the probability of the network been operational. This can be used, if the battle losses from supporting weapons are little compared with other weapon systems.
If the supporting weapon systems have strong effect to the target unit, the expected value method is not useful. If for example a platoon is hit with an air strike, the unit could be beaten, if attacked, and fully operational, if not. In this case analysis must be done using event tree analysis and separate braches simulated with working network and without communications.

The event tree type simulation gives probabilities and the outcome, which can be used for further analysis.

4 Conclusions and future work

The success probabilities of the communication networks are essential for operation analysis and overall operation success analysis.

The *Sandis* code provides a novel tool for overall combat loss and operation success calculations. It has basic tools for PRA and the further development will make the simulation data more available for PRA calculations.

Probabilistic data can be calculated for radio networks. A fast enough method has been presented and the used calculation methods with Monte Carlo simulation are described in [9]. Thus probabilistic network data is available for military operation analysis with PRA.

The *Sandis* code does not have a built-in model for network simulations. The traditional radio connection analysis will be added to the *Sandis* during co-operation project with FFI (Forsvarets Forskninginstitut, Norway), but until August 2007 analysis of different scenarios is time consuming, when a scientist must use both the *Sandis* combat model and radio calculation computer programs separately, and then combine the results by hand.

After the co-operation project the reliability of radio networks each separate communication can be calculated, but the probability calculations of entire automatic network remain beyond *Sandis*. Thus traditional EW calculations can be done with the same tool as operation success probability and combat losses calculations, but not the probability calculations for future automatic networks. So the analysis time remain long for future automatic networks, because two different simulation codes must be used and the results combined by hand.

Thus further development of the *Sandis* code and other simulation models are needed in order to have ability for real time operation analysis with EW and complex automatic communication networks.

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Publication XI

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XI

Direct Fire Target Selection in Sandis Combat Simulation

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Abstract: When simulating direct fire between units of different sizes in brigade-level combat simulations, there is often a need to automatically determine the ratios of fire directed at different possible targets. We construct a simple and effective rule for dividing fire between different targets, which takes into account the effects of different weapon systems on each other and the need to target not only the most valuable objectives, but also the enemy units which pose an immediate threat. The proposed model will be implemented in Sandis operation analysis tool.

Keywords: simulation, operations research, decision making, military operation analysis

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1. INTRODUCTION

Modern military operation analysis tools include combat simulators for wargaming. Such simulators exist for various scales of both time and the number of troops or weapon systems. When analysing brigade-level operations, the number of smallest simulated units on the map is in the order of hundreds. Sandis is designed to handle scenarios of this size with the input of weapon and communication characteristics, units and their equipment, fault logic for the units and operation success, the map, and user actions for the units at company or platoon level [1][2]. An example of such scenario is shown in figure 1.

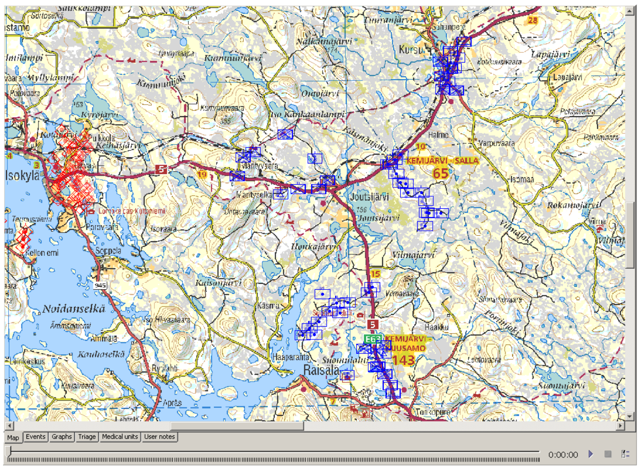

Fig. 1. A screenshot of a typical scenario in Sandis map view, with a blue brigade. A brigade may have 7000 soldiers and over 1000 vehicles distributed in an area of over 1000 square kilometers.

This poses no challenge for the computational resources, but instead the ability of the human operator to manage the actions of the units. However, when the battles actually take place, several units will concentrate to a small area (such as in figure 2), and the user needs to make detailed decisions about their movement and use of firepower.

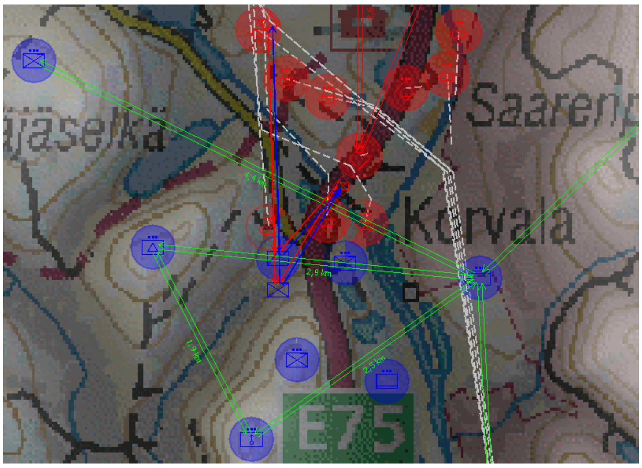

Fig. 2. A screenshot of a local battle within a larger operation. The terrain and roads force both sides to concentrate on this choke point.

To handle these low-level problems intelligently inside a large framework without placing a large burden on the user, practicality demands that the units make decisions on small immediate matters based on a general rule set, rather than the operator first setting up all possible weapon-target pairs by hand. An simplified example of different choices of targets is shown in figure 3.

An example of such logic would be for the troops to open fire on any enemy unit closer than a set distance. As a general rule it is a good starting point, but it does not address, for example, how the available firepower should be divided between several enemy units or how much resources to conserve if the target is weak or unimportant, or if the weapons are relatively ineffective against it. Also the enemy units which pose immediate threat should be targeted in order to minimise losses in our own most important weapon systems.

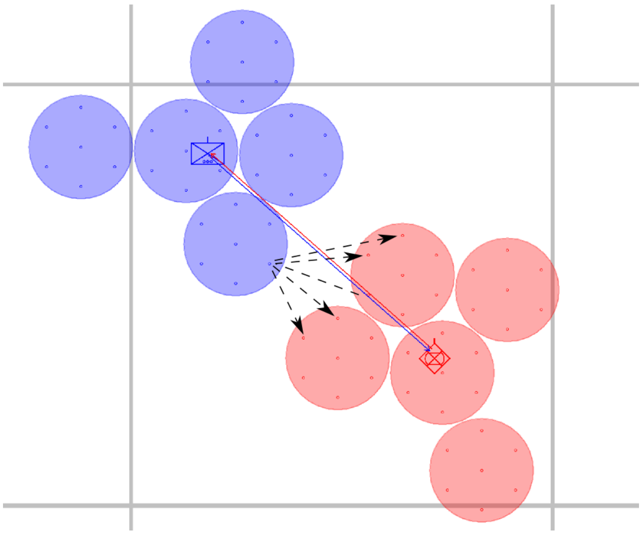

Fig. 3. A screenshot of Sandis map view. The solid lines are target relationships set by the operator, i.e. the companies are defined as each others targets. The dotted lines show the momentary choices of targets which are automatically determined by the model during each time step.

When both sides optimise for the minimal losses by selective targeting of the opposing force, the situation leads to a game-theoric problem, which we do not attempt to tackle here. Optimizing the distribution of firepower has been studied by Kråkenes [3], where the coefficients in a *target value function* (TVF) were optimised using a genetic algorithm, and the values of different targets were used in allocation decisions. Kaasinen [4] has used a genetic algorithm to optimise the tactics of a unit on a broader scope, including advancing, taking cover and firing in order to achieve an objective. Here we take a simpler approach by combining the most important decision criteria into a TVF which determines the use of firepower for a single unit, and whose parameters are the properties of the own and opposing unit. The aim is to model the fast decision-making of a squad leader in combat situation, and hence the scope of our TVF is the local fire fight between units rather than the whole scenario.

1.1 Unit-level model in Sandis

Here we will call the lowest level of the troop model hierarchy the "unit". Under usual circumstances, the smallest unit is a platoon with some special units modelled as squads, and units of higher order consist of these. However, since a platoon can realistically be spread over a large area relative to weapon ranges, the internal structure of an unit has been added to the model in Sandis. A unit is modelled a distribution inside the circular unit with radius r, which is for calculation purposes discretised into seven or more points, as seen in figure 3.

A weight vector w corresponding to each unit represents the "probability mass" of troops residing at a point inside the unit (Figure 4). The weights w_i sum up to 1 and are used as multipliers when calculating weapon effects on different parts of the unit, or the available firepower at a given location. The weight distribution changes throughout the simulation as a result of weapon effects and "cooling down" towards the initial distribution as a function of time, representing the reorganisation of the troops inside the unit. The goal isn't to accurately model the behaviour of the unit's soldiers or vehicles, but to give reasonable accuracy when the simulation is run on a large scale.

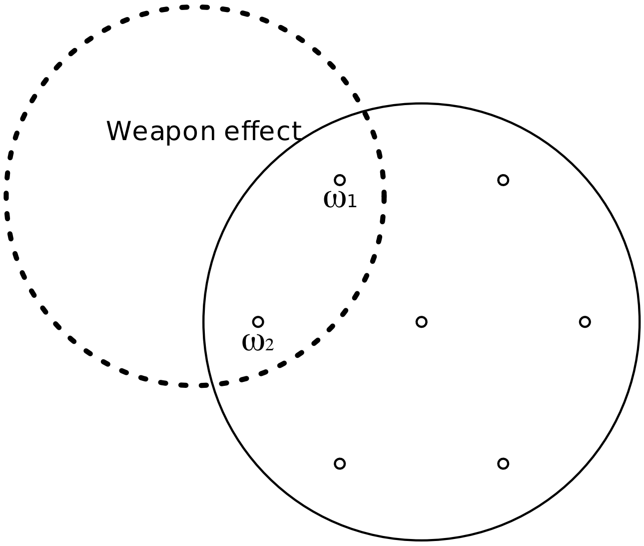

Fig. 4. Weapon effects are weighted by the weights of the points they affect. Thus the weapon effect pictured will not wipe out the unit, however high the kill probability is inside the effect radius.

In parallel to dividing the troops by location, they are also divided by weapon classes, i.e. a platoon's infantry and assault vehicles are handled separately for purposes of both firing and being fired at, even though they are parts of the same unit. This is important, as different weapons are efficient against different targets.

2. THE TARGET VALUE FUNCTION

We construct the TVF which we use to rank the available targets in order of importance. One of our objectives is to maximise enemy losses, so we make the TVF proportional to the expected number of losses our fire inflicts on the target. We denote value by L_{enemy}. If we have a choice of multiple weapons, we need to scale this number according to the fire rate of each weapon. Even though we use a single symbol to denote this, it is practical to separate it to the value of a single shot and the fire rate of the weapon.

We use the concept of unit "value", which is the value of a soldier, vehicle or other system in our platoon or other organisation, and denote this value by V. We divide the "value" of a destroyed enemy in two components. The "material value" is a generic value arbitrarily assigned to different types of soldiers or vehicles on the battlefield, as eliminating a main battle tank or a mortar system is obviously preferable to eliminating a foot soldier, for example. This component also serves to assign a nonzero value to strategic targets that are not weapon systems, and can be varied if the operation requires focusing on specific targets. We denote this by V_{enemy}

The other component "immediate value" is due to the loss of firepower threatening our own unit, or the thus avoided losses in value. We define it as the losses the enemy unit could inflict on our own units, and denote it by V_{own}. Our TVF then takes the form

$$TV = L_{enemy} \times (V_{enemy} + V_{own}) \tag{1}$$

When simulating the behaviour of troops, it is important to keep in mind that troops on the battlefield do not always make globally optimal decisions. In the heat of the battle, even an experienced fighter will prioritise first his greatest immediate threats, even if focusing on some other unit would be more important for their strategy as a whole. This can to some extent be taken into account in the term V_{own}, but we can easily enough separate the two effects - the perceived threat to the platoon and that to the individual squad.

To incorporate this to our model we add a new term $V_{personal}$ to describe the losses to the firing unit itself. To make this value significant enough, we use a special constant for the units' own value for themselves, which should be set higher than any real unit's value. The revised function ends up as

$$TV = L_{enemy} \times (V_{enemy} + V_{own} + V_{personal}) \tag{2}$$

2.1 Dividing the firepower of a unit

If a unit has several targets of near equal target value, we will want to divide our firepower between them. Also, if there is a single target small enough that concentrating all fire on it would be overkill, we will want to determine how much firepower to spend on it. This can be achieved by running the calculations for all the weapons in the unit separately, instead of the whole unit's arsenal at once, and iterating the choice of targets over the unit's weapons. On the first step of the iteration we assign some amount of fire to the unit's best target, and update the damage potential to describe how much we gain from additional resources. This will result in diminishing returns, eventually forcing the iteration to switch to the originally second best target, or stop completely if no target stays above the defined threshold.

3. IMPLEMENTATION

A short description of Sandis's direct fire model can be found in [1]. To implement the method described above in this framework, we utilize the existing manner of simulation in a much "predictor-corrector"-like fashion.

First, we iterate over all the units which have been assigned targets, and calculate the losses each unit could cause to each other. We use the results as the L_{enemy} in (2) and calculate the target value for each target of each unit.

Then, for each unit, we sort the list of targets according to their target value, and proceed to iterate over them as described in the previous section. the result is the amount of firepower allocated at each target for each weapon. We then proceed to "fire", that is, calculate the effects of the allocated weapons on their targets, producing the final result. Presenting this as pseudocode:

```
foreach Troop
  potentialTargets = calculateTargetValues()
foreach Troop
  while weapons left
    bestTarget = findMaxValue(potentialTargets)
    if value(bestTarget) > threshold
     assignFire(bestTarget)
    updateLossPotential(bestTarget)
  fire()
```

where function calculateTargetValues returns a list of targets, which includes the potential losses to the enemy and its value. As our model simulates targeted direct fire by calculating the loss probability for one shot and repeating for the number of shots, updating the loss probability here similarly gives us an accurate approximation. The amount of firepower assigned in one step is a tradeoff between increasing the number of iterations or losing accuracy by treating a larger number of shots as equal, but using a number of shots equal to the amount of targets balances these fairly well.

Sandis uses a time step of 1 minute for the combat simulations. The error caused by the long time step can be compensated by using the predictor-corrector-algorithm described in [5]. The predictor-corrector method is also naturally combined with the algorithm described in this paper, as both include making an initial round of simulation and then refining the calculation using the initial result.

4. CONCLUSIONS

The principal weakness of the algorithm presented herein is the difficulty of validating it experimentally. Instead, validation most likely needs to be done using military personnel's expert opinions on the validity of results. Obviously such opinions can vary greatly.

While the algorithm was developed for Sandis, it is quite generic and offers many possibilities in adapting it for different platforms. With little modifications the behaviour of units could be easily shifted to spread, concentrate or regulate fire, for example. Alternatively, discarding the terms V_{own} and $V_{personal}$ leaves us with a very lightweight algorithm to provide a threshold for opening fire and some logic for targeting, while still retaining the option for previously mentioned alterations.

Test arrangements with limited options of weapon systems and scale could be arranged as a part of military exercises using electronic weapon simulators, such as the TASI vests used by the Finnish Defence Forces, which record hits along with the origins of the hitting shots. Such experiments could be used to provide validation data of e.g. a platoon vs. platoon fire fight.

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APPENDIX

Jussi Sainio, Bernt M. Åkesson, Esa Lappi, Santtu Pajukanta and Walther Åsen. Electronic Warfare Modeling in Operation Analysis Tool Sandis. 2nd Nordic Military Analysis Symposium, Stockholm, Sweden, November 17-18, 2008.

The Electronic Warfare Model in Operational Analysis Tool Sandis

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Abstract

This paper presents the electronic warfare model used in Sandis, a software tool for operational analysis research, developed in collaboration by the Finnish Defence Forces Research Centre and the Norwegian Defence Research Establishment.

One of the uses of Sandis is investigating the capabilities and influence of electronic warfare (EW) equipment in brigade-level scenarios. A major challenge for the operator has been to keep track of events that change the state of communications of the units and decide how the units react to the change.

The electronic warfare model consists of three components: the radio wave calculations, the links for each unit and the action model, which determines how loss of communication affects each unit. The action model incorporates rules for actions to be taken in various situations. This is intended to ease the workload of the operator and to allow consistent handling of EW events in the scenario.

1. Introduction

Command and communication systems are essential in modern warfare. Furthermore, the use of electronic warfare (EW) is a part of modern military operations. Hence there is a strong need for analytical methods for evaluating the capabilities of electronic warfare systems and their impact on the outcome of the battle.

An initial attempt at EW analysis at the Finnish Defence Forces Technical Research Centre (PVTT) was presented at the Nordic Military Operational Research Symposium in October 2004 [7]. The analysis was initially carried out using a method based on the Quantitative Judgment Method (QJM) [8]. It was realized, however, that a QJM-based analysis was not accurate enough for operational analysis purposes and the method was abandoned. Work was instead focused on developing a probability distribution-based combat model for brigade-level simulation. This combat model was developed into a software tool which became later known as Sandis.

The idea of collaboration between PVTT and FFI was discussed at the first Nordic Military Operational Research Symposium in October 2004. It was noted that collaboration would be beneficial to both parties, the purpose being to develop a software tool for EW analysis. The project plan for the collaboration project was accepted in August 2006. The software for radio wave calculations, called CalcRadio, was provided by FFI and incorporated into the combat model provided by PVTT. A general description of Sandis and its use in operational analysis is given in [9].

Sandis relies on the operator to make decisions concerning unit actions. The process of creating a scenario can become very time-consuming for the operator, especially when radio links are included. The development of a rule-based artificial intelligence system was started in 2007, with the purpose of easing the burden on the operator. Rules can be set up for sets of units, such that certain actions are taken when certain events are triggered.

This paper is organized as follows. CalcRadio is presented in Section 2. The rule system is described in Section 3. Finally, some conclusions are presented in Section 4.

2. Description of CalcRadio

2.1 CalcRadio radio wave calculations

In 1994 the Norwegian Post and Telecommunications Authority (PT) purchased a system for frequency planning which uses Picquenard's model [1] for calculating radio wave energy loss by obstructions, such as mountains and hills.

One of the authors, at that time working for PT, conducted a measurement campaign in order to check the validity of these radio wave calculations over different types of terrain and mountains, using measured levels of FM signals from main broadcasting towers in southern Norway. A van was equipped with advanced receiver equipment for automatic recording of measurements, and a GPS receiver was integrated in order to attain precise navigation. In this way a total of about 2 million signal level measurements were obtained, one for every meter travelled. The amount of data was then averaged down to 115614 different estimates (one every 40 meters), corresponding to 115614 different terrain path profiles.

The results have later been analyzed by the same author at the Norwegian Defence Research Establishment (FFI), taking propagation and antenna patterns into account. The antenna diagrams of the broadcasters had previously been measured from helicopter, and the detailed antenna diagrams were used in the analysis and comparison of the measurements with the Picquenard model. It has been shown that the original Picquenard method, taking all obstacle contributions (approximated as 'knife edges') into account, strongly overestimates the propagation loss. However, by restricting the calculations to the most important contributions, a new, much more successful method, has been constructed. We have named the improved method Picquenard 1,67 because it calculates the most dominant diffraction obstacle loss and then adds the loss of the second most dominant obstacle loss multiplied by 0,67. More details of the measurements and the improved wave propagation model are found in [2].

In order to further assess our model we have compared it with an international standard, and discussed the deviations between model and measurements in terms of expected accuracy of the experiment.

Firstly, we have compared this new model to the current model recommended by the International Telecommunication (the ITU model, [3]) and found that the new model performs considerably better in practice than the ITU model, at least for the Norwegian terrain paths that we have investigated (See Table 1 and Figure 1). Table 1 gives a good indication of the absolute performance (RMSE, root mean squared errors) of the different models investigated, whilst Figure 1 gives a useful comparative indication of how good the average predictions are. Small deviations from 0 in figure 1 means good average performance.

TABLE 1: RMSE (IN DECIBELS) FOR THE ITU MODEL, THE GENERAL PICQUENARD MODEL AND THE PICQUENARD 1,67 MODEL

RMSE (dB)	ITU model	Picquenard (all diffraction terms included)	Picquenard (1,67 diffractions included)	**Number of observations**
line-of-sight	9.1	8.5	8.5	10920
1 obstacle	11.5	8.2	8.3	27742
2 obstacles	11.6	12.5	9.1	35345
3 obstacles	12.2	23.9	9.5	23696
4 obstacles	12.5	37.5	9.6	11333
5 obstacles	13.1	51.8	9.4	4501
6 obstacles	13.3	65.9	9.5	1506
7 obstacles	13.4	82.0	8.7	411
8 obstacles	12.7	95.7	7.8	118
9 obstacles	14.7	112.7	6.8	37
Overall	**11.7**	**22.9**	**9.0**	**115614**

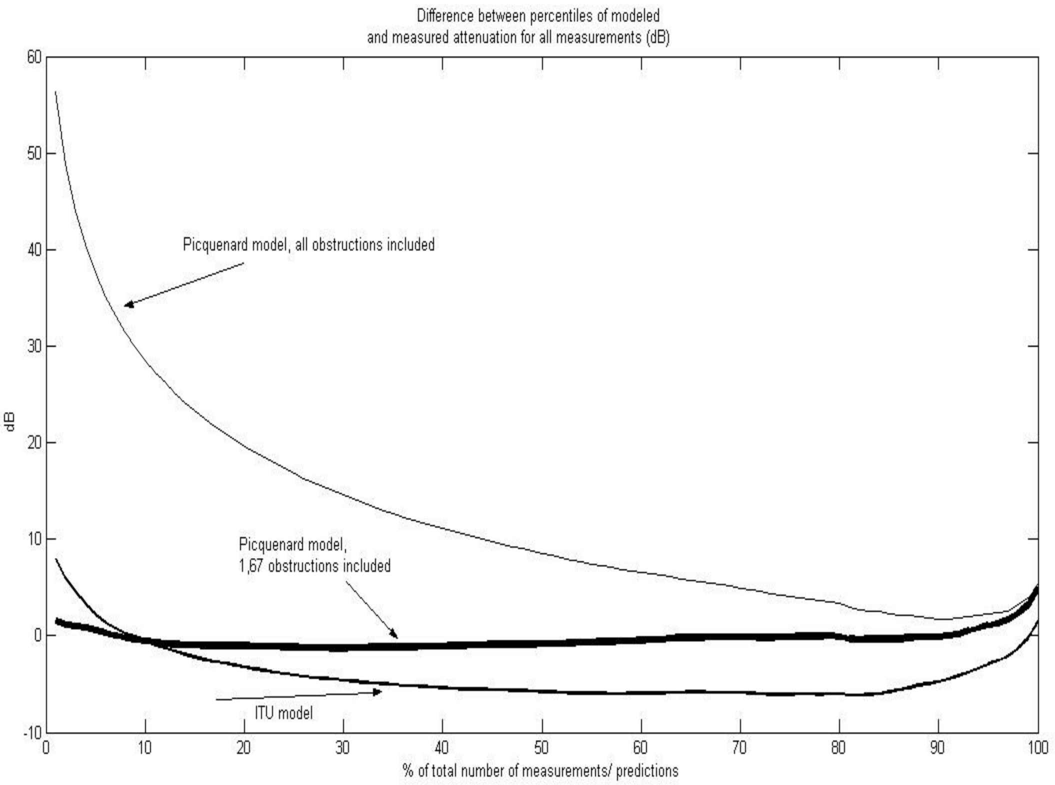


Figure 1. Cumulative distribution of predicted propagation loss relative to an arbitrary threshold, minus the cumulative distribution of measured loss relative to the same threshold.

Secondly, the expected standard deviations of the difference between the Norwegian Digital Terrain Elevation Data (DTED) and true heights have been deduced from a Norwegian Master's thesis [4], and by using the Okumura-Hata height-correction term [5], a frequency dependent expected uncertainty in received signal strength has been calculated from uncertainty in height. Such calculations have shown that the new method performs within the expected uncertainty of the experiment, whilst the ITU model contains additional discrepancies which we have not been able to explain.

For these two reasons the FFI improved model (Picquenard 1,67) is used by the CalcRadio software.

2.1 Radio calculations performed in Sandis

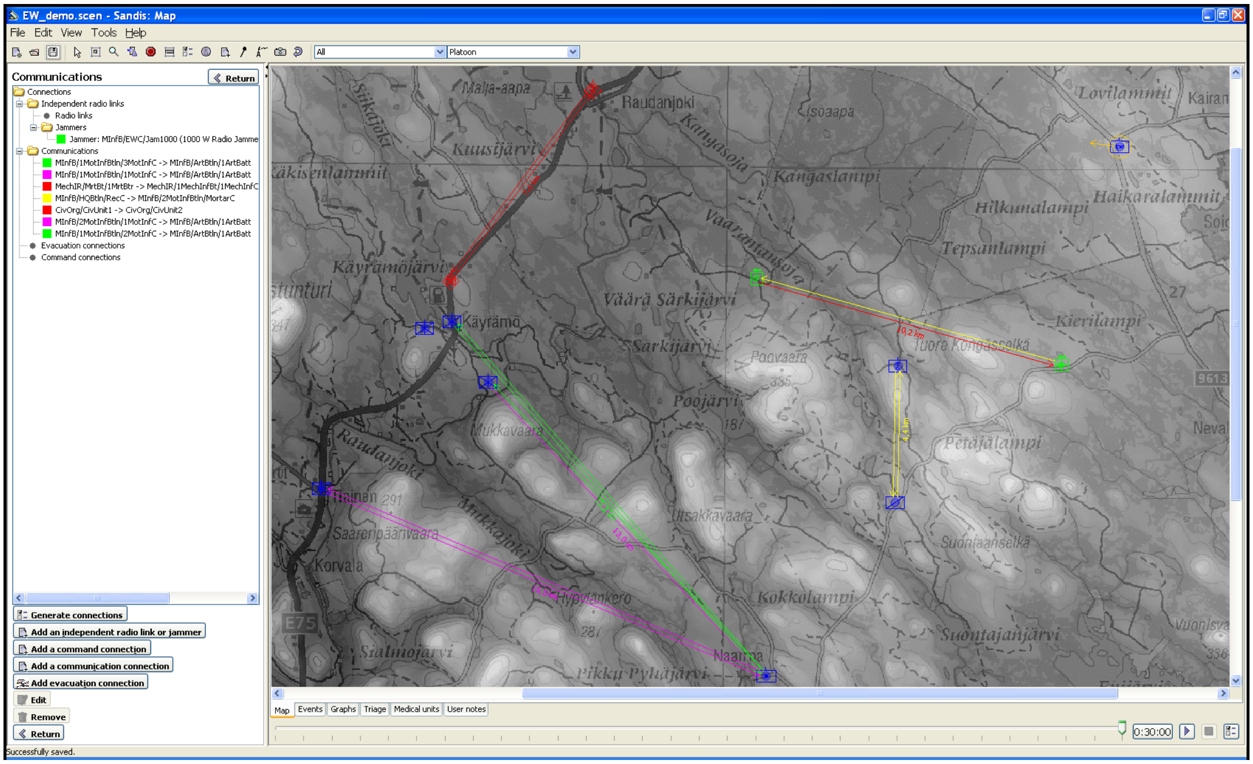
The above mentioned propagation model is applied between all communication units in Sandis. The effect of using directive antennas is also incorporated, as long as the antenna beam diagrams are known and provided in an appropriate format.

CalcRadio is used to perform emitter–receiver pair calculations between communication transceiver units. In addition to calculating the signal levels between units that are meant to be communicating, CalcRadio is also used to calculate interference with friendly and enemy receivers. Finally, and most important, CalcRadio is used to calculate whether enemy units are being jammed or not. More information on how CalcRadio works is found in [6].

Simulated troops in Sandis can have an arbitrary set of communication equipment (transceivers, jammers, and antennas). The equipment set defines the radio frequencies and the emitter power a troop is able to use.

Desired radio links and jammers are set up manually. The user can decide whether a particular link or jammer is active at a particular time. Inactive links are not included in the calculations. This way a jamming unit may move into position while remaining inactive and then be activated by the user at a certain time. Currently, antennas are positioned automatically directly towards the opposite transmitting/receiving troop, and the antenna height is fixed on the ground level.

After running the calculation, the status of a radio link can be one of the following: successful, jammed, disrupted by foreign radio link or totally broken. The resulting radio links between troops are represented with coloured arrows on the scenario map. A textual link list can be also used for observing the results. Figure 2 shows a view of the map window in Sandis illustrating the colour coding of radio link status. A Blue Force jamming unit in the northeast corner of the map is disrupting the communication between the two Red Force units, with the jammed links shown in red. Two civilian units are also included, shown in green. One of them is affected by the jamming, while the other one is transmitting on the same frequency as two Blue Force units. The interfered links are shown in yellow. The mountainous terrain in the southern part of the map causes the links between two Blue Force units to be broken, shown in purple. For two more Blue Force units the link in one direction is broken. Links in different directions can operate on separate frequencies as in the case with the civilian units.



Connections
- Independent radio links
  - Radio links
  - Jammers
    - 🟩 Jammer: MInfB/EWC/Jam1000 (1000 W Radio Jamme
- Communications
  - 🟩 MInfB/1MotInfBtln/3MotInfC -> MInfB/ArtBtln/1ArtBatt
  - 🟪 MInfB/1MotInfBtln/1MotInfC -> MInfB/ArtBtln/1ArtBatt
  - 🟥 MechIR/MrtBt/1MrtBtr -> MechIR/1MechInfBt/1MechInfC
  - 🟨 MInfB/HQBtln/RecC -> MInfB/2MotInfBtln/MortarC
  - 🟥 CivOrg/CivUnit1 -> CivOrg/CivUnit2
  - 🟪 MInfB/2MotInfBtln/1MotInfC -> MInfB/ArtBtln/1ArtBatt
  - 🟩 MInfB/1MotInfBtln/2MotInfC -> MInfB/ArtBtln/1ArtBatt
- Evacuation connections
- Command connections

Successfully saved.

Figure 2. The map window of Sandis showing colour coded radio links. Green means the link is OK, red means it is jammed, purple means the signal-to-noise ratio is too low and yellow means the

link is interfered by a foreign transmitter. Inactive links are not shown on the map. A fifth colour, blue, is used to denote links that have not been calculated (not shown on map).

When provided with a map of digital terrain elevation data (DTED) in an appropriate format, Sandis will use this terrain model for radio link propagation calculations in CalcRadio. Usage of real physical coordinate data is supported in the model and thus the simulation and simple analysis of real world radio communication scenario is quite straightforward.

3. A rule system for assisting the operator

In November 2007 the EW simulation capabilities of Sandis were evaluated in a joint session between the Finnish and Norwegian ends of the project. At that time it was noted that while Sandis performed well in specific calculations, managing the EW of an entire battle required too much manual work that made the process very time-intensive. For example, when an attacking unit notices that its communications are being jammed, it would probably halt their movement, switch to a secondary frequency or take other actions to compensate for the jamming; in Sandis as of 2007 the operator would need to manually identify this situation and have the unit act accordingly.

To alleviate this problem it was decided that a way to automate the behaviour of units on the battlefield be developed. One of the authors laid the groundwork for such an artificial intelligence and another took up the task of software design and implementation in the Sandis software.

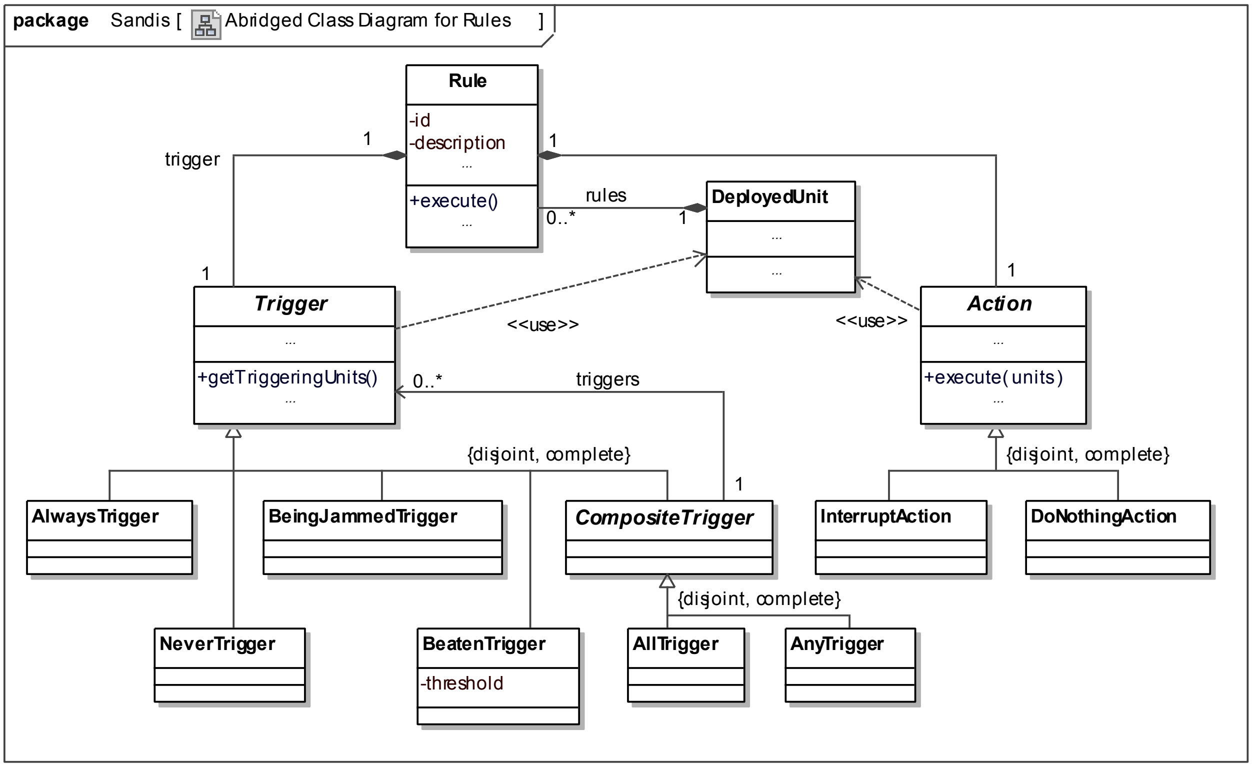


Figure 3. An abridged class diagram describing the entities and relations between them in the rule system.

As a first step towards this artificial intelligence for EW a rule-based automation system was implemented. In the rule system the behaviour of a unit is described in terms of rules, and each rule consists of a trigger and an action. Rules are associated with units and they apply to that unit and its children. These rules are checked at the end of each time step and whenever the conditions set by the trigger are met, the action is executed. The triggers and actions both operate on sets of units instead of single units; whenever a trigger is fired, the set of triggering units is passed as input to the action. The structure of the rule system is illustrated in UML notation in Figure 3.

The rule system has been designed to be extensible so that trigger and action types can easily be added. As of August 2008 a handful of triggers and two action types have been implemented. Among the implemented trigger types are “being jammed” and “beaten”. The “being jammed” trigger is fired whenever any of the monitored units is experiencing jamming on any of their radio communication links, whereas the “beaten” trigger is fired when the probability of a monitored unit being beaten (that is, having their effective strength reduced to zero) rises above a set threshold. The two implemented action types are “do nothing” and “interrupt and alert the operator”, the latter of which interrupts the simulation, describes the circumstances leading to the interrupt and awaits further input from the operator.

Many new trigger and action types have been proposed, such as the “communication to upper echelon lost” and “enemy at firing distance” triggers and “top movement”, “retreat”, “open fire” and “cease fire” actions. The current set of triggers and actions enables evaluation and prototyping of the rule system.

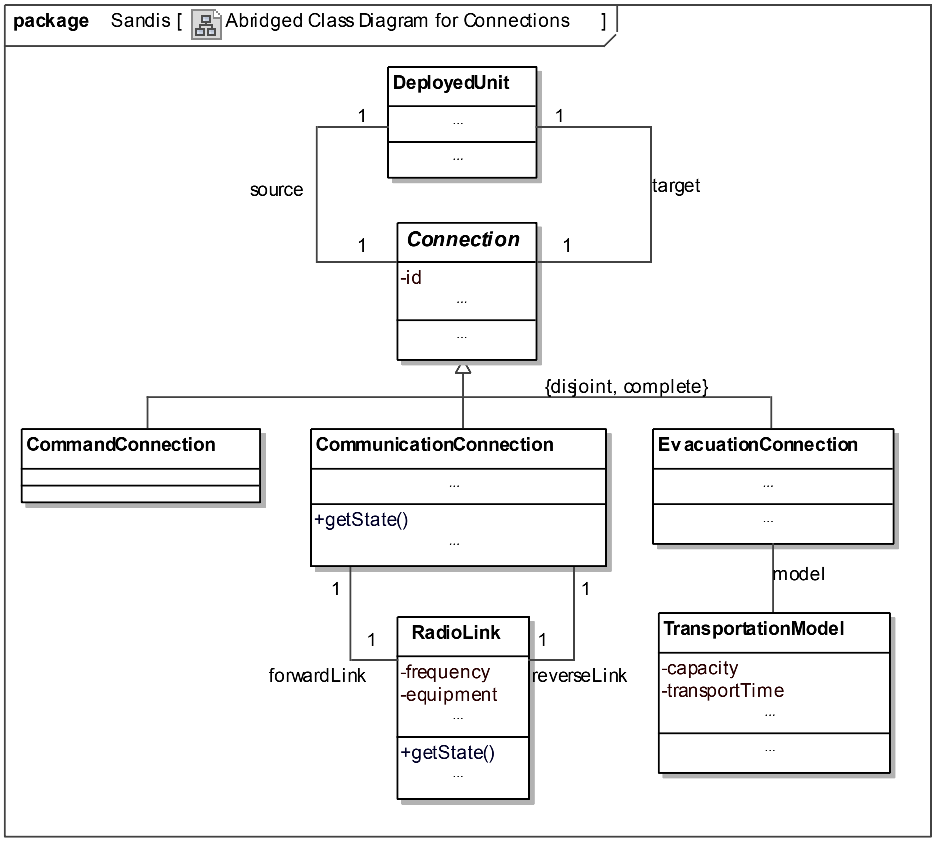


Figure 4. An abridged class diagram describing the entities and relations between them in the connection model.

Certain desired, more specific trigger types, such as “A unit loses communications to its upper echelon”, were found to require more information about the units than was readily available in the existing Sandis data model. The model was lacking information about how the units interact with each other. Many types of interaction between units on the battlefield can be identified; to name a few, units receive orders from their headquarters, issue artillery orders to supporting artillery units and ship their wounded to designated field hospitals.

To describe such ways of interaction, a generic connection system was added to the Sandis data model. The connection system is designed to overcome certain architectural challenges imposed by the design of the Sandis data model. Using object-oriented programming methods, this is done in a generic way that reduces code duplication and facilitates reuse of code. The structure of the connection system is illustrated in UML notation in Figure 4.

Each connection belongs to a connection type that defines a set of parameters and also whether connections of that type are symmetric or asymmetric. The connection types implemented as of August 2008 are “command” and “communications”; new types can easily be added by the programmer. The “command” type of connections represents command structure: a command connection between two units states that the source unit (usually headquarters) commands the target unit. The “communications” type of connections represents radio communications between two units and stores parameters required by the radio propagation model that has been discussed earlier in this paper.

While initially developed for the needs of EW simulation, the connection model was also reused and extended in the field medical model that was being developed at the same time. The field medical model simulates the evacuation and treatment of wounded soldiers on the battlefield. The evacuation infrastructure – from the battlefront to the hospital – is expressed in the model in terms of evacuation connections. The field medical model is described in detail in [10].

Preliminary testing has shown that the rule system already reduces the burden on the operator. Future work will include finding common behaviour patterns for units on the battlefield and formalizing them in the terms of Sandis into an “operator's handbook”. This process will help identify the new features that would be of most use to the users of Sandis, be it certain new trigger or action types or something completely different.

4. Conclusions

Operational analysis software Sandis includes a model for communications EW, which allows the user to set up links between units on the map and monitor the states of the links during the course of the scenario.

A rule system for managing unit actions has been introduced. It can be used to alert the operator in case of important events in the scenario, where operator input is required. Although setting up the rules for critical units takes time, it will be of great benefit in large scenarios. Furthermore, rules can be stored and then duplicated to units of the same type. In addition, this artificial intelligence system contains no “black boxes”.

In future work the electronic warfare model will be developed further. In addition, an “operator’s handbook” will be developed, detailing unit actions in various situations. This will in turn allow the rule system to be extended to handle additional situations.

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