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Measuring combat effectiveness

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Summary

Much of the work we do at the Norwegian Defence Research Establishment (Forsvarets forskningsinstitutt – FFI) is related to developing and testing solutions (concepts, technologies, etc.) that might increase *combat effectiveness*. But what is really meant by combat effectiveness, which factors affect combat effectiveness, and how can combat effectiveness be quantified and measured? These are the three main questions we address in this report.

There is no precise and unambiguous definition of combat effectiveness. However, combat effectiveness can in general be said to be *a measure of a combat system's ability to solve a given task or mission*, or *a measure of how well a combat system solves a given task or mission*. In this context, a *combat system* can for example be a weapon system, a group of fighting entities, a force structure element, or a force structure.

Generally, there are mainly two directions regarding which factors that are important for combat effectiveness. The first direction looks at combat effectiveness mainly as a result of human factors. The other direction has a more holistic view of combat effectiveness and is concerned with all factors that can possibly affect the course of a battle, including both human and material resources, environment, and task or mission. In this report, we will follow the holistic view of combat effectiveness.

Measuring and analyzing combat effectiveness is a complex and challenging task. Data from real-world warfare are often scarce, and it is of course not possible to experiment with warfare in the real world. Modelling and simulation (M&S) is therefore essential for experimenting with different weapon systems and force structure elements. Combat models, however, are simplifications and will never represent all aspects of reality. Simulation of modern combat with sufficient realism is very challenging, especially when it comes to human factors.

What we are mainly interested in, is to assess and compare the relative combat effectiveness of different combat systems executing the same task or mission against the same enemy. To estimate the relative combat effectiveness between two or more combat systems is something that usually can be done, with sufficient confidence, by using simulations and simulation-supported wargames.

In this report we first describe the background for this work. Then, we give an introduction to modelling and simulation (M&S) of combat. After this, we discuss what combat effectiveness means from a system-theoretic perspective, present some definitions of combat effectiveness, and discuss the factors that can affect combat effectiveness. Moreover, we describe and discuss some of the approaches for quantifying and measuring combat effectiveness that have been suggested in the literature. Finally, we discuss how we use simulations and simulation-supported wargames to assess and compare the relative combat effectiveness of different combat systems.

Sammendrag

Mye av arbeidet vi gjør ved Forsvarets forskningsinstitutt (FFI) er relatert til utvikling og testing av løsninger (konsepter, teknologier osv.) som kan øke *stridseffektivitet*. Men hva menes egentlig med stridseffektivitet, hvilke faktorer påvirker stridseffektivitet, og hvordan kan stridseffektivitet kvantifiseres og måles? Dette er de tre hovedspørsmålene vi diskuterer i denne rapporten.

Det finnes ingen presis og entydig definisjon av stridseffektivitet. Imidlertid kan stridseffektivitet generelt sies å være *et mål på et stridssystems evne til å løse en gitt oppgave eller et gitt oppdrag*, eller *et mål på hvor godt et stridssystem løser en gitt oppgave eller et gitt oppdrag*. I denne sammenhengen kan et stridssystem for eksempel være et våpensystem, en gruppe av kampentiteter, et styrkestrukturelement eller en styrkestruktur.

Generelt finnes det hovedsakelig to retninger vedrørende hvilke faktorer som er viktige for stridseffektivitet. Den første retningen ser hovedsakelig på stridseffektivitet som et resultat av menneskelige faktorer. Den andre retningen har et mer helhetlig syn på stridseffektivitet og er opptatt av alle faktorer som kan påvirke forløpet i en strid, inkludert både menneskelige og materielle ressurser, miljø og oppgave eller oppdrag. I denne rapporten vil vi følge det helhetlige synet på stridseffektivitet.

Å måle og analysere stridseffektivitet er en kompleks og utfordrende oppgave. Data fra krig i den virkelige verden er ofte vanskelig å få tak i, og det er selvfølgelig ikke mulig å eksperimentere med krigføring i den virkelige verden. Modellering og simulering (M&S) er derfor avgjørende for å eksperimentere med forskjellige våpensystemer og styrkestrukturelementer. Modeller av strid er imidlertid forenklinger og vil aldri representere alle aspekter av virkeligheten. Simulering av moderne strid med tilstrekkelig realisme er svært utfordrende, spesielt når det gjelder menneskelige faktorer.

Det vi hovedsakelig er interessert i, er å vurdere og sammenlikne den relative stridseffektiviteten til forskjellige stridssystemer som utfører samme oppgave eller oppdrag mot samme fiende. Å estimere den relative stridseffektiviteten mellom to eller flere stridssystemer er noe som vanligvis kan gjøres, med tilstrekkelig pålitelighet, ved å bruke simuleringer og simuleringsstøttede krigsspill.

I denne rapporten beskriver vi først bakgrunnen for dette arbeidet. Deretter gir vi en introduksjon til modellering og simulering (M&S) av strid. Etter dette diskuterer vi hva stridseffektivitet betyr fra et systemteoretisk perspektiv, presenterer noen definisjoner på stridseffektivitet og diskuterer faktorene som kan påvirke stridseffektivitet. Videre beskriver og diskuterer vi noen av tilnærmingene for å kvantifisere og måle stridseffektivitet som er foreslått i litteraturen. Til slutt diskuterer vi hvordan vi bruker simuleringer og simuleringsstøttede krigsspill til å vurdere og sammenlikne den relative stridseffektiviteten til forskjellige stridssystemer.

Contents

1 Introduction

Much of the work we do at the Norwegian Defence Research Establishment (Forsvarets forskningsinstitutt – FFI) is related to developing and testing solutions (concepts, technologies, etc.) that might increase *combat effectiveness*. But what is really meant by combat effectiveness, which factors affect combat effectiveness, and how can combat effectiveness be quantified and measured? These are the three main questions we address in this report.

There is no precise and unambiguous definition of combat effectiveness. However, combat effectiveness can in general be said to be *a measure of a combat system's ability to solve a given task or mission*, or *a measure of how well a combat system solves a given task or mission*. In this context, a *combat system* can for example be a weapon system, a group of fighting entities, a force structure element, or a force structure.

A related term that is often used is *combat power*. Combat power is a measure of the quantity and quality of the elements of a combat system, whereas combat effectiveness is a measure of the quality of the actual combat execution. Combat effectiveness will of course depend on combat power.

Generally, there are mainly two directions regarding which factors that are important for combat effectiveness. The first direction looks at combat effectiveness mainly as a result of human factors. The other direction has a more holistic view of combat effectiveness and is concerned with all factors that can possibly affect the course of a battle, including both human and material resources, environment (e.g. terrain and weather), and task or mission. In this report, we will follow the holistic view of combat effectiveness.

Modern combat is highly complex and highly dynamic. Combat effectiveness is affected by many different factors, and measuring and analyzing combat effectiveness is a complex and challenging task. Data from real-world warfare are often scarce, and for obvious reasons it is of course not possible to experiment with warfare in the real world. Modelling and simulation (M&S) is therefore essential for experimenting with, and assessing and comparing the performance and combat effectiveness of, different weapon systems and force structure elements. Combat models, however, are simplifications and will never represent all aspects of reality. Simulation of modern combat with sufficient realism is very challenging, especially when it comes to human factors.

What we are mainly interested in, is to assess and compare the *relative combat effectiveness* of different combat systems executing the same task or mission against the same enemy. For example, to investigate which one of two, or more, alternative combat systems that solves a selection of tasks or missions best. To estimate the relative combat effectiveness between two or more combat systems is something that usually can be done, with sufficient confidence, by using simulations and simulation-supported wargames.

This report focuses especially on combat effectiveness in the land domain. However, most of the content should be relevant for the air and sea domain as well. The work with this report has been done under FFI-project 1508, “Combined-arms operations in the land domain”.

This report is organized as follows: First, in Chapter 2, we briefly describe the background for this work. Next, in Chapter 3, we give an introduction to modelling and simulation (M&S) of combat. After this, in Chapter 4, we discuss what combat effectiveness means from a system-theoretic perspective, present some definitions of combat effectiveness, and discuss the factors that can affect combat effectiveness. Moreover, we describe and discuss some of the approaches for quantifying and measuring combat effectiveness that have been suggested in the literature. Finally, in Chapter 5, we discuss how we use simulations and simulation-supported wargames to assess and compare the relative combat effectiveness of different combat systems.

2 Background

At FFI we address complex issues related to warfare. One of the research questions we investigate is how to increase combat effectiveness in land domain operations. As part of this work we assess and compare the performance and effectiveness of different combat systems, which may vary with regard to composition of material and equipment (for example introduction of new technologies), tactical organization, or operational concept. Examples of combat systems are groups of fighting entities, force structure elements, and force structures.

For obvious reasons it is not possible to experiment with combat systems in an actual combat environment. Moreover, data from modern real-world combat are often scarce. Especially, it is difficult to obtain data from real-world combat that encompass the use of new technologies (e.g. new sensor systems, weapon systems, or protection systems) and new and novel operational concepts. We therefore use modelling and simulation (M&S) as our primary tool for experimenting with, and analysing the performance and effectiveness of, different combat systems.

Generally, we use *virtual* simulations (see Section 3.5) in experiments where human system operators are essential, for example when experimenting with technologies that directly affect human performance or how humans operate at the technical level. An example is the experiments where we used virtual simulations to evaluate the operational benefit of augmented reality (AR) for improved situational awareness in combat vehicles, by comparing the performance and effectiveness of combat vehicles with and without the AR system [1][2]. For practical reasons, the sizes of our virtual simulation experiments have been limited to a few platoons (reduced company level).

To simulate larger operations, typically at the battalion and brigade level, we use *constructive* simulations (see Section 3.5) with *semi-automated forces* (SAF). An example is the series of simulation-supported wargames conducted in FFI-project "Future land forces", where the performance and effectiveness of five fundamentally different land force structures were tested in a set of chosen scenarios [3][4]. The goal of the experiment series was to rank the force structures based on their relative performance and effectiveness.

In general, we strive to collect as much data as possible from our simulation experiments, including both quantitative and qualitative data. Examples of quantitative data we collect during a simulation session are entity positions, detections from sensors, weapons fired, and entities hit and killed. From these data we can for example construct *kill matrices*. A kill matrix is essentially a matrix that shows which entity types on one side killed which entity types on the other side. Examples of qualitative data we collect are observations made during the operational planning process before the simulated operation, observations made during the simulated operation, and notes from discussions with the operators/players at the after action review (AAR) session.

These data then form the basis for the analysis where we usually want to rank the tested combat systems based on their relative performance and effectiveness. This is not always an easy task.

For example, in cases where we assess and compare a set of combat systems, and two or more of them solve the given tasks or missions, it is useful to have additional measures of performance (MOPs) and measures of effectiveness (MOEs) (see Section 4.1.2) to rank the combat systems. Furthermore, there is always a risk that the conclusions may be too much based on human judgement without having enough supporting data, or too much based on the kill matrices alone and thereby fail to take into account the complete picture of the battle. It would therefore be useful to have quantifiable measures of performance and effectiveness that can support manual judgement and widen our understanding of the battle. For example, measures that can help explain why one combat system solved its task or mission and another combat system failed. Ideally, what we want is a clear definition of combat effectiveness and a way to measure this as quantitatively as possible. This report is intended as a step towards this goal.

3 Modelling and simulation of combat

Modelling and simulation (M&S) is essential for being able to experiment with, and analyse the combat effectiveness of, different weapon systems and force structure elements. "M&S in general is often used in situations where exercising or experimenting with the real-world subject of the simulation would be too difficult, too expensive, or too dangerous, and military applications in particular include some of the most extreme examples of difficult, expensive, and dangerous situations" [5]. In this chapter we give a short introduction to combat M&S. For a more comprehensive survey of models and tools for combat M&S, see [6].

3.1 Ways to study a system

A *system* can be defined as "[a] collection of components organized to accomplish a specific function or set of functions" [7]. "A system may be *physical*, something that already exists, or *notional*, a plan or concept for something physical that does not exist" [8]. Often it is not feasible or possible to study the actual system because of cost, availability, safety, or existence. To be able to study a system, it is therefore often necessary to build a model as a representation of the system. Figure 3.1 outlines different ways in which a system can be studied [9].

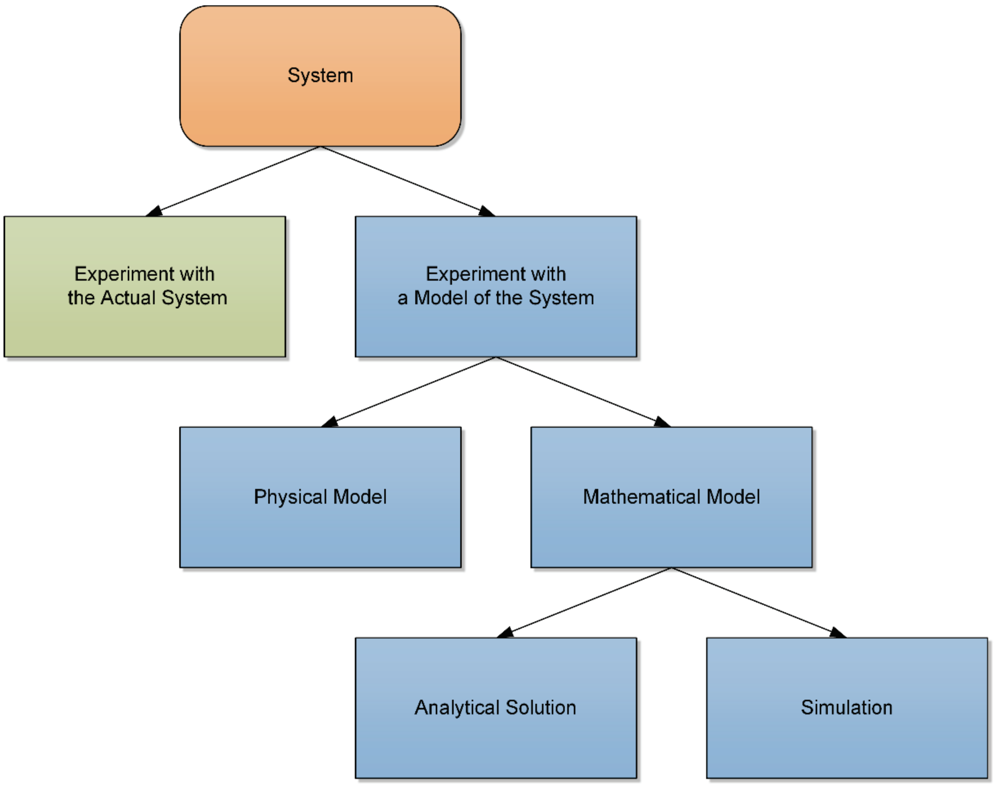

Figure 3.1 Ways to study a system [9].

3.2 Models and simulations

A model can be defined as "[a] physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process" [7]. In more general terms, a model can simply be said to be "a representation of something else" [10]. Models are simplifications and will never be exact representations of reality.

A simulation can be defined as "[a] method for implementing a model over time" [7]. We refer to the underlying model of a simulation as the simulation model.

3.3 Combat modelling

Combat modelling can be described as the activity of purposefully abstracting and simplifying combat entities, their behaviour, activities, and interrelations to answer defence-related research questions [11]. The core activities of the combat units or fighting elements on every battlefield, that need to be modelled in a combat simulation, are: *moving*, *observing/sensing*, *shooting/engaging*, and *communicating* [11]. Depending on the resolution of the simulation, the combat units can be either single *entities* or *aggregated units* [6]. These core activities are performed in the combat units' *situated environment*, which also needs to be modelled. A model of the situated environment is often referred to as a *synthetic natural environment* (SNE) or virtual environment, and includes the terrain with lakes, seas, rivers, and vegetation. It also includes static human-built structures like buildings, roads, and bridges. Another important component of the environment is the weather. Figure 3.2 illustrates the core components of combat modelling.

The SNE conceptual reference model [12] outlines the interactions between the military system representations and the representation of the environment. Figure 3.3 shows the SNE conceptual reference model.

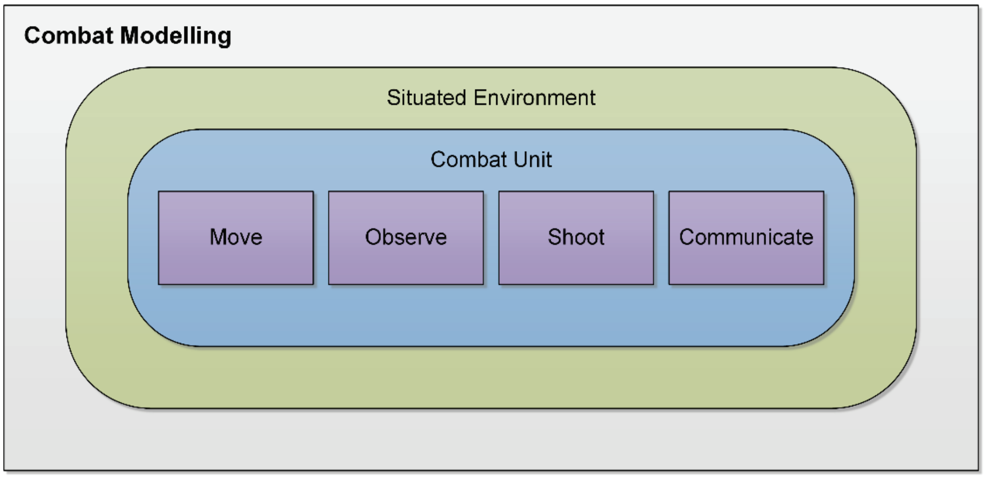

Figure 3.2 The core components of combat modelling [11].

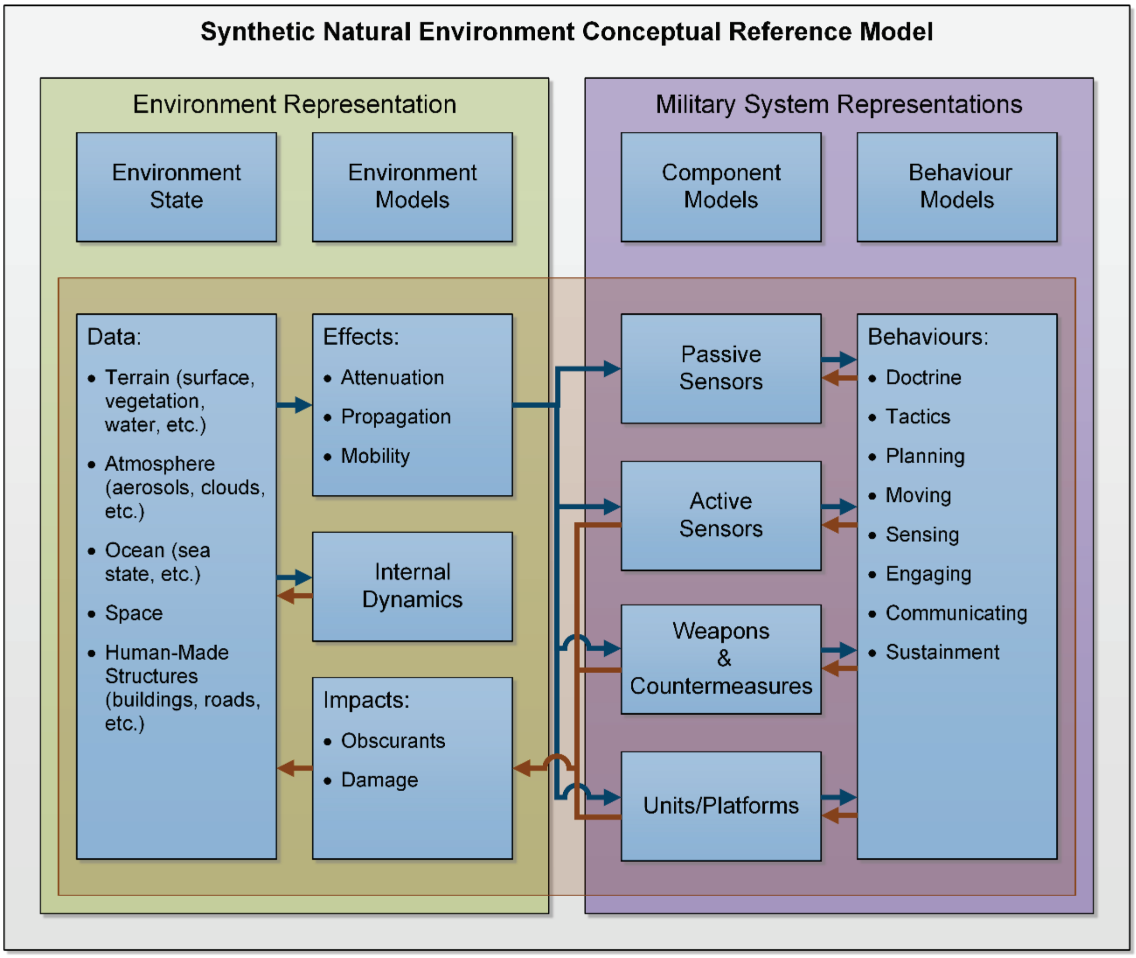

Figure 3.3 The synthetic natural environment (SNE) conceptual reference model [12].

What needs to be included in a combat model depends on the purpose of the simulation. Generally, all factors that can potentially affect the result of the military operation being simulated should be included. On the other hand, each element in a military operation can be described to an almost non-ending degree of detail. Introducing more and more factors, and the relations between them, however, will cause the complexity of the model to increase exponentially [11]. In practice, time and resource constraints often limits what can be modelled. It is therefore always essential that the model's limitations and shortcomings are clearly described as a part of the simulation results. An important principle is that the level of fidelity should be balanced throughout the model. This will reduce the risk of introducing systematic biases in the combat model.

3.4 The combat simulation spectrum

Combat simulations cover a wide spectrum of activities, ranging from large-scale field exercises, with potentially thousands of people involved, through computer-based simulations with varying degrees of human involvement, to fully computerized closed-loop simulations. Figure 3.4 shows the traditional outline of the spectrum of military simulations, together with considered associated operational realism and cost on one side, and considered associated abstraction and convenience and accessibility on the other [13].

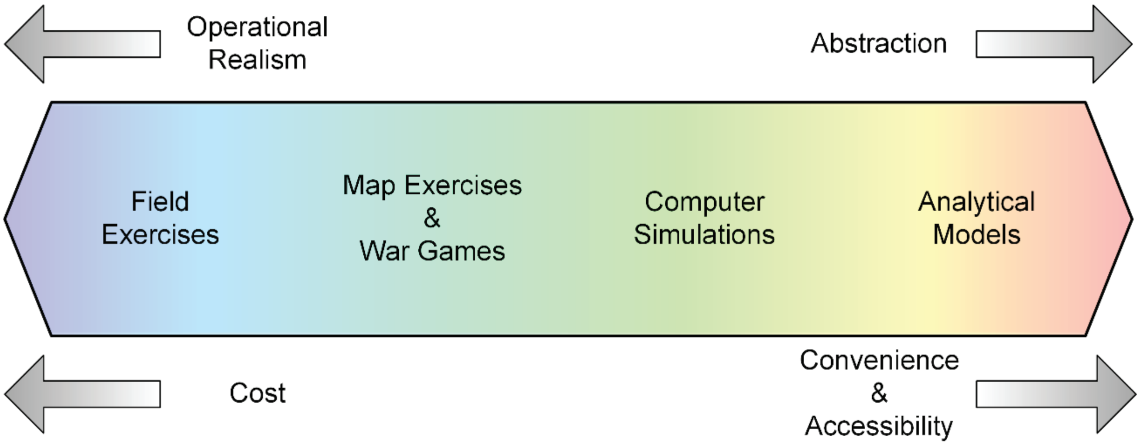

Figure 3.4 The traditional spectrum of military simulations, together with considered associated operational realism and cost on one side, and considered associated abstraction and convenience and accessibility on the other [13].

Military simulation is applied on all levels of military operations, from the strategic level, through the operational and tactical levels, to the technical level of individual platforms. Figure 3.5 illustrates this hierarchy of different simulation models on different levels of military operations, together with typical applications.

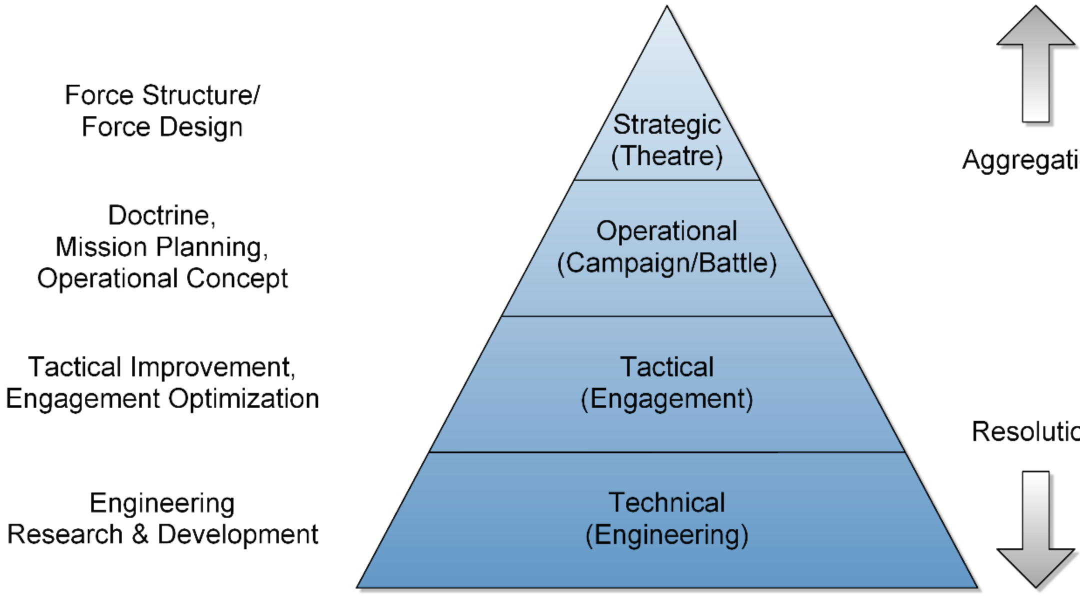

Figure 3.5 Hierarchy of different levels of military simulation.

3.5 Live, virtual, and constructive (LVC) simulation

Live, *virtual*, and *constructive* (LVC) simulation is a broadly used taxonomy for classifying simulations, especially in defence-related M&S:

- *Live* simulation "involves real people operating real systems. Military training events using real equipment, [for example field exercises], are live simulations. They are considered simulations because they are not conducted against a live enemy" [7].

- *Virtual* simulation involves "real people operating simulated systems. Virtual simulations inject human-in-the-loop in a central role by exercising motor control skills (i.e., flying an airplane), decision skills (i.e., committing fire control resources to action), or communication skills (i.e., as members of a C4I team)" [7].

- *Constructive* simulation "includes simulated people operating simulated systems. Real people [can] stimulate (make inputs to) such simulations, but are not involved in determining the outcomes. A constructive simulation is a computer program. For example, a military user may input data instructing a unit to move and to engage an enemy target. The constructive simulation determines the speed of movement, the effect of the engagement with the enemy, and any battle damage that may occur" [7].

It should be noted that "live, virtual, and constructive simulations always include a real or [simulated] person in the simulation, as contrasted with a science-based simulation which typically models a phenomenon or process only" [7]. Table 3.1 summarizes the nature of the people and systems involved in live, virtual, and constructive simulation. Figure 3.6 shows images with examples of live, virtual, and constructive simulation.

Simulation type	People	Systems
Live	*Real*	*Real*
Virtual	*Real*	*Simulated*
Constructive	*Simulated*	*Simulated*

Table 3.1 The nature of the people and systems involved in live, virtual, and constructive simulation.

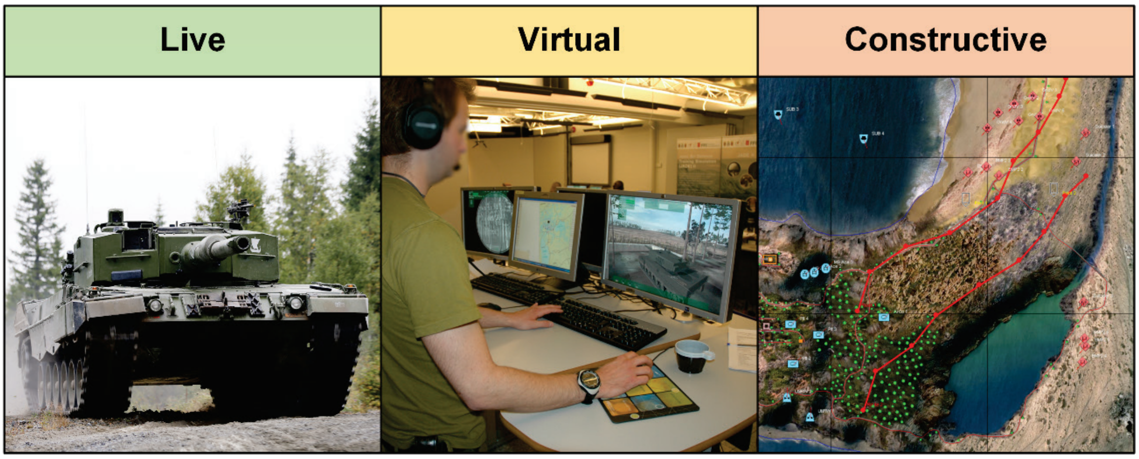

Figure 3.6 Examples of live, virtual, and constructive simulation.

3.6 Wargaming

NATO (North Atlantic Treaty Organization) defines a wargame as "a simulation of a military operation, by whatever means, using specific rules, data, methods and procedures" [14]. In his book *The Art of Wargaming: A Guide for Professionals and Hobbyists* [15], wargame expert Peter Perla defines a wargame as "a warfare model or simulation that does not involve the operations of actual forces, in which the flow of events affects and is affected by decisions made during the course of those events by players representing opposing sides". The essential parts of a wargame, emphasized in Peter Perla's definition, are the *human players representing opposing sides* and *their decision-making*.

There are several types or styles of wargames, ranging from simple seminar-type, discussion-based wargames to more detailed wargames with physical models on a paper map, and on to even more detailed wargames with computer-based simulation support. The different types of wargames have different advantages and disadvantages regarding their complexity of setup and execution, resource usage, flexibility, fidelity, and credibility.

A simulation-supported wargame can in M&S terminology be classified as a *human-in-the-loop* (HITL) simulation where the human players interact with a *constructive simulation* with *semi-automated forces* (SAF). The human players are thus a part of the simulation as a whole. A characteristic of HITL simulations is that the humans influence the outcome in such a way that it is difficult, if not impossible, to reproduce exactly.

M&S, wargaming and experimentation are in many ways fundamentally intertwined. They all exist on a spectrum ranging from very simple to highly complex, and there are several opportunities for cross-domain solutions between these techniques [16].

3.7 Modelling human behaviour

Human behaviour is the "collective set of actions exhibited by human beings, either individually or in groups of various sizes and compositions" [17]. Factors that may determine and affect human behaviour include physical properties (e.g. strength and endurance), cognitive properties (e.g. memory and reasoning), and social properties (e.g. cultural norms and role in social group) [18].

Modelling realistic human behaviour and cognition, including decision-making and creativity, is the hardest and most complex challenge in combat simulation [19]. Modelling human behaviour is challenging because "[h]uman behaviour is not generally yet thought to obey observable laws" [20]. "In general, the behaviour of large number of human beings does not currently appear to behave in accordance with deterministic rules" [20]. Consequently, the current status for human behaviour simulation is that it can be used "to understand, [but] not necessarily predict, the aggregate behavior of an inherently complex system for which we have no better model" [17]. When using human behaviour models "it is often possible to perform sensitivity analysis and identify broad trends as opposed to exact predictions" [17]. For example, a simulation using computer-generated forces (CGF) may show that increasing the number of main battle tanks (MBTs) has a positive effect on the outcome of a scenario, but it cannot be used to pinpoint the exact number of MBTs required to win the battle with a certain probability [17].

Human behaviour can be divided into the physical, tactical, and strategic level, based on the complexity of the goal of the behaviour and the duration of the performed activity [17]. At the physical level human behaviour is driven by physiology and automated processes like stimulus response and motor skills. "Decisions are done at an instinctive or reactive level, and emotions have little impact on the process; instead, performance is governed by the level of workload, fatigue, situational awareness, and other similar factors" [17]. Examples of this level of behaviour are walking, driving a vehicle, and firing a weapon. Human behaviour at the tactical level is driven by short-term goals and includes tactical decision-making and emotions [17]. At the strategic level human behaviour involves long-term planning and complex, high-level decision-making based on experience, intuition, and emotions [17].

3.8 Modelling the "will to fight"

A factor that is often ignored or considered only by "hand-waving" when modelling combat, is the "will to fight". How important this factor is, is a matter for debate, but it is highly likely that it does have an impact on the outcome of combat. In [21], the authors argue that this is perhaps the most important factor. While this is a strong claim, they also argue that since it is at least one of several important factors, failing to include it in models will make these models give incorrect results – sometimes very wrong results.

In this section, we discuss possible ways to include the "will to fight" in combat models. We will look at how it is implemented in commercial games, and discuss what "will to fight" means on different levels of the organization.

3.8.1 Examples from commercial games

There is an abundance of commercial games which simulate combat. Some try to do it relatively realistically, while others only have entertainment value. Several games include the “will to fight” as a factor in one way or another, though, and we will here look at some of the ways in which it is modelled.

3.8.1.1 Advanced Squad Leader

Advanced Squad Leader (ASL) is a two player, turn-based board game which simulates World War II combat at a low level. The units are squads or single vehicles. The game tries to simulate combat accurately; with the obvious restrictions that follow a turn-based game. The rules are complex for a board game. A typical scenario can consist of 5–25 squads on each side, with a duration of 5–15 turns, where each turn consists of one “player turn” for each player.

In ASL, squads have several parameters, and the three most important are firepower, range and morale. Firepower and range indicate their ability to inflict damage at various distances, while morale is an attempt to capture their “will to fight”. When one squad fires on another squad in ASL, two dice are rolled, certain modifiers are applied, and the result is checked on a table called the Infantry Firing Table (IFT). The possible results on this table are:

1. Killed in action (KIA) (meaning the target was destroyed)

2. K/x (meaning the squad was partially destroyed, which in game terms means it is replaced by a “smaller” squad if possible, or destroyed if not possible), followed by a (modified) morale check (MC) by the remaining unit

3. xMC, which means a morale check modified by the number x

4. Pin task check (PTC)

Of these, the MC is by far the most common, and the one that interests us when it comes to “will to fight”. The morale varies from unit to unit, but is typically in the range of 6–8. A morale check means that two dice are rolled, and if the sum of these dice and any modifiers is smaller than the unit’s morale, it “passed” the MC, and there was no effect. If, however, the sum is greater than their morale, the unit failed the MC, and is “broken”. If the result is equal to the unit’s morale, it is “pinned”. A PTC is similar, except failing a PTC results in a squad becoming “pinned”, not “broken”.

Being “pinned” means the squad can no longer move during the current player turn. It is still allowed to fire, although with reduced effect. The effect of being “pinned” is very temporary, and always ends at the end of the player turn.

Becoming “broken” is a different matter. Essentially, the player loses control of “broken” units. They may not move normally, and they cannot fire. Instead of ordinary movement, “broken” units "route" according to specific rules. These rules generally say that the units never can move closer to any known enemy unit, and they try to reach cover as soon as possible. To recover from their "broken" status, they have to "rally". This usually requires the presence of a squad leader, of whom there usually are rather few. Making sure one has decent "route paths", and also a leader available to help units "rally", is very important when playing ASL. "Broken" units who are unable to "route" for some reason, usually surrenders, or, in some cases, are destroyed.

On rare occasions, people under fire become more determined rather than scared. In ASL, this is represented as something called "heat of battle", which happens whenever a unit rolls two ones on the dice. When this happens, the unit may become "battle hardened" (meaning its quality increases), a hero may be created from the ranks (as a separate unit with special abilities), or the unit becomes "berserk" (which causes it to run towards the nearest enemy unit in an attempt to destroy it in close combat).

3.8.1.2 Command Ops 2

Command Ops 2 is a real-time computer game for one or two players. It aims to simulate World War II combat at a quite realistic level. The resolution of the game is such that a single unit usually is a company, with some elements being platoons and some elements being battalions. It is possible for a player to give orders to higher-level headquarters and have them automatically turn this into orders for units at lower levels.

Units have a wide range of parameters that determine their options and effectiveness. When considering "will to fight", the most important parameters are morale, cohesion, fatigue and suppression.

Units' suppression level increases whenever they are fired upon, especially so when fired upon by artillery. Units with a high suppression level become less able to spot and fire at enemy units, to move, and to direct artillery fire. Suppression is a temporary effect, which will recede quickly once the unit is no longer under fire.

Fatigue is not directly a "will to fight"-parameter, but it has somewhat similar effects and affects how easily a unit's cohesion or morale may drop. Fatigue increases when the unit is active, particularly when it is fighting, or force marching, or marching during night. Fatigue will slowly recede when the unit is resting. Another effect of fatigue is that tired units move slower, and fire slower and with less accuracy. Very tired units (those with exceedingly high fatigue) may decide to rest instead of carrying out their orders immediately.

Morale in Command Ops 2 is meant to measure a unit's "will to fight". Units with poor morale are more likely to retreat or rout when fired upon. Morale is lowered when a unit is fired upon, and even more when it takes losses. Morale increases slowly when a unit rests, and it can also increase when the unit inflicts heavy losses on the enemy.

Cohesion is meant to measure how well organized a unit is. Units with poor cohesion may need to stop and reorganize, rather than follow their assigned order. Such units are also more vulnerable to enemy fire, and they are less able to return fire. Cohesion drops whenever a unit is fired upon, takes losses, or change formation. It is slowly recovered when the unit remains stationary and faster recovered when the unit is reorganizing.

The likelihood of a unit to surrender, retreat or dissolve depends on these parameters. Units rarely fight to the last man, and thus is not utterly physically destroyed, rather, the unit's "will to fight" is destroyed (although this is more likely if a large part of the unit is already physically destroyed).

These two examples show that even commercial games recognize the importance of units' "will to fight", and find ways to handle such effects. While the realism in the representation of "will to fight" in these games is uncertain, it at least shows us that there are ways to handle these effects.

3.8.2 A real world example

In his book *On Wargaming: How Wargames Have Shaped History and How They May Shape the Future* [22], Matthew B. Caffrey recounts how wargames have been used throughout history. One example is how wargaming was used prior to operation Desert Storm in 1990. Caffrey states that wargames were helpful in making good plans and strategies and predicted several outcomes well. However, there was one point where these wargames missed. Many of the wargames had the Iraqis fight to the last man, causing high casualties to the American coalition. In reality, many Iraqi units retreated, surrendered or simply dissolved, due to taking casualties, fear and perhaps lacking loyalty to their leadership. The wargames did not properly model the "will to fight".

3.9 Validation and credibility

For models or simulations to be useful, we must have confidence in their predictive ability and in their results. Such confidence can be obtained through validation. Validation is "[t]he process of determining the degree to which a model or simulation and its associated data are an accurate representation of the real world, from the perspective of the intended uses of the model" [7]. It is important to keep in mind that a model or simulation is validated for an intended use. Models are always simplifications of the real world, and can therefore never be absolutely valid.

More specifically, *face validation* is "the process of determining whether a model or simulation based on performance seems reasonable to people knowledgeable about the system under study. The process does not review software code or logic, but rather reviews the inputs and outputs to assure that they appear realistic or representative" [7]. "Subject-matter experts (SMEs) are a hallmark of face validation, since they compare the simulation structure and output to their area of expertise in the real world" [23]. A step-by-step guide for conducting a face validation can be found in [23].

The *credibility* of a model or simulation can be understood as "a measure of how likely its results are to be considered acceptable for an application" [10]. In more simple terms, we can say that the credibility of a model or simulation is a *measure of how much confidence it is reasonable to have in its outcomes and results*.

The main challenge with validating combat simulations is that it is most often not possible to compare the results to real-world situations (which of course is not really a bad thing). Even if the technical properties of the individual combat elements have been validated separately, combat is so complex, especially in its human aspects, that we have no way of predicting the behaviour of the overall system [6].

4 Combat effectiveness

Combat effectiveness measures the quality of actual combat execution. In this chapter, we will take a conceptual look at evaluation of combat and measurement of combat effectiveness. Specifically, we will first look at what combat effectiveness means from a system-theoretic perspective. After this, we will look at some definitions of combat effectiveness and discuss the factors that can affect combat effectiveness. Finally, we will describe and discuss some of the approaches for quantifying and measuring combat effectiveness that have been suggested in the literature.

4.1 Evaluation of combat

As mentioned in Chapter 2, our primary goal for analysis of combat is to compare different land combat systems or force structures, which may vary with regard to composition of material and equipment, tactical organization, or operational concept. To this end, it is useful to have a set of criteria and preferably a set of measurable parameters for ranking the quality of combat execution.

4.1.1 Economy, efficiency and effectiveness

If we look at a system in general, it is often useful to consider the three "E"s: *economy*, *efficiency* and *effectiveness*. A system usually has *inputs* and *outputs*. A useful system also has *outcomes*, which are the effects of the outputs on the external environment. The external environment is everything outside the boundary of the system. Figure 4.1 shows a system with inputs and outputs.

For a system, *economy* relates to minimizing inputs, *efficiency* relates to the ratio of outputs to inputs, and *effectiveness* concerns the maximization of desired outcomes [20]. This is illustrated in Figure 4.2. It is important to recognize that "[e]conomy and efficiency are not the same as effectiveness, and this is particularly true in combat" [20]. Military units and combat systems need to be robust and have redundancy to survive, and therefore, to some extent, need to be inefficient and uneconomical in order to be effective.

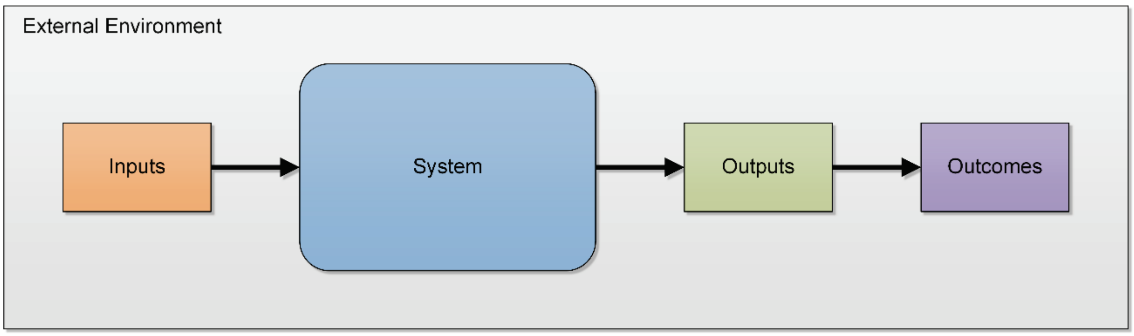

Figure 4.1 A system with inputs and outputs [20].

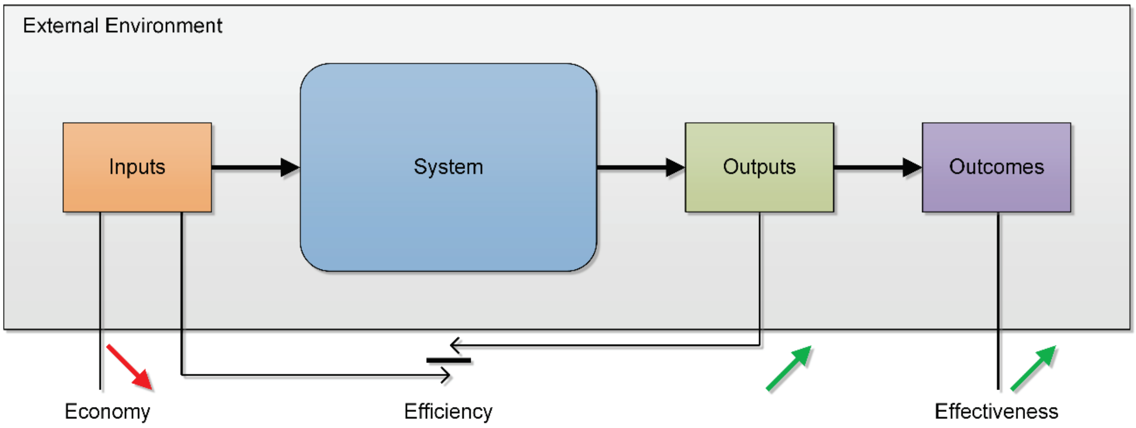

Figure 4.2 Economy, efficiency and effectiveness of a system [20].

In Chapter 3, we defined a *system* as "[a] collection of components organized to accomplish a specific function or set of functions" [7]. In this report, we generally use the term *combat system* for any *system that has a function or set of functions in combat execution*. Examples of a combat system are a weapon system, a group of fighting entities, a force structure element, or a force structure.

4.1.2 Measures of performance and measures of effectiveness

When assessing a combat system it is useful to develop specific *measures of performance* (MOPs) and *measures of effectiveness* (MOEs). MOPs generally have the following characteristics [24]:

- They assess what a combat system achieve in terms of technical performance.
- They measure what a combat system is doing.
- They are typically quantitative.

Examples of MOPs are the number of enemy targets destroyed and the time it takes to advance to a phase line.

MOEs generally have the following characteristics [24]:

- They assess the impact of the actions of a combat system on the effectiveness of achieving a task or mission.
- They assess changes in behaviour, capability, or operational environment.
- They measure what is accomplished.
- They do not measure task performance.
- They are typically more subjective than MOPs and can be both qualitative and quantitative.

Examples of MOEs are mission accomplishment, casualty effectiveness (i.e. the ability to cause higher enemy casualties relative to own losses) and spatial effectiveness (i.e. the ability to advance, and take and hold territory).

A system with high performance will naturally also have good prerequisites for achieving high effectiveness. The term *combat effectiveness* is generally used to describe the quality of actual combat execution. Much of the research work we do at FFI is related to how to increase combat effectiveness.

4.2 Definitions of combat effectiveness

There is no precise and unambiguous definition of *combat effectiveness*. NATO defines combat effectiveness as "[t]he ability of a unit or formation, or equipment to perform assigned missions or functions" [14]. Technically, from a system-theoretic point of view, *combat effectiveness is a measure of the outcomes from a combat system*. That is, a *measure of the effects of the outputs from the combat system on the external environment* (see Figure 4.2). In more practical terms, we can say that combat effectiveness is *a measure of a combat system's ability to solve a given task or mission*, or *a measure of how well a combat system solves a given task or mission*.

A key element here is the last part, "*…a given task or mission".* This means that we measure how effective a combat system is in this particular situation only. This cannot be transferred to other situations or scenarios. If we have two different combat systems, A and B, it may well be the case that system A performs better than B in one scenario, while B performs better than A in another scenario. An overall or absolute combat effectiveness does not really make sense. This is very important to understand. This also means that when comparing two different combat systems, it is vital to decide what scenarios you expect these combat systems to perform in, and measure and compare the combat effectiveness in the relevant scenarios.

It would be useful to be able to predict the combat effectiveness of a combat system. However, combat is not deterministic – at least not in practice. Theoretically, combat may be deterministic, but it is not useful to consider it so [20]. This means that (at least in practice) it is not possible to find and know the states of the necessary set of initial conditions, and compose (and be able to execute) a simulation model with the necessary level of fidelity, that will let us determine the exact outcome of a combat task or mission. The best we can hope for is therefore to estimate the probabilities for a set of predefined categories of outcomes (for example success and failure). Since combat effectiveness is a measure that is directly tied to the outcome of a task or mission, it can in a predictive sense, only be used to say something about the probability of a combat system to be able to solve a given task or mission.

Generally, if a combat system repeatedly has shown the ability to solve a given task or mission well, we can say that it has high combat effectiveness for this task or mission. Then it is reasonable to expect that it will also have a high combat effectiveness, for the same type of task or mission, in the future. In [25], Philip Hayward writes that "[i]t is reasonable to postulate that the greater the combat effectiveness of the unit under consideration, the greater the probability of achieving a given degree of success”. Furthermore, he proposes the following definition of combat effectiveness: “combat effectiveness is the probability of success in combat operations” [25].

A related term that is often used is *combat power*. NATO defines combat power as “[t]he total means of destructive and/or disruptive force which a military unit/formation can apply against the opponent at a given time” [14]. Combat power is a measure of the quantity and quality of the elements of a combat system, whereas combat effectiveness is a measure of the quality of the actual combat execution. Combat effectiveness will of course depend on combat power. A combat system with high combat effectiveness can be expected to make better use of its combat power [26].

4.3 Direct and indirect effects

We have established that combat effectiveness is a measure of the effects of the outputs from a combat system on the external environment. These effects can be either *direct* or *indirect* [27]. *Direct* effects are caused directly by an action, for example destroying a combat vehicle by firing a weapon. *Indirect* effects are, on the other hand, not directly caused by an action. An example is the *force-in-being* effect, where the mere existence of a combat system, and its potential to act, has an effect on the behaviour of an opposing force. The indirect effects are thus in fact decided by the opposing force, and not directly by the combat system itself [28].

4.4 Factors that affect combat effectiveness

In the literature, there are mainly two directions regarding which factors are important for combat effectiveness. The first direction looks at combat effectiveness mainly as a result of human factors. In [29], for example, “skill to fight” and “will to fight” are considered the essential components of combat effectiveness. This more narrow view of combat effectiveness is of course useful when studying combat between symmetric forces with roughly the same material resources. The other direction has a more holistic view of combat effectiveness and is concerned with all factors that can possibly affect the course of a battle, including both human and material resources. In this report, we will follow the holistic view of combat effectiveness.

Following Philip Hayward, we argue that the factors that affect the combat effectiveness of a combat system essentially can be placed in the following main categories [25]:

- **Combat system (Blue force) capabilities:**
  This category includes all human and materiel resources of the combat system. These resources comprise both quantitative and non-quantitative factors. Human resources include number of personnel and their job specifications, experience, training level and so on. Examples of materiel resources are vehicles, weapon systems, sensor systems, communication infrastructure, and ammunition. Important factors for the fighting entities are firepower, protection and mobility. Included in this category are also the organisation of units, doctrine, tactics, and human factors like leadership, “will to fight” (or morale),

and cohesion. Essentially, this category represents the combat power of the combat system.

- **Enemy (Red force) capabilities:**
  This category includes all human and materiel resources of the enemy force. It includes exactly the same factors as the previous category. Essentially, this category represents the combat power of the enemy force. An enemy force with much combat power is expected to be harder to fight, so the enemy capabilities will obviously affect the probability of a combat system to solve a given task or mission.

- **Environment:**
  This category includes terrain, vegetation and human-built structures, in addition to climate and weather. It is not surprising that the environment will affect the probability of a combat system to solve a given task or mission. Rain, snow or fog are examples of weather conditions that may reduce the combat system's combat effectiveness.

- **Combat system (Blue force) task or mission:**
  This factor needs to be included, because it is not possible to determine if a given task or mission has been solved, unless it has been defined. Furthermore, a given combat system may have a high combat effectiveness for one task or mission, but a negligible combat effectiveness for a task or mission of another nature.

- **Enemy (Red force) task or mission:**
  The enemy mission will also affect the probability of the combat system to solve a given task or mission.

These categories, and how they interact, are illustrated in Figure 4.3.

If we only look at the factors in the "combat system capabilities" category, and keep all the other factors constant, there are mainly three overall factors that determine the combat effectiveness:

- Force strength of the combat system relative to the enemy force
- Technological lead of the combat system relative to the enemy force
- Force employment of the combat system

Force employment appears to be the most decisive factor in modern combat. In his book *Military Power: Explaining Victory and Defeat in Modern Battle* [30], Stephen Biddle presents compelling arguments based on historical data that force employment has played a more important role for the outcome of warfare than either force strength or technological lead since the beginning of the twentieth century. Biddle states that effective force employment (which he calls modern system force employment) is "a tightly interrelated complex of cover, concealment, dispersion, suppression, small-unit independent maneuver, and combined arms at the tactical level, and depth, reserves, and differential concentration at the operational level of war" [30].

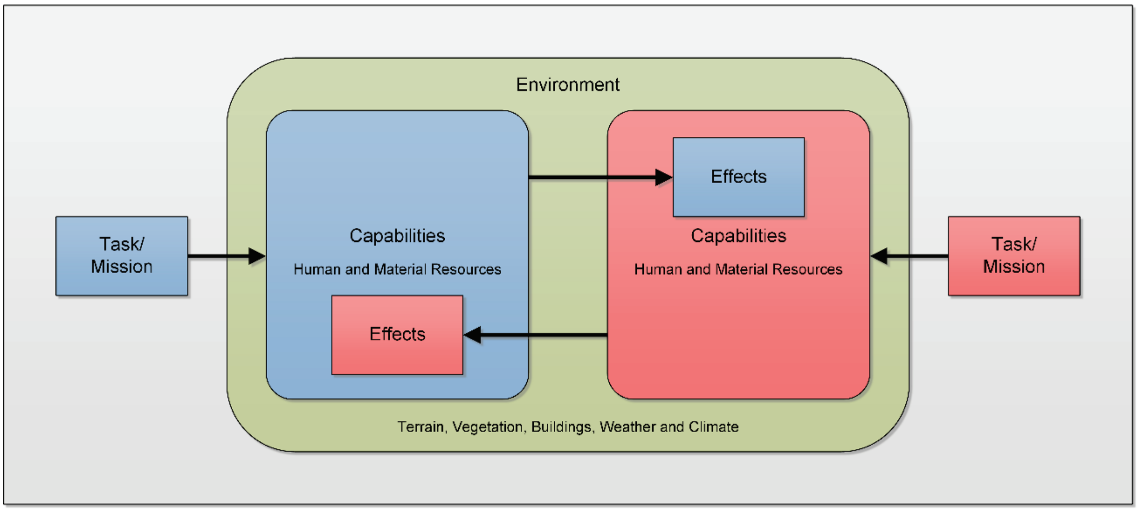

Figure 4.3 Factors that affect combat effectiveness.

4.5 How can combat effectiveness be quantified and measured?

There are three main approaches for measuring the combat effectiveness of a combat system:

1. Use data from actual combat situations.
2. Use a mathematical model of combat and solve it analytically.
3. Use data from simulations and wargames.

Figure 4.4 illustrates the three approaches. The approaches follow from Figure 3.1, which shows the different ways to study a system.

The only way of accurately measuring the combat effectiveness of a combat system is by using data from actual combat. However, data from actual combat are often scarce, and for the kind of studies we conduct, it is almost impossible to find useful data from actual combat. The second approach, deriving a useful mathematical model for combat and solving this analytically, is generally considered too complex. This leaves us with the last approach; estimating combat effectiveness by using data from simulations and wargames. We will discuss this approach further in Chapter 5.

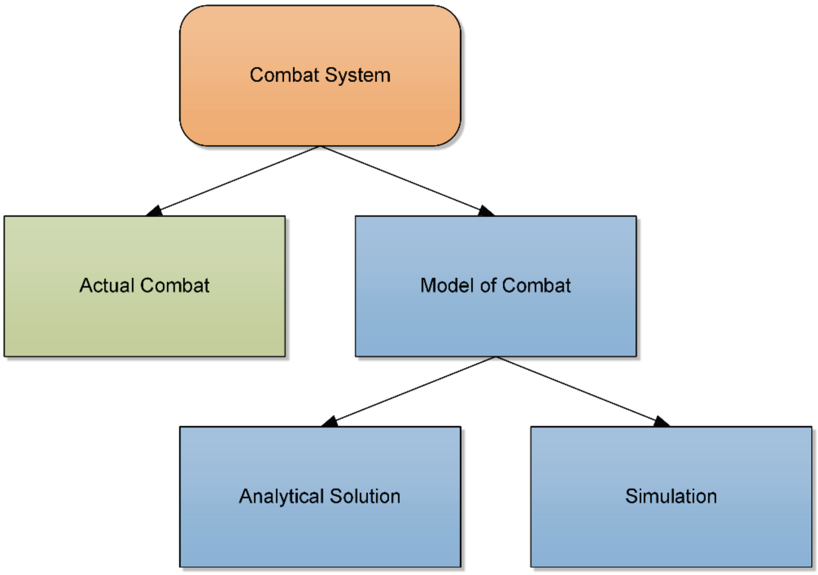

Figure 4.4 Main approaches for measuring combat effectiveness.

In the sections from 4.5.1 to 4.5.5 below, we will take a look at some of the approaches for quantifying and measuring combat effectiveness that have been suggested in the literature in more detail.

4.5.1 A formal equation for combat effectiveness

In [25], Philip Hayward suggests the following expression for the combat effectiveness of a combat system:

$$\begin{aligned}\text{Combat effectiveness} &= \text{Probability of success in combat}\\ &= P(S)\\ &= f(x_1 \dots x_n;\, y_1 \dots y_n;\, e_1 \dots e_m;\, m_1 \dots m_r)\end{aligned} \quad (4.1)$$

where:

$$\begin{aligned}x_i &= i\text{th capability of the combat system,}\\ y_i &= i\text{th capability of the enemy force,}\\ e_i &= i\text{th environmental parameter,}\\ m_i &= i\text{th mission parameter.}\end{aligned}$$

Then, “the problem of estimating combat effectiveness comes down to (a) determining what variables the sets X, Y, E, and M include; (b) developing appropriate quantitative expressions for those variables; (c) determining the functional form of the dependence of $P(S)$ on those variables” [25]. We are not aware of any successful solution to this problem, and it is doubtful that it is solvable, at least in practice. Hayward himself writes, “it is quite possible that even the most thoroughgoing analysis will leave a rather large number of independent variables, the influence of which on combat effectiveness remains to be assessed” [25].

Hayward's expression for combat effectiveness, and his five main categories of factors that affect combat effectiveness, are useful as a conceptual framework. However, it is not possible to use it to quantify or measure combat effectiveness in practice.

4.5.2 Quantified Judgement Model

The Quantified Judgement Model (QJM) is a set of equations and rules developed by Trevor N. Dupuy in the late 1960s, based on analysis of historical data from 60 battles from World War II. In QJM, *combat power* (P) is quantified as follows [31]:

$$P = S \times V \times CEV \tag{4.2}$$

Here S represents *force strength*, V represents the *variables affecting the employment of force under the circumstances existing at the time of the battle or engagement*, and CEV represents the *combat effectiveness value*.

The force strength (S) is calculated from the following three steps [32]:

1. The lethality of each weapon is quantified in a process that considers the characteristics of the weapon, to arrive at an Operational Lethality Index (OLI). The weapons are divided into six categories: infantry, anti-armour, artillery, air defence, armour, and air support.
2. The variable factors influencing the effectiveness of the weapons on the battlefield, such as weather, terrain, and season, is applied to the OLIs for each category of weapon.
3. Force strength (S) is the sum of the modified OLIs for the weapons for each side.

V represents the variables affecting the force as a whole, rather than just the weapons. The model includes more than 20 such factors, but the most important are posture (e.g. offensive or defensive), terrain, weather, mobility, and vulnerability [32].

CEV (combat effectiveness value) represents the quality of the fighting personnel. This includes human factors such as leadership, "will to fight" (or morale), training level and experience.

Since the components of CEV are not directly measurable, Dupuy defines the theoretical combat power (P') as [31]:

$$P' = S \times V \tag{4.3}$$

CEV for the Blue (CEV_{B}) and Red (CEV_{R}) force can then be calculated from the actual battle result ratio divided by the theoretical combat power ratio:

$$CEV_{\mathrm{B}} = \frac{\dfrac{R_{\mathrm{B}}}{R_{\mathrm{R}}}}{\dfrac{P'_{\mathrm{B}}}{P'_{\mathrm{R}}}} = \frac{R_{\mathrm{B}}}{R_{\mathrm{R}}} \times \frac{P'_{\mathrm{R}}}{P'_{\mathrm{B}}} \tag{4.4}$$

$$CEV_{\mathrm{R}} = \frac{\dfrac{R_{\mathrm{R}}}{R_{\mathrm{B}}}}{\dfrac{P'_{\mathrm{R}}}{P'_{\mathrm{B}}}} = \frac{R_{\mathrm{R}}}{R_{\mathrm{B}}} \times \frac{P'_{\mathrm{B}}}{P'_{\mathrm{R}}} \tag{4.5}$$

Here *R* is the *actual battle result*, quantified as follows [31]:

$$R = M + G + C \tag{4.6}$$

where *M* represents *mission accomplishment*, *G* represents *ability to gain or hold ground*, and *C* represents *casualty effectiveness*.

The original QJM is a deterministic, static, mathematical model developed to predict the outcome of division-level battles. In 1990, however, Dupuy in collaboration with James G. Taylor, introduced representation of time into the model by using differential equation methodology for attrition [26]. This new model was called the Tactical Numerical Deterministic Model (TNDM).

4.5.3 Loss exchange ratios

"The most commonly used metric of combat effectiveness is casualty effectiveness, which is the ability of one side to cause losses of another compared to their own losses" [26]. The *loss exchange ratio* (LER) can generally be defined as the ratio of the number of fighting entities lost by the enemy divided by own losses. Since this ratio may vary throughout the battle, it is often useful to follow the development of the LER as a function of time into the battle:

$$LER(t) = \frac{R_0 - R(t)}{B_0 - B(t)} \tag{4.7}$$

where:

t = time into the battle,
R_0 = initial number of Red entities,
$R(t)$ = number of Red entities left at time t,

B_0 = initial number of Blue entities,
$B(t)$ = number of Blue entities left at time t.

If we divide the losses on each side by the initial number of fighting entities, we get what is known as the *force exchange ratio* (FER) or *fractional exchange ratio*:

$$FER(t) = \frac{\frac{R_0 - R(t)}{R_0}}{\frac{B_0 - B(t)}{B_0}} = \frac{B_0}{R_0}\left(\frac{R_0 - R(t)}{B_0 - B(t)}\right) = \frac{B_0}{R_0} LER(t) \tag{4.8}$$

The losses that are counted are usually personnel, but it can also be combat vehicles or other weapon platforms. Using weighted sums of the relative combat values of the entities from the different categories of fighting entities in use will probably give the best overall picture of the ratio of combat power that has been lost on each side.

Historical data show that the percentage of losses for successful forces are almost always lower than the percentage of losses for their unsuccessful opponents, regardless of who is attacker and who is defender [26]. The LER is therefore a well-founded measure for combat effectiveness. Nevertheless, loss exchange ratios have limited usefulness regarding insights into the details and dynamics of the battle and the analysis of cause-and-effect relationships. The LER has the advantage of being a measureable parameter, but the slight disadvantage that inflicting losses is not really the primary purpose of combat. Very often it would appear better to achieve the mission with fewer losses on both sides. However, casualty effectiveness does correlate to some extent with combat effectiveness.

Even though the LER is a very rough metric for combat effectiveness, it could be useful to implement functionality for monitoring the LER in our combat simulations. Especially, if we implement a LER based on the weighted sum of the relative combat values of the different entities. This will give us a rough indication on the status of the battle in real time and may help us detect turning points and break points during the battle.

4.5.4 Battle Trace

In [33], Barr, Weir & Hoffman suggest an approach for measuring combat effectiveness, which they call the Battle Trace. They point out that there is a need for quantitative measures of effectiveness that can illuminate the following questions [33]:

- Who could see who, when, where, with what sensors/weapons?
- What weapons were fired, when, where, at what ranges?
- Who was destroyed, when, where, from what cause?

The Battle Trace indicates the degree of success of a force as a function of time into the battle. If the battle is divided into time intervals Δ_1, Δ_2, …, Δ_n, the Battle Trace for a given time interval Δ_i, is defined as [33]:

$$BT(\Delta_i) = \frac{\dfrac{R(t_i) - R(t_{i-1})}{R(t_i)}}{\dfrac{B(t_i) - B(t_{i-1})}{B(t_i)}} = \frac{\dfrac{\Delta R_i}{R_i}}{\dfrac{\Delta B_i}{B_i}} \tag{4.9}$$

where:

t = time into the battle,
Δ_i = time interval from t_{i-1} to t_i,
$R(t)$ = number of (effective) Red entities left at time t,
$B(t)$ = number of (effective) Blue entities left at time t.

It is emphasised by Barr et al. that the number of forces used to calculate BT for a given time interval should include only entities that are able to affect opposing entities, for example by having line of sight and weapon range [33].

From equation (4.9) we can see that:

- If $BT < 1$ at a given time interval, the Red force is most successful.
- If $BT > 1$ at a given time interval, the Blue force is most successful.

The Battle Trace is a measure of which force that appears to be winning the battle at a given time. It is especially suitable for being used on data from detailed, entity-level combat simulations, where it can trace the course of the battle in real time.

Since the Battle Trace is not symmetric about the value of $BT = 1$, in the sense that values of $BT < 1$ must be interpreted differently form values of $BT > 1$, it is more intuitive to plot the logarithm of the Battle Trace, log(BT). Plots of log(BT) have a symmetric interpretation with respect to Blue and Red, in an additive sense[1]. Figure 4.5 shows an example of a plot of log (BT). In this example, the Red force is most successful at the beginning of the battle, while the Blue force is most successful towards the end.

Like the LER, it could be useful to implement functionality for monitoring the Battle Trace in our combat simulations. This will give us an indication on the status of the battle in real time and may help us detect turning points and break points during the battle. To use this approach in practice, however, clear criteria for which entities that should be counted must be defined. In addition, like with the LER, it would probably be better to use weighted sums of the relative combat values of

[1] This is because the logarithm of a ratio is equal to the logarithm of the numerator minus the logarithm of the denominator.

the entities from the different categories of fighting entities in use. As mentioned in section 4.5.3, inflicting losses is not the primary aim of combat, but the number of entities left is measurable.

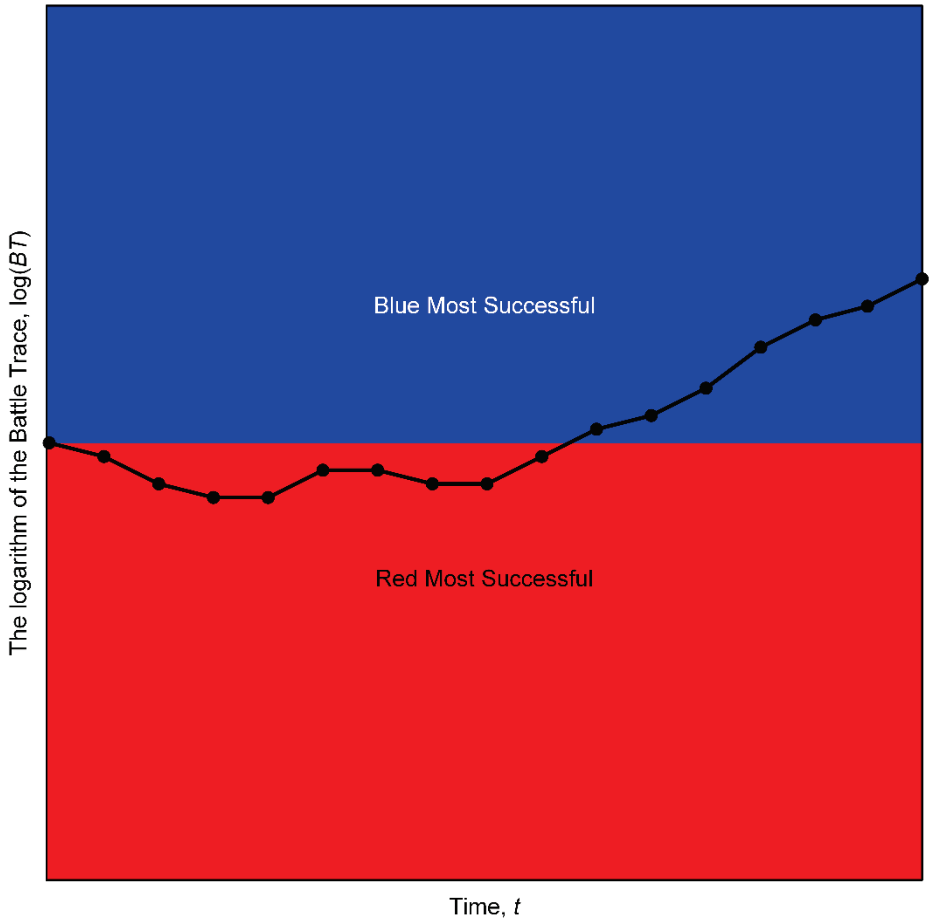

Figure 4.5 Example of a plot of the logarithm of the Battle Trace, log(BT).

4.5.5 Identifying and counting fire engagement opportunities

In [34] and [35], Lee & Lee, suggest an approach for measuring combat effectiveness by identifying and counting fire engagement opportunities. They argue that combat effectiveness of a force under a direct fire engagement can be reasonably assessed by the number of attack opportunities it is able to create. An attack opportunity can either be created by a single entity, or by collaboration between two or more entities. Moreover, they model the combat environment as a *heterogeneous network* and use this representation to identify and count the occurrence of isolated and networked attack opportunities. Figure 4.6 shows the network structures for isolated (to the left) and networked (to the right) attack opportunities.

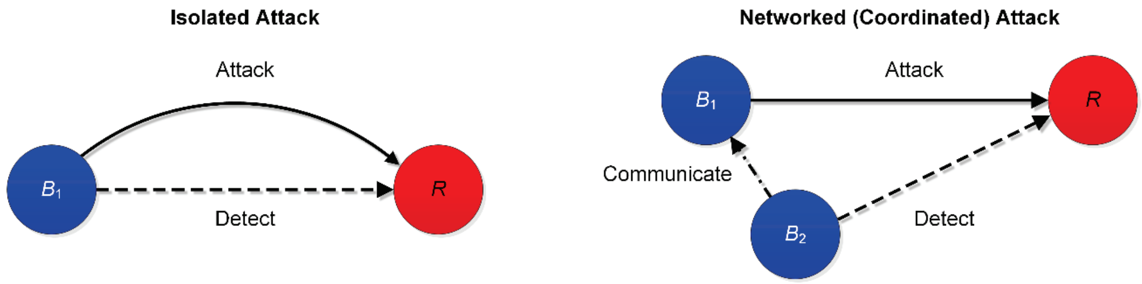

Figure 4.6 Network structures for isolated (to the left) and networked (to the right) attack opportunities [35].

The concept of identifying and counting fire engagement opportunities is something we should investigate further. It should be possible to implement an automatic system for counting fire engagement opportunities in our combat simulations. Maybe this approach could also be extended to identify and count indirect fire engagement opportunities. If so, it would give us a measure of combat effectiveness that includes combined arms effects.

5 Estimating combat effectiveness using simulations

As we saw in the previous chapter, using modelling and simulations (M&S) is the only feasible way in which we can study possible future combat scenarios. Especially when it comes to assessing the combat effectiveness of new and novel combat systems. For example, systems using new technologies, systems utilizing new ways of organizing units, or systems employing new concepts of operation. It is, however, important to keep in mind that combat models are simplifications and will never represent all aspects of reality. Military operations are highly complex and M&S of such operations, with sufficient realism, is very challenging. Especially when it comes to the human factors.

In this chapter, we will first discuss the two main approaches for combat simulations and their pros and cons. Then, we will discuss how we use simulations to assess and compare the relative combat effectiveness of different combat systems and how to determine task or mission success. After this, we outline an example of a typical simulation experiment for assessing and comparing the relative combat effectiveness of different combat systems. Finally, we will discuss the most important limitations of using combat simulations and simulation-supported wargames.

5.1 Combat simulation approaches

There are mainly two approaches for conducting combat simulations: using fully automated closed-loop simulations (without any human interaction) or using human-in-the-loop (HITL) simulations (with varying degrees of human interaction).

Closed-loop combat simulations can usually be run much faster than real-time. They can therefore be repeated hundreds or thousands of times to get a statistical distribution of the outcomes. Still, there is obviously a danger in removing the human elements entirely from the simulations since the human aspects are so important in combat, and human behaviour is very difficult to model (see Section 3.7). Current computer-generated forces (CGF) can execute battle drills and lower-level tactics with a high degree of realism. However, it is currently not possible to create realistic models of the planning and decision-making (based on experience, intuition, and emotions) that are done by officers at the higher levels of the chain of command. In closed-loop combat simulations, the outcomes are only as good as the simulation model and associated input data themselves. Validation thus becomes very important, but as mentioned in Section 3.9, combat simulations are in general very difficult to validate since it is most often not possible to compare the results to real-world situations.

HITL combat simulations are mainly associated with virtual simulations in the LVC taxonomy (see Section 3.5), but constructive simulations may also require a certain degree of human interaction, for example to control semi-automated forces (SAF). Virtual simulations include human combat system operators. Constructive simulations with SAF include humans (e.g. officers) controlling the forces. Including real humans in combat simulations, and especially using virtual simulations, is obviously the approach that gives the most realistic representation of the human aspects of combat. Using subject-matter experts (SMEs), like real system operators or real military commanders, in combat simulations will also function as an additional built-in face validation of the simulations (see Section 3.9). It is usually also easier to follow the course of the battle and identify cause-and-effect relationships in a HITL simulation, and thereby better understand what led to the outcome. Including military personnel, and especially military leaders, in the simulations, will also often lead to more confidence in the results among stakeholders [3][4]. HITL simulations, and especially virtual simulations, are also more flexible when it comes to trying out new tactics and new ways of operating. HITL simulations are, however, time and resource consuming, and for virtual simulations it is often impractical, or not even technically possible, to use human operators for every entity in a simulation with hundreds of entities. In general, it is also problematic to execute HITL simulations faster than real-time, and this of course greatly limits the number of times a HITL simulation can be repeated.

HITL simulations will also include the element of competition (since human participants generally don't like to lose). In a combat simulation with Blue and Red forces, both teams will do everything they can to win the battle, and the losing team will try to modify and improve their tactics for the next run.

To summarize the discussion above, we have to choose between:

1. Closed-loop combat simulations that can be run much faster than real-time and thus repeated many times, but give a less realistic representation of the human aspects of combat.
2. HITL combat simulations that must be run in real-time and thus can be repeated only a few times, but give a more realistic representation of the human aspects of combat.

In our simulation experiments, which are often focused on trying out new technologies and new ways of operating, we mainly use HITL simulations. As mentioned in Chapter 2, we use virtual simulations in experiments where human system operators are essential, for example when experimenting with technologies that directly affect human performance or how humans operate at the technical level. To simulate larger operations, typically at the battalion and brigade level, we use constructive simulations with SAF. These simulations are conducted as simulation-supported, two-sided (Blue and Red) wargames, where human players (typically officers) on both sides give orders to the SAF. Our methodology and best practices for conducting successful simulation-supported wargames for assessing force structures can be found in [37].

5.2 Relative combat effectiveness

From the discussions in Chapter 4 we concluded that for a measure of combat effectiveness to be useful in general, it should be able to give an estimate of a combat system's probability of success in a given mission type. An absolute value for the combat effectiveness of a combat system, or the probability of a combat system to be able solve a given task or mission, would in practice be very hard to estimate with any particular confidence using simulations. Moreover, this estimate would in any case only be valid for a specific mission against a specific enemy in a specific environment.

As we discussed in the previous section, closed-loop simulations can be repeated many times but they are hard to validate and usually fall short in representing the complexity of warfare, especially when it comes to the human aspects. HITL simulations are better able to represent the human aspects and complexity of combat and can at least to some degree be validated using face validation, but they cannot be repeated enough times to get a statistical distribution of the outcomes.

Which one of two or more combat systems that has the highest *relative combat effectiveness* is, however, something that usually can be determined with more confidence in our simulation experiments than estimating an absolute value for combat effectiveness for each combat system. What we are mainly interested in, is to assess and compare the relative combat effectiveness of different combat systems executing the same task or mission against the same enemy. For example, to investigate which one of two or more alternative combat systems (e.g. weapon systems, groups of fighting entities, force structure elements, or force structures) that solves a selection of tasks or missions best. In our simulation experiments, we therefore seek only to vary the factors in the "combat system capabilities" category (see Section 4.4) and keep all the other factors as constant as possible.

It is, however, reasonable to expect that an enemy with a large pool of force elements to choose from will use a force that is somewhat customized and suitable to fight the expected opponent (for example if the combat system capabilities do not include main battle tanks, the enemy will probably not bring a lot of anti-tank capabilities). The enemy force should therefore be allowed to adapt to changes in the combat system capabilities, even if this makes it more difficult to compare the different combat systems [36][37].

5.3 Determining task or mission success

Battles are rarely fought until all units on one of the sides are completely destroyed. Usually, one side will reach some point where it no longer is able to reach its goal or function as a cohesive force. In a simulation-supported wargame the simulated operation will usually reach a point where there is a consensus among the umpires, and the Blue and Red players, as to whether the Blue combat system has successfully solved its task or mission or not.

Additionally, quantitative measures like *breakpoints* can be used to determine success or failure. One approach for modelling breakpoints is to monitor the ratio between the remaining Blue and Red force and their initial force. When a certain percentage of one of the side's force has been lost, this force will no longer be able to continue the battle. This approach is known as the *absolute breakpoint rule* [11]. Figure 5.1 shows the development of the ratio of remaining Blue and Red forces in a battle until Blue wins as a result of the absolute breakpoint rule. Another approach is to monitor the ratio between the Blue and the Red force in a battle. If this ratio reaches a level where one of the side's force is heavily outnumbered, this force may choose to retreat or surrender.

This approach is known as the *proportional breakpoint rule* [11]. Figure 5.2 shows the development of the ratio of remaining Blue and Red forces in a battle until Blue wins as a result of the proportional breakpoint rule.

The loss exchange ratio (LER) (see Section 4.5.3) and the Battle Trace approach (see Section 4.5.4) also give useful indications of which side is most successful. It is also important to note that more specific tasks or missions, for example in smaller virtual simulation experiments, can have other more specific qualitative or quantitative criteria for success. Criteria for task or mission success and specific measures of performance (MOPs) and measures of effectiveness (MOEs) (see Section 4.1.2) must be developed based on the combat system being evaluated and the given task or mission.

A typical simulation experiment for comparing relative combat effectiveness is outlined in the following section.

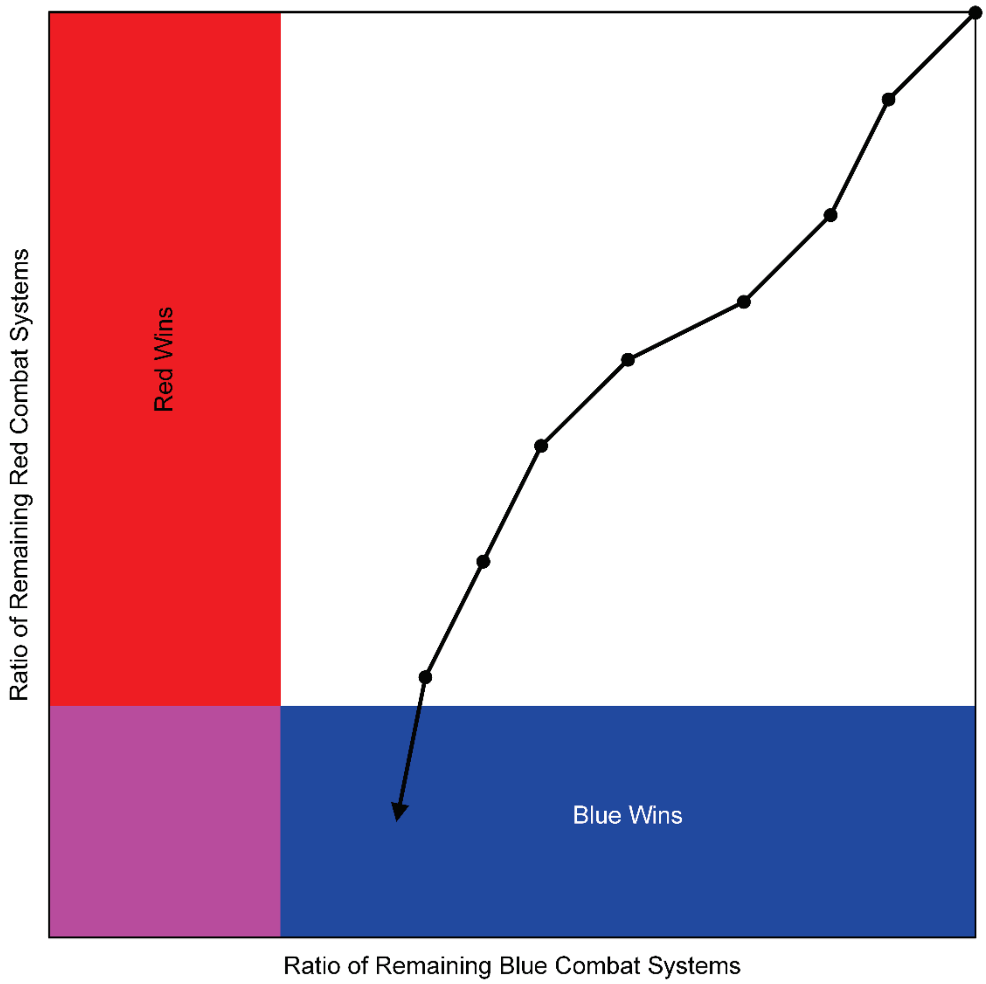

Figure 5.1   Absolute breakpoint rule.

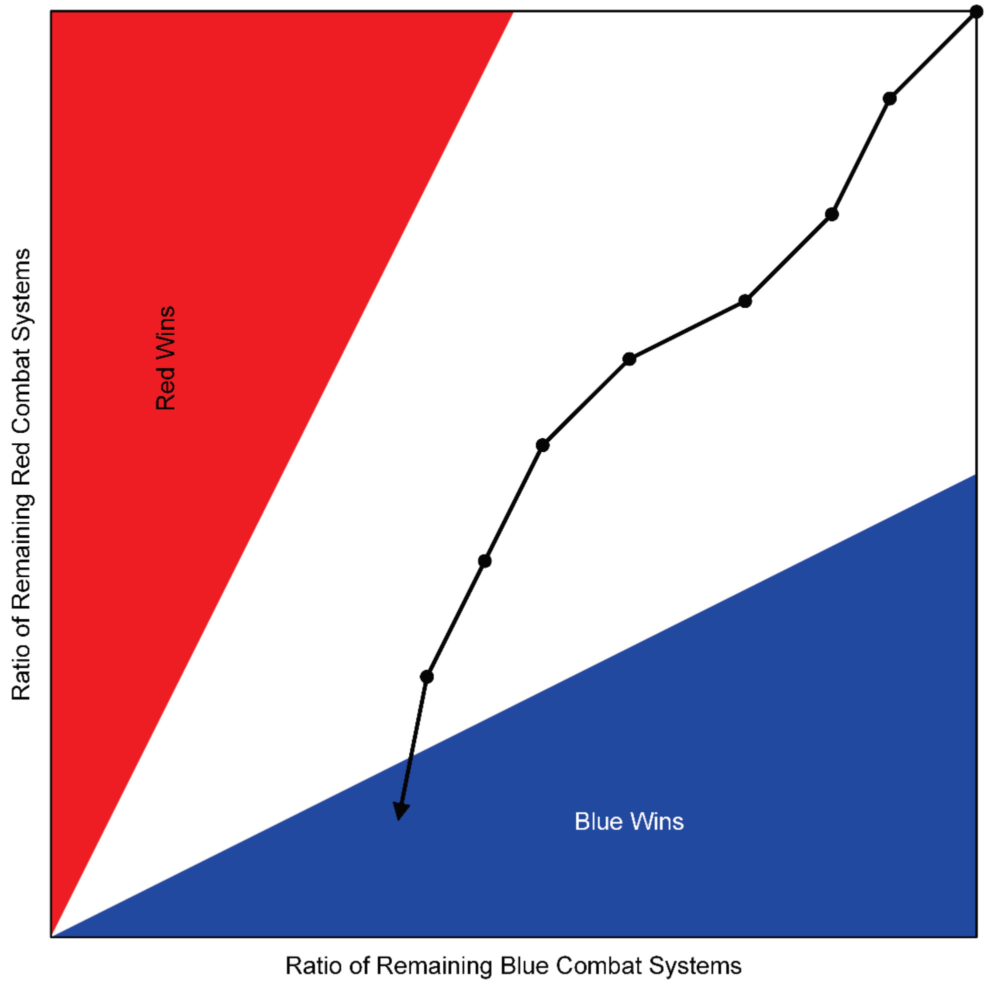

Figure 5.2 Proportional breakpoint rule.

5.4 Outline of simulation experiments

A typical research task for us can be to assess and compare the relative combat effectiveness of three different combat systems in three different scenarios. The three combat systems can for example consist of a combat system currently in use, CS_0, and two suggested alternative improvements (e.g. regarding materiel or concept of operation) of this combat system, CS_1 and CS_2. To test the combat systems we can for example choose three scenarios (or tactical vignettes[2]). A scenario must include a geographic location, a task or mission for the combat systems and a task or mission for the enemy force. The scenarios should span the different tasks/missions the combat systems can be employed in. The scenarios we use are often derived from overarching national defence scenarios.

[2] A tactical vignette is a specific playable course of battle extracted from a larger scenario.

Depending on the level of human operator involvement necessary, and the size of the operation that needs to be simulated, the simulation experiments can be either virtual or constructive with SAF (i.e. simulation-supported wargames). It is also possible with simulation experiments that include both virtual and constructive entities. However, when virtual and constructive simulation models are combined, difference in resolution between them can lead to fair-fight issues [6]. Conducting virtual simulations to collect system performance data, and then using these data to calibrate subsequent constructive simulations, can also be an applicable approach.

Our primary indicator for combat effectiveness is a combat system's ability to solve the given task or mission based on given criteria. A typical result from a simulation experiment series with three combat systems tested in three scenarios can be in the form of a 3 x 3 matrix where the cells are coloured in green for success or red for failure. An example of such a result matrix is shown in Table 5.1. In this example, CS_0 fails to solve the task or mission in all three scenarios, while CS_1 and CS_2 successfully solves the task or mission in all three scenarios.

In addition to being able to solve a task or mission, it is, as mentioned in the previous section, often also useful to define other more specific MOPs and MOEs to evaluate the combat systems. In the example shown in Table 5.1, both CS_1 and CS_2 solves the given task or mission, but there could be a difference in how well or how effectively the tasks or missions are solved. Examples of additional criteria can be to complete the task or mission without losing more than 40 percent of the force or complete the task or mission within 24 hours. An example of a result matrix with an additional criterion is shown in Table 5.2. Here the cells are coloured in yellow for task or mission success, but failure to fulfil the additional criterion. Furthermore, the cells are coloured in green if the additional criterion is fulfilled. In this example, CS_1 fails to fulfil the additional criterion in two of the scenarios, while CS_2 fulfils the additional criterion in all three scenarios. This gives us an indication that CS_2 has the highest overall combat effectiveness of the three combat systems in the three chosen scenarios.

	Scenario 1	**Scenario 2**	**Scenario 3**
CS_0	Failure	Failure	Failure
CS_1	Success	Success	Success
CS_2	Success	Success	Success

Table 5.1 Example of a result matrix from a simulation experiment series (with three combat systems tested in three scenarios) that shows whether the combat systems solved the given task or mission.

	Scenario 1	Scenario 2	Scenario 3
CS_0	Failure	Failure	Failure
CS_1	Success	Success	Success
CS_2	Success	Success	Success

Table 5.2 Example of a result matrix from a simulation experiment series (with three combat systems tested in three scenarios) that shows whether the combat systems solved the given task or mission and fulfil an additional criterion.

If both CS_1 and CS_2 fulfil (or fail to fulfil) the additional criterion, and no clear distinction in their combat effectiveness can be found, possible ways forward may be to repeat some, or all, of the scenarios or add new scenarios. The conclusion may also be that the simulation experiments indicate that their combat effectiveness is about equal.

In any case, it is important to seek to understand why one combat system has a better relative combat effectiveness than the others do. For that reason, identifying major strengths and weaknesses of a combat system and its utilization is an important part of the analysis phase after an experiment series. The analysis phase may also result in suggested improvements that can further increase the combat effectiveness for the tested combat systems. Improved versions of the combat systems may then be tested in new simulation experiment series.

5.5 Limitations of using combat simulations and wargames

M&S is essential for most defence experimentation. Combat simulations and wargames can of course not be used to predict the exact outcome of a battle or a war, but they can produce plausible outcomes. The term "indication" has been suggested to describe any insights drawn from the outcome of a wargame [22][38].

As we mentioned in Section 3.9, it is challenging to validate combat simulations in general since it is most often not possible to compare the results to real-world situations. This becomes even more challenging for combat simulations that involve the use of future technologies and new and novel operational concepts. Even if the technical properties of the individual combat elements can be validated separately, combat is so complex, especially in its human aspects, that the best we can do to validate the simulation as a whole is to conduct face validation.

Today, it is possible to create synthetic environments that to a high degree replicate the physical properties of the real world. Modelling realistic human behaviour and cognition, on the other hand, is recognized as the hardest and most complex challenge in combat simulation [19].

As we saw in Section 4.4, the combat effectiveness of a combat system depends on five main categories of factors (combat system capabilities, enemy capabilities, environment, combat system task or mission, and enemy task or mission). When using simulations to estimate relative combat effectiveness it is important to consider if these categories of factors (especially the first three) are sufficiently represented in the simulations. Furthermore, it is important to consider what effects any weaknesses and limitations in the simulations can have on the results. For example, we have seen that entity-level simulation systems that do not represent micro-terrain features make cover and concealment difficult, and this systematically favours long-range, direct fire weapon systems [6]. It is also a known issue that current entity-level models tend to produce attrition levels that are higher than those observed historically [39][40]. "Possible phenomena present in actual combat and accounted for in [the parameters of aggregate-level attrition models (such as the Lanchester models)] but not [in the] entity-level combat models that could explain this include target duplication, shooter non-participation, suppression effects, self-preservation, and suboptimal use of weapons and targeting systems" [39]. In other words, current constructive entity-level combat models lack good representations of the human aspects of combat and combat friction, resulting in that the simulated operations tend to run smoother than they would in the real world.

We know that modelling realistic human behaviour and cognition is very complex, and all simulation systems consequently have a limited representation of human factors. It is important to make an assessment of what effects this can have on the results.

6 Summary and conclusion

In this report, we have discussed *combat effectiveness* and how it can be quantified and measured. We have looked at some definitions of combat effectiveness, discussed the factors that can affect combat effectiveness, and described and discussed some of the approaches for quantifying and measuring combat effectiveness that have been suggested in the literature. Moreover, we have discussed how we use simulations to assess and compare the relative combat effectiveness of different combat systems.

Combat effectiveness can in general be said to be *a measure of a combat system's ability to solve a given task or mission*, or *a measure of how well a combat system solves a given task or mission*. The factors that can affect the combat effectiveness of a combat system can essentially be placed in the following main categories: combat system capabilities (human and materiel resources, organisation, doctrine, tactics, etc.), enemy capabilities, environment (terrain, vegetation, human-built structures, climate and weather, etc.), combat system task or mission, and enemy task or mission [25].

If we only look at the factors in the "combat system capabilities" category, and keep all the other factors constant, there are mainly three overall factors that determine the combat effectiveness: force strength of the combat system relative to the enemy force, technological lead of the combat system relative to the enemy force, and force employment of the combat system. Force employment seems to be a decisive factor in modern combat [30].

There are three main approaches for measuring the combat effectiveness of a combat system: (1) use data from actual combat situations, (2) use a mathematical model of combat and solve it analytically, and (3) use data from simulations and wargames. However, data from actual combat are often scarce, and deriving a useful mathematical model for combat and solving this analytically, is generally considered too complex. The only feasible option for us, especially when it comes to assessing the combat effectiveness of new and novel combat systems, is therefore to use data from simulations and wargames.

There are two main approaches for conducting combat simulations: using fully automated closed-loop simulations (without any human interaction) or using human-in-the-loop (HITL) simulations (with varying degrees of human interaction). Closed-loop combat simulations can be run much faster than real-time and thus repeated many times, but give a less realistic representation of the human aspects of combat. HITL combat simulations must be run in real-time and thus can be repeated only a few times, but give a more realistic representation of the human aspects of combat.

In our simulation experiments, which are often focused on trying out new technologies and new ways of operating, we mainly use HITL simulations. We use virtual simulations in experiments where human system operators are essential, for example when experimenting with technologies that directly affect human performance or how humans operate at the technical level. To simulate larger operations, typically at the battalion and brigade level, we use constructive simulations with

SAF. These simulations are conducted as simulation-supported, two-sided (Blue and Red) wargames, where human players (typically officers) on both sides give orders to the SAF.

An absolute value for combat effectiveness of a combat system, or the probability of a combat system to be able solve a given task or mission, would in practice be very hard to estimate with any particular confidence using simulations. We use HITL simulations to assess and compare the *relative combat effectiveness* of different combat systems. Which one of two (or more) combat systems that has the highest relative combat effectiveness is something that usually can be determined with more confidence in our simulation experiments than estimating an absolute value for combat effectiveness for each combat system.

Before a simulation experiment, it is important to develop criteria for task or mission success and additional specific *measures of performance* (MOPs) and *measures of effectiveness* (MOEs) based on the combat system being evaluated and its task or mission. In a simulation-supported wargame the simulated operation will usually reach a point where there is a consensus among the umpires, and the Blue and Red players, as to whether the Blue combat system has successfully solved its task or mission or not. In addition, quantitative measures like *breakpoints* based on remaining force ratios, *loss exchange ratios* (LERs) and the *Battle Trace* approach [33] can give useful indications of which side is most successful. Finally, it is always important to identify major strengths and weaknesses of a combat system and its utilization, and seek to understand why one combat system has a better relative combat effectiveness than the others do.

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Abbreviations

AAR	After Action Review
AI	Artificial Intelligence
AR	Augmented Reality
ASL	Advanced Squad Leader
C4I	Command, Control, Communications, Computers, and Intelligence
CEV	Combat Effectiveness Value
CGF	Computer-Generated Forces
FER	Force Exchange Ratio
HITL	Human-in-the-Loop
IFT	Infantry Firing Table
KIA	Killed in Action
LER	Loss Exchange Ratio
LVC	Live, Virtual, and Constructive
M&S	Modelling and Simulation
MBT	Main Battle Tank
MC	Morale Check
MOE	Measure of Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organization
OLI	Operational Lethality Index
PTC	Pin Task Check
QJM	Quantified Judgement Model
SAF	Semi-Automated Forces
SME	Subject-Matter Expert
SNE	Synthetic Natural Environment
TNDM	Tactical Numerical Deterministic Model

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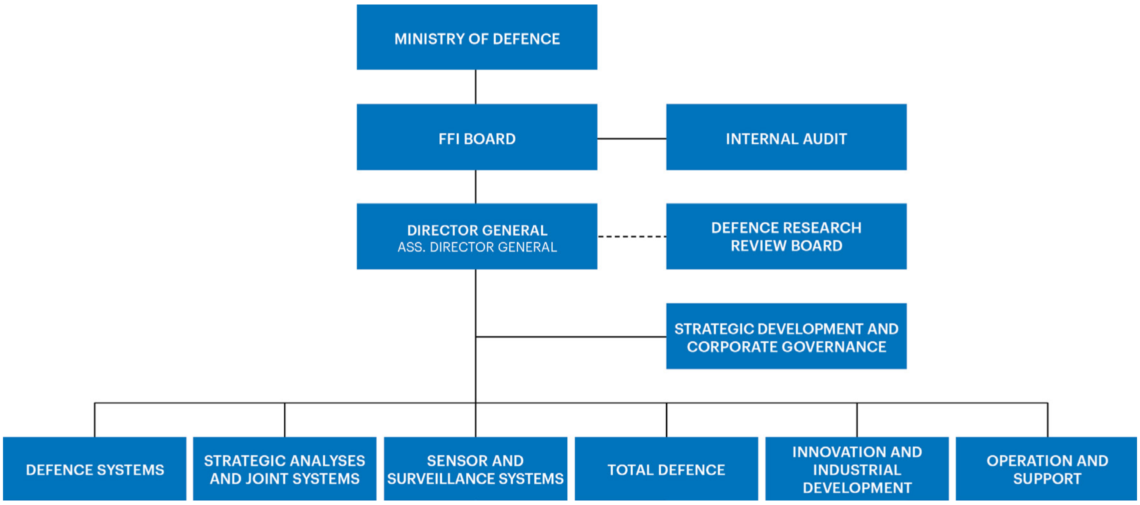

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