Component kill criteria

A literature review

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Sammanfattning

En litteraturstudie har genomförts för att hitta metoder, experimentellt underlag och empiriska samband som kan användas för att ansätta skadekriterier på komponenter. I detta arbete har endast skador orsakade av penetrerande stridsdelar behandlats.

Skadekriterier för komponenter används vid simuleringar av ett vapens verkan i olika typer av mål. Kriterierna används för att bedöma om en komponent upphör att fungera, fungerar med reducerad förmåga eller inte påverkas av den skada som verkansdelen orsakat. Utifrån skadeutfallen hos de enstaka komponenterna kan man via ett felträd beskriva vilka av målets huvudskaliga funktioner som påverkats eller inte påverkats av bekämpningen.

I de allra flesta fall är detaljinformation rörande verkansvärderingsprogram (program utvecklade för värdering av vapeneffektivitet eller måls sårbarhet/överlevnadsförmåga) hemlig. Även mycket av den information som utgör indata till dessa program klassas som hemlig, både på grund av informationen i sig och på grund av den kostnad som förelegat vid framtagandet av informationen. Härav följer att det internationella vetenskapliga utbytet inom området har varit och fortfarande är begränsat.

Trots detta finns några äldre, främst amerikanska, beskrivningar av hur skadekriterier tagits fram. Dessa är till stor del baserade på begreppet sårbar yta, som beskriver hur stor del av komponentens projicerade area i en viss riktning som är sårbar för ett visst hot. För vissa speciella komponenttyper, t.ex. kablar och virar, finns empiriska samband för utslagssannolikhet som funktion av splittermassa eller splitterstorlek och anslagshastighet publicerade. I enstaka fall går det till och med att hitta empiriska modeller i internationella vetenskapliga tidskrifter. Dessa artiklar syftar dock till att utveckla skadekriterier för satellitutrustning utsatt för rymdskrot varför anslagshastigheterna som redovisas i de flesta fall är mycket högre än de som är aktuella vid normal vapenverkan. Det finns även vissa försök att skapa nästan analytiska samband för utslagssannolikheter, dock verkar de flesta sluta i att man måste ansätta några former av gränsvärden.

I vissa fall utgör tiden en av skadekriteriets variabler. Tiden används då för att bestämma tidsåtgången mellan att komponententräff och erhållen skadeeffekt. Utan att ta hänsyn till tid som en påverkansfaktor blir det svårare att beskriva utslagningen. Att veta om rörelseförmågan hos ett fordon slås ut omedelbart eller efter en viss kort eller lång tid kan vara mycket viktigt ur både verkans- och sårbarhetssynpunkt.

Bristen på internationell samverkan har även lett till en brist på både gemensam nomenklatur och gemensamt format på hur komponenters skadekriterier bör anges. Detta försvårar samverkan ytterligare samtidigt som behovet av samverkan ökar i och med att många länder nyttjar samma materiel och genomför gemensamma operationer.

En kort genomgång av hur olika värderingsprogram använder skadekriterier ges för att visa på variationen och bristen på samsyn.

Nyckelord: *Verkansvärdering, skadekriterier, utslagskriterier, kriterium, stryktålighet, komponenter, penetration, krater, hål, Pk, Pk|h, AVAL*

Summary

A literature review has been conducted in order to find methods, experimental data and empirical relationships that can be used in order to define kill criteria for components. Only damage caused by penetration is considered.

Kill criteria for components are used in simulations of weapons effects in various types of targets. The criteria are used to judge whether a component has stopped working, works with reduced capacity or works normally after the damage. Based on the conditions of each component, a fault tree can be used in order to describe which of the targets main functionalities that are affected or not by the attack.

Detailed information regarding vulnerability and lethality codes are most often classified, as well as much of the information used as input data to those codes. The reason for classification can be to protect the information it self as well as to protect the economic value the information represents. Hence, there is little international scientific sharing.

Despite the classification problems, there are some old,descriptions (mostly from US) , on how kill or damage criteria have been assessed. These are often based on the concept of vulnerable area, which describes the portion of the projected area in a direction that is vulnerable for a certain threat. For some special component types, like cables and wires, there are empirical relationships between the kill probability as function of fragment mass or size and impact velocity. Empirical relationships can also be found in international peer review scientific journals, but these are extremely rare. These published relationships are mainly focused on kill criteria for satellite components exposed to the threat of space debris, and the impact velocities are thus higher than for normal weapons effects. There have also been a few attempts to establish almost analytical relationships, but they often seem to end up requiring some kind of limiting values.

Time is sometimes included as a factor in the criteria. It is then used either to decide when the component should be considered failed or when the failed component affects any connected system. Neglecting time as a factor gives limited possibility to handle results such as the enemy vehicle stops firing at you immediately or some minutes or hours later.

The lack of international scientific cooperation has resulted in an absence of common terminology and standard formats on how component criteria should be formulated, which in turn complicates exchange and cooperation within this field. The need of international cooperation will probably increase since the same equipment is used by several nations and often in joint missions.

A short summary on how different vulnerability/lethality assessment codes use kill criteria is given, partly in order to show the variations and lack of standard format.

Keywords: *Vulnerability assessment, lethality assessment, kill criteria, damage criteria, criterion, toughness, components, penetration, crater, hole, Pk, Pk|h, AVAL*

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1 Introduction

Components or parts in a target which is subjected to an enemy attack can be damaged due to many different types of weapon effects. This report only consider damage due to impacts by different kinds of penetrators such as fragments, small arms bullet, kinetic energy (KE) projectiles, shape charge (SC) jets and explosively formed projectiles (EFP). There is of course also a need to define the ability of the components' to withstand other types of loads, such as accelerations, shock waves, overpressure, heat, laser, microwaves etc.., but that will not be covered in this report.

The aim of this literature review is to find and review published experimental studies and methodologies on how to estimate component kill criteria given that the component is hit, $P_{k|h}$. In addition to this, a list of examples of how kill criteria are used in different vulnerability and lethality (V/L) codes are given.

Xiangdong et. al. [1] formulated a definition of damage criterion when stating that "*the damage criterion is a judgement that is used to determine whether a component is damaged*". They continue by stating; "*According to the definition of the damage criteria of components, the damage criteria include two meanings. One is the definition of damage. Another is the relation between the damage degree of component and damage elements, which act on the component*" [1].

This statement pin-points the problem of defining kill criteria, how to define when a component should be regarded as damaged and how to estimate how much damage it can withstand before reaching the state when it is defined as damaged. Consider a pipe to a bilge pump in a ship. It can intuitively be considered as damaged if there is a hole in it and water leaks out inside the ship, but it might at the same time be able to deliver water out of the ship (with some leakage and thus not at the highest capacity). The pipe should be defined as damaged only if the top capacity of the bilge system is considered, but it might still be able to run the bilge system at 50% or 75% capacity and if this is enough the pipe should not be considered as killed. This problem can be handled by using some kind of smooth degradation measure, like a 100% to 0% function. Ball [2] describes component kill as "*The inability of a component to provide the function(s) it was designed to provide is referred to variously as a component dysfunction, damage, failure, fault or kill depending upon the type of analysis being performed and the performing organization*". Obviously there is no standardized terminology. This is further emphasised by Driels [3] who describes the kill probability as function of impacting fragment velocity and mass "*fragility curve*".

It is neither definite that degradation of component function is needed. Less [4] says "*Failure criteria for components of "normal" systems - avionics, electrics, hydraulics etc. - can be regarded as being binary, i.e. a pipe is pressure tight or is not*". This should be regarded in comparison with Less' discussion about a method of assessing structural integrity of airborne targets.

Since most Vulnerability and Lethality tools (V/L) are classified, the sharing of information and direct comparisons between them are sparse. A five party comparison was carried out by NATO (Applied Vehicle Technology (AVT) 127) in 2004-2007 [5]. The participants of this comparison are presented in Table 1. A different use of kill criteria may be one of the reasons for the differences in the results according to Puech et. al. [5]; "*The overall results show a good agreement with trends for areas of high and low Pk being consistent across all five nations. Nevertheless, there are some areas where the resulting Pk values differ. This is due to a number of reasons based upon target geometry and small variations in methodologies applied for instance: the use of perforation instead of penetration as a damage mechanism; and the interpretation and conversion of damage scoring rules*".

Table 1. Participants in NATO AVT 127 [5].

Nation	Establishment	V/L code
France	CEG	Pleiades A
Germany	IABG	UniVeMo
Netherlands	TNO	TARVAC
Spain	ITM (formerly LQCA)	AVAL
United Kingdom	Dstl	INTAVAL

The need of increased sharing and openness of component kill criteria is also stated by NATO Naval Armaments Group / Maritime Capability Group 6 / Sub Group 7 which is working with the vulnerability and recoverability elements of survivability. Sub Group 7 sees "*a significant benefit in developing and maintaining common baselines and areas of expertise in the constituent elements that make up vulnerability and recoverability analyses. Experience in member nations shows that the majority of the costs involved in developing and maintaining vulnerability and recoverability codes aeries from developing the underpinning knowledge base, for example the conduct of trials to determine structural response to damage mechanisms, equipment and personnel kill criteria, material testing, etc.*" [6].

Even though this report primarily deals with damages caused by weapons effects, a citation from Putzar et. al. [7], where they discuss vulnerability of satellites hit by space debris, can be used to emphasize the need for penetration component kill criteria in many fields; "*Space debris and meteoroids protection requirements are presently formulated in terms of the probability of no penetration. This approach is driven by the lack of data available for assessing the internal damage following penetration of the external wall and leads to unnecessarily heavy structures*". It is obvious that the same basic problem is present in totally different objects as heavy armoured main battle tanks, satellites and frigates. There are of course differences in the damaging phenomena for different types of penetrators and for different impact velocities, but nevertheless; component penetration kill criteria are needed.

In 1992 the US Army Research Laboratory (ARL) hosted a workshop on component $P_{k|h}$ with several US governmental branches [8]. In this workshop the problem, customer needs and a solution were defined and the participating branches presented their use of $P_{k|h}$'s. Some of the published results from this workshop will be presented in different chapters of this literature review. In a paper by Shnidman and Fisher, (included as part of appendix C in [8]), a figure is presented that gives an overview of the parts in a V/L-tool (for land vehicles) and thus gives the context for the component kill criteria. A redrawn version of that figure is presented here as Figure 1.

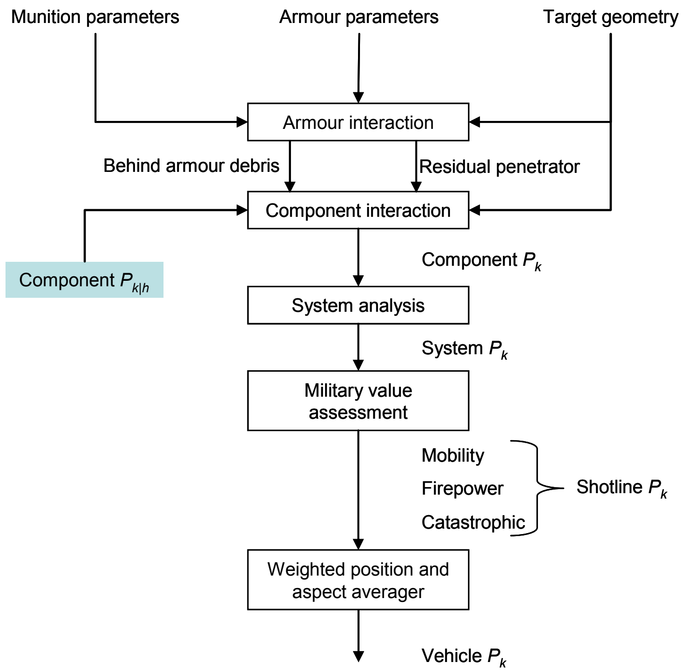

Figure 1. Flow diagram for a v/l-tool [8].

An assessment shall contain even more than what is illustrated in Figure 1. Deitz and Starks [9] give quite a clear illustration of what should be included in different types of assessments, here redrawn and presented as Figure 2. The focus of this literature review is on the mapping from level 1 to level 2.

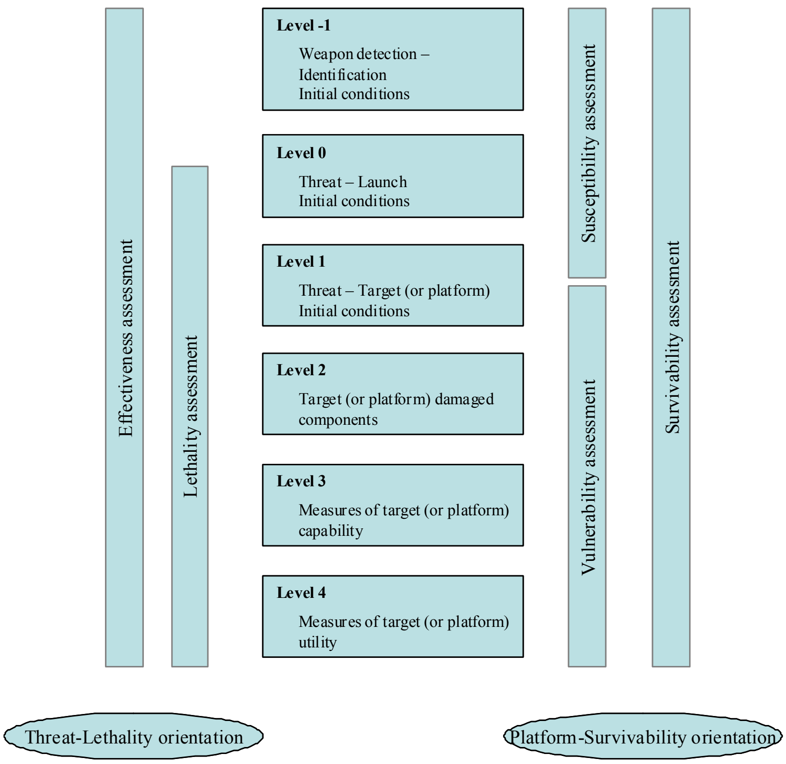

Figure 2. Levels of revelance to lethality and vulnerabilty assessments according to Dietz and Starks [9].

2 Component kill criteria

2.1 Possible metrics

There are only a few physical penetrator properties that can be used for a kill criterion. If the penetrator is well defined, such as a kinetic energy (KE) projectile or a small arms bullet the mass and the shape are known parameters. This can, if combined with the impact velocity, be used according to Table 2. In most cases in Table 2 it is also possible to evaluate the kill probability independently for each hitting object or to use some kind of accumulated metrics to estimate the kill probability.

Table 2. Different possible metrics for kill criteria when the component is hit by KE-projectiles or fragments.

	Metrics	**Possible kill criteria**
Statistical properties		
	Number of hits	P_k vs. number of hits. One special case of this is the “Killed if hit” criterion
Physical properties		
	Mass	P_k vs. impact mass
	Velocity	P_k vs. impact velocity
	Mass and velocity	P_k vs. impact mass and velocity
	Momentum	P_k vs. impact momentum
	Kinetic energy	P_k vs. kinetic impact energy
Calculated properties		
	Deposited energy	P_k vs. deposited kinetic energy in the component
	Penetration depth	P_k vs. the actual penetration distance in the component
	Penetration capacity	P_k vs. the penetration capability of the penetrator, regardless of the geometrical path in the component
	Hole area	P_k vs. the area of the created hole
	Hole volume Lost Mass	P_k vs. the volume of the created hole or lost mass if multiplied with the density of the material
	Intensity	P_k vs. impact energy or momentum per area unit

For shaped charge (SC) and explosively formed projectile (EFP) warheads, the mass of the penetrator is not known with the same accuracy as for other penetrators. This reduces the possible metrics to the ones presented in Table 3.

Table 3. Different possible metrics for kill criteria when the component is hit by SC or EFP.

	Metrics	**Possible kill criteria**
Statistical properties		
	Number of hits	P_k vs. number of hits. One special case of this is the “Killed if hit” criterion
Calculated properties		
	Penetration depth	P_k vs. the actual penetration distance in the component
	Penetration capacity	P_k vs. the penetration capability of the penetrator, regardless of the geometrical path in the component
	Hole area	P_k vs. the area of the created hole
	Hole volume Lost mass	P_k vs. the volume of the created hole or lost mass if multiplied with the density of the material

2.2 Example of criteria definitions

Neider [10] gives an example of the most simple method to formulate kill criteria, where each component is given a damage probability P_{damage}, if it is hit by a fragment. The kill probability P_k of that component is then given by equation (1), where P_{hit} is the hit probability and N is the number of effective fragments within the ejection area of the location of the component. Fragments are considered to be effective if they are able to reach the component and perforate the components’ own protection.

$$P_k = 1 - (1 - P_{damage} P_{hit})^N \tag{1}$$

Even though the method may seems to be simple, the main problem remains; how to estimate P_{damage} (in this case P_{damage} equals $P_{k|h}$).

Already in 1970, Sten [11] wrote a report in which he stated that it is suitable to base component kill criteria on fragments’ penetration capacity, I. The penetration capacity is proportional to the impulse and inversely proportional to the displayed area of the fragment [11]. Sten gives two examples of how the criteria can be described, one simple according to equation (2) and one more refined according to equation (3), where I_0 and I_1 are penetration capacity limits.

$$P_{k|h} = \begin{cases} 0 & I \le I_0 \\ 1 & I > I_0 \end{cases} \tag{2}$$

$$P_{k|h} = \begin{cases} 0 & I \le I_0 \\ 0.25 & I_0 < I \le I_1 \\ 1 & I > I_1 \end{cases} \tag{3}$$

In order to use this, Sten provides the following example. If the penetration capacity of a fragment is between I_0 and I_1, the kill probability of the component will be P_k. A rectangular distributed random number X is drawn and the component is killed if $X \le P_{k|h}$. Again the main problem is left unsolved; how to estimate the limits for I_i, but this can actually be called a kill criterion.

Xiangdong et al. [1] present an idea where the damage is defined by fuzzy limits, instead of crisp or strict limits. Following this, they also regard the damage set as a fuzzy one. They use a function called action loss function *LF* where $0 \le LF \le 1$. Loss function equals to zero means that the component has lost its function completely and $LF=1$ means that the component is totally undamaged. $LF=0.5$ then means that the component has lost half of its function (rate or whatever measured).

Using criteria defined by a sharp limit has several disadvantages according to Xiangdong et. al. [1]:

- Components cannot be partly incapacitated, they are either fully operable or totally incapacitated.
- It is hard to set the limits defining when the component will be killed.

In order to avoid these problems, Xiangdong et. al. [1] suggested that the damage criteria shall be built on basis of a fuzzy damage set. As an example of this they present a study of the damage of a component that is hit by fragments. For some reason they only consider fragments that are effective in damaging the component. This probably means that the fragments that are capable of perforating the protective part of the component. Equation (4) represents this damage criterion which is defined using sharp limits, where P_d is the kill probability, n the number of effective fragments hitting the component and n_c is the critical number of effective fragments.

$$P_d = \begin{cases} 0 & n < n_c \\ 1 & n \ge n_c \end{cases} \tag{4}$$

Instead of equation (4) Xiangdong et. al. [1] suggest a fuzzy damage set according to equation (5) and Figure 3 in their example, where n_1 and n_2 are number of effective fragments defining the limits.

$$P_d = \begin{cases} 0 & n < n_1 \\ \dfrac{n - n_1}{n_2 - n_1} & n_1 \le n < n_2 \\ 1 & n > n_2 \end{cases} \tag{5}$$

If the probable density function of number of effective fragments acting on the component is $p(n)$ then the damage criterion of the component is given by equation (6), where μ_d is a membership function representing the degree of how n belongs to a fuzzy set D.

$$P_d = \int_0^\infty \mu_D(n) p(n) dn \tag{6}$$

It is not clear how this can be used in defining kill criteria for components. In the example given by Xiangdong et. al. [1] you still need to define the limits n_1 and n_2. When this is done P_d gives the relative function loss of the component. Another complication with the proposal from Xiangdong et. al. is that it is not defined which of the fragments' properties it is that make them effective. Is it the penetration depth capacity, the ability to create a hole with a certain volume or what is it?

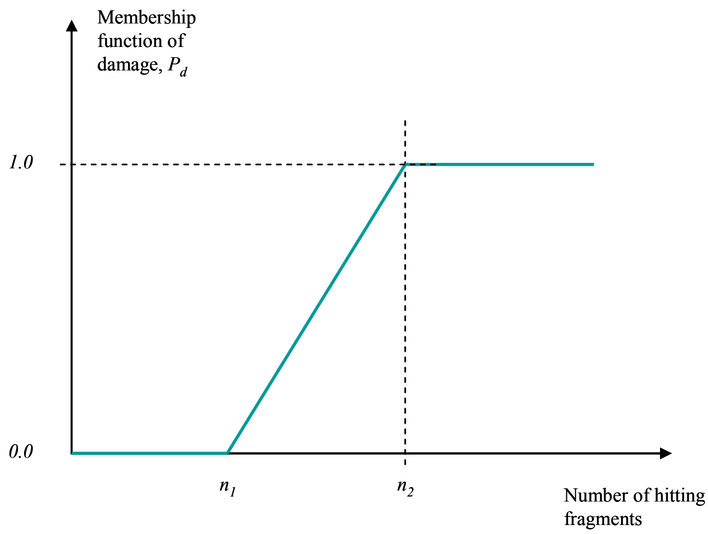

Figure 3. P_d as function of number of hitting effective fragments, according to equation (5).

It is obvious that Xiangdong et. al. suggest that accumulated damage should be used in the criteria since the kill probability increases with increasing number of hits by effective fragments.

Haskell [12] outlines the complete vulnerability assessment process, in which one of the defined processes are "*Determine component conditional kill probabilities and repair times*". In this case, the kill probabilities are defined based upon the anticipated evaluation time, since the degradation of a component's performance does not occur until some time after it was hit. If necessary for the assessment, the repair times are also included.

The conditional kill probability $P_{k|h}$ given hit is defined as the probability of achieving a preselected damage level by the application of a threat-caused damage mechanism. These $P_{k|h}$'s are evaluated for several directions of attack on the component since the component's ability to withstand damage often varies with the impact direction.

Examples of damage metrics are; amount of material that must be removed from a drive shaft for it to failure, requirements for failure for a structural member, minimum diameter of hole in a fuel tank or line for engine starvation within a specified time period. Figure 4 gives an example of a kill probability function based on fragment impact velocity. Input for this can be obtained from weapons testing, development tests, shop repair manuals, mechanics, manufacturers, accident records, combat data and engineering judgement and experience.

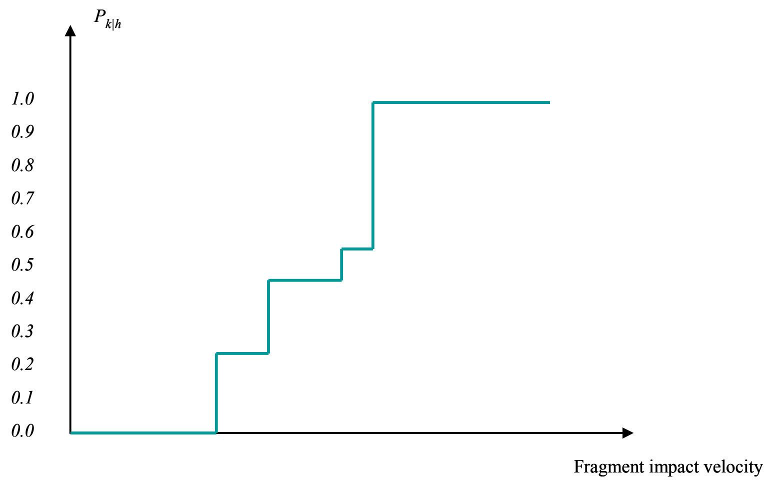

Figure 4. Example of kill probability function [12].

Another criteria type is presented by Beverly [13]. In this stochastic model, the states of samples of fragments that have perforated a given amount of material are assumed to be given by probability density functions (PDF) of incomplete sets of parameters. The killing probability of a spall burst described by $B^*(\vec{a_0})$ is calculated in terms of the expectation of the PDF of each impacting fragment and the kill function $R^*(\vec{a_1})$ of the component. Analytically this is described by equations **(7)**-(9),

$$P_k = 1 - e^{-\lambda} \tag{7}$$

where λ is given either by equation (8) or in the more concise form according to equation (9) and the other quantities as listed in Table 4.

$$\lambda = \int_{\infty} B^*(\vec{a_0}) T^* \left[\vec{a_0}, \vec{g} \rightarrow P^*(\vec{a_1} / \vec{a_0}) \right] \int_{\infty} P^*(\vec{a_1} / \vec{a_0}) R^*(\vec{a_1}) dA_1 dA_0 \tag{8}$$

$$\lambda = \int_{\infty} B^*(\vec{a_0}) \int_{\infty} P^*(\vec{a_1} / \vec{a_0}) R^*(\vec{a_1}) dA_1 dA_0 \tag{9}$$

Table 4. Quantities used in equations (7)-(9) [13].

Quantity	**Description**
$\vec{a_0}$	A set of parameters which incompletely describes a source fragment
$\vec{a_1}$	A set of parameters which incompletely describes a residual fragment at impact with a critical component
$\vec{g}$	A set of parameters which describes the medium between the fragment origin and the critical component
dA_0	The infinitesimal volume associated with $\vec{a_0}$
dA_1	The infinitesimal volume associated with $\vec{a_1}$
$B^*(\vec{a_0})$	The spall-burst source term
$R^*(\vec{a_1})$	The average killing probability of a representative sample of fragments described by a_1, as they impact the critical component

Quantity	Description
$P^*(\overrightarrow{a_1}/\overrightarrow{a_0})$	The probability density function (PDF) of residual fragment states derived from a source fragment described by $\overrightarrow{a_0}$
$T^*\left[\overrightarrow{a_0},\vec{g} \to P^*(\overrightarrow{a_1}/\overrightarrow{a_0})\right]$	The operation which describes the average transport of a representative sample of source fragments, all described by $\overrightarrow{a_0}$, to a possible impact with the critical component

Equation (8) is called the kill integral in [13]. The star superscript identifies problem-dependent quantities. In order to simplify equation (8), four approximations are made;

1. all fragments in a burst (source fragments) originate from the same point,
2. all fragments follow straight paths to the interaction with the component,
3. the probability density functions describing an average burst are symmetrical around a spall symmetry axis and
4. the PDF states that for a fragment emerging from a transport operation, these are replaced by the mean value of the used parameters.

With these approximations, equation (8) becomes

$$\lambda = \int_0^{\pi/2}\int_0^{\infty}\int_0^{\infty} B^*\left(\overrightarrow{r_0}, m_0, v_0, \theta\right) T^*\left(\overrightarrow{r_0}, m_0, v_0, \theta, \overrightarrow{g_0} \to \overrightarrow{r_1}, \overline{m_1}, \overline{v_1}\right) R^*\left(\overrightarrow{r_1}, \overline{m_1}, \overline{v_1}\right) dm_0 dv_0 d\theta \qquad (10)$$

where the quantities are listed in Table 5.

Table 5. Quantities used in equation (10) [13].

Quantity	Description
m_0	The mass of a source fragment.
v_0	The velocity of a source fragment.
θ	The angle made by the fragment path with the spall axis of symmetry.
$\overline{m_1}$	The average expected mass of the residual fragment at impact with a component for all source fragments having mass m_0 and velocity v_0.
$\overline{v_1}$	The average expected velocity of the residual fragment at impact with a component for all source fragments having mass m_0 and velocity v_0.

The $\overline{m_1}$ and $\overline{v_1}$ are to be calculated using the Thor equations in [13]. In order to evaluate the approximated kill integral, equation (10), Beverly outlines three different Monte Carlo methods [13];

1) *The Forward Transport of Sample Fragments from the Spall-Burst Origin to A Possible Impact with the Critical Component*, without importance sampling in the picking of sample path rays. The PDF of sample fragments is approximately that of fragments in an actual burst.

2) *The Forward Transport of Sample Fragments from the Spall-Burst Origin to A Possible Impact with the Critical Component*, with importance sampling in the picking of sample path rays. The path of a sample fragment is constructed through a point chosen with equal probability at any location within a rectangular volume

which barely encloses the component. The PDF of sample fragments differs from that of fragments in an actual burst.

3) *The Adjoint Transport of Sample Residual Fragments from the Outer Surface of the Critical Component to the Spall-Burst Origin*. The importance sampling from the second method is reused. The sample events do not correspond to any actual events.

The details of these three methods will not be given here. When tested in [13] they all gave results which agree within the standard deviations of the calculations.

Ipson et. al. [14] present empirically based equations for breaking velocity predictions of cables and wires. These equations are here given as equations (11)-(15), where V_{bw} is the breaking velocity (feet/second), d_w the wire diameter (inches), d_I the diameter of the plastic insulator (inches), M_p the fragment mass (grains) and θ the angle of obliquity (degrees).

Solid copper wire [14]
$$V_{bw} = 400\left[1 + \frac{385 d_w^2}{M_p^{2/3}}\right]\sec\theta \qquad (11)$$

Solid aluminium wire [14]
$$V_{bw} = 700\left[1 + \frac{120 d_w^2}{M_p^{2/3}}\right]\sec\theta \qquad (12)$$

Stranded copper wire [14]
$$V_{bw} = 320\left[1 + \frac{385 d_w^2}{M_p^{2/3}}\right]\sec\theta \qquad (13)$$

Stranded aluminium wire [14]
$$V_{bw} = 560\left[1 + \frac{120 d_w^2}{M_p^{2/3}}\right]\sec\theta \qquad (14)$$

Coaxial cable [14]
$$V_{bw} = \left[320 + 1050 d_I\right]\left[1 + \frac{385 d_w^2}{M_p^{2/3}}\right]\sec\theta \qquad (15)$$

One 25 conductor multiple cable was also tested and the result is presented in Figure 5.

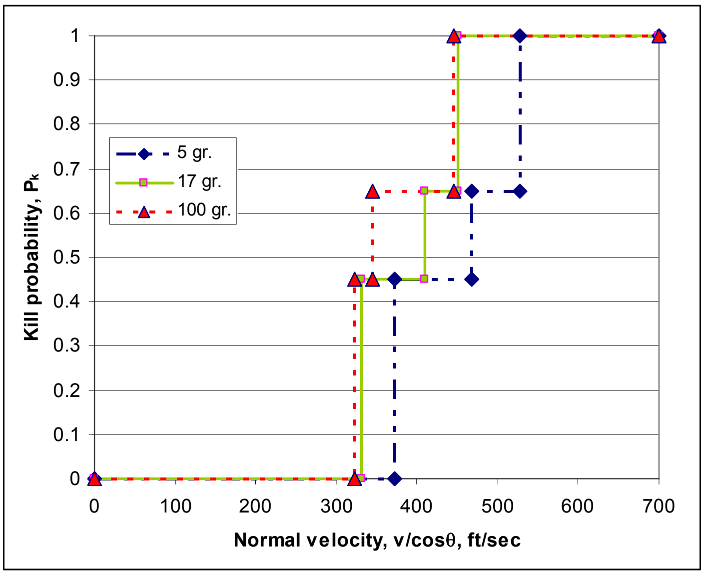

Figure 5. Kill probability for a 25 conductor multiple cable hit by fragments of different masses and velocities, (reconstruction of figure 7 in [14]).

It is quite obvious that a cable or wire is killed if it is broken, but in the case of multi-conductor cables the damage can grow gradually until a total failure occurs. There might also be problems related to shortcuts between the conductors during the damage process.

2.3 Compartment level criteria

Even though it is out of scope of this literature review, it should be mentioned that many codes give (or did it in the past) kill criteria not on a component level but on a compartment level. However, a component representing a radio could be regarded as a "radio compartment" since all internal components are included in the radio component. Examples of compartments of a land vehicle [15] are:

- crew space (the total volume that is, or could be, occupied by crew members),
- passenger space (the total volume that is, or could be, occupied by passengers),
- space for drive trains (the total volume occupied by the engine, cooling system, batteries, transmission, final drives, wheels suspension and tracks (some of these systems are mounted on the outside of the vehicle hull)),
- ammunition space (the total volume occupied by ammunition at full capacity),
- fuel space (the total volume occupied by fuel when the vehicle is fully fuelled (some of this fuel may be carried outside the vehicle hull)),
- equipment space (the total volume occupied by data buses, instruments, communications equipment, fire suppression devices and other equipment needed for the vehicle to function effectively) and
- weapon and sensor space (the total volume occupied by the main and secondary armament, fire control equipment, range finders, auto loaders, target acquisition and engagement optics and electro-optics and the stabilization and turret traverse mechanisms).

In [15], damage is classified in three categories that cover the full range of outcomes; Destruction, Damage and No effect. In the given example, a crew space destruction means that more than 50% of the crew is dead or seriously injured, damage means that one crew member is dead or seriously injured and the meaning of no effect is obvious.

A compartment description of a target does not define each component. The crew space is one compartment "containing" the crew and the kill criteria would in the example above be given in such a way that a worse threat gives a higher probability of destruction of the compartment than a less severe threat.

3 Tools to create or set kill criteria

3.1 COMPKILL

In the mid eighties, the US Army Ballistic Research Laboratory (later renamed to Army Research Laboratory, ARL) worked with a computerized expert system (ES) for predicting component kill probabilities [16]. This ES is supposed to guide the user to get kill probabilities, *not to replace him*. The basic idea of the component methodology is that the probability that a random hit by a penetrator of known mass and velocity will render a non-functional component. The probability is determined by a ratio of the sensitive area to the presented area of the component, provided that the penetrator makes a large enough hole in the component. One part of the ES is a program called COMPKILL, designated to compute the probability of conditional kill (probability of kill given a hit in the component) for components impacted by fragments with known characteristics. The input parameters that should be provided to COMPKILL is:

a) presented area,
b) sensitive area,
c) hole diameter required to render component non-functional,
d) numbers of barriers in the fragment path,
e) material type of each barrier and
f) thickness of each barrier.

It is obvious that the system is in part reliant on the subjectivity of the users, especially in parameters b) and c).

The BRL ES operates in three stages. First, it obtains and validates the physical properties of the component (initially the components could be; rods, shafts or cables). The validation is based on rules, e.g shafts are normally not made of soft materials and the ES would question such a combination. Secondly, it derives the input parameters to COMPKILL and last it feeds the results to COMPKILL and prepares input to another program called VAST. The final results are tables with conditional kill probabilities vs. fragments of varying masses and velocities.

3.2 PKHDOC

PKHDOC provides a method for computing the $P_{k|h}$'s for critical or vital components of a target [17]. The methodology used is applicable to attacks by penetrators such as fragments, bullets or flechettes. The program considers fragments of selected masses, impacting at velocities between a specified minimum and maximum at intervals of 100 feet per second. A set of equations are used to calculate the penetration and perforation processes. Upon penetration of the sensitive area, the size of the hole made by fragments is computed, and a determination is made whether or not the component is killed. The kill requirement for a component is thus defined in terms of a minimum hole size in the sensitive area that will kill the component. These minimum hole areas are defined by an evaluator, who "*…in predicting this minimum hole, draws upon his background and experience to estimate the fracture, breaking, lodging, electrical shortening, shock, or whatever effect he believes would have resulted from the impact of the predicted fragment.*" [17].

The $P_{k|h}$ for each fragment mass and velocity is computed as the ratio of the amount of sensitive area killed by these fragments to the total presented area of the component. This means that the calculated $P_{k|h}$ is a weighted average over all expected attack directions and it results in a single $P_{k|h}$ for the component independent of attack direction. In this way, the $P_{k|h}$ for each fragment mass and velocity combination is computed and tabulated.

3.3 PKGEN

PKGEN is a code that evaluates the $P_{k|h}$ of a three dimensional representation of a component [8]. It has the ability to use component descriptions for BRL-CAD. PKGEN allows a number of kill criteria;

- fragment mass and/or velocity,
- depth of penetration,
- hole size,
- residual mass at depth,
- kinetic energy / momentum transferred or
- mass removal.

PKGEN also allows combinations of the above criteria using operators like AND and OR [8].

3.4 hres.c

hres.c is a code developed to model components on a level of detail which is suitable for electronics, e.g. switches and circuit boards [8]. Figure 6 presents the input and output scheme for hres.c, where *K(t,h)* is the probability of component kill given that the fragment can penetrate at least thickness *t*, can produce a hole size *h* at *t* and encounters a critical region at *t*.

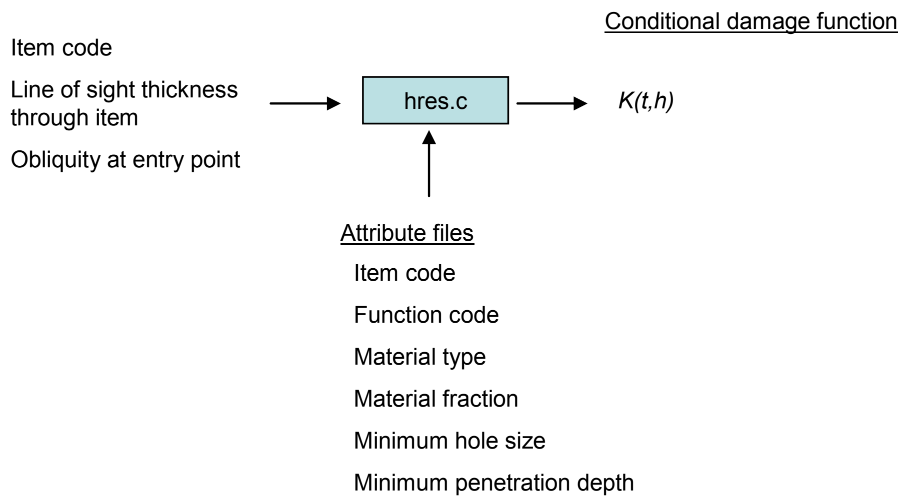

Figure 6. Input and output for hres.c [8].

4 Methods to create or set kill criteria

4.1 Simulations

In order to use kill criteria of the type presented above some kind of load limits are needed. One way of finding these is presented by Hartmann [18] and Eriksson and Hartmann [19]. The basic idea is to describe a component as a target in a V/L-tool. In this component-target-description, the components shall be so small and sensitive that it is reasonable to classify them as killed if hit. This target description is used in simulations with a scalable penetrator that is shot at different velocities and in all angles relative to the target. The results of the hitting penetrators are then analyzed by weighting the kill probabilities from all directions into an averaging probability for the specified penetrator with its diameter and penetration capacity (or velocity). A generic radio was used as component in [18, 19] and it is shown in Figure 7.

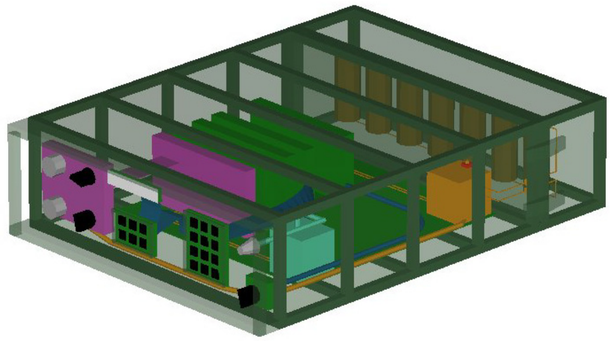

Figure 7. The generic radio target description used in [18, 19].

The simulations performed on the radio did not fully utilise the basic idea that components should be killed if hit. It was assumed that many components were able to withstand some damage without breaking, and thus were given individual kill criteria. These kill criteria were set very narrow and the components were all easily killed. Figure 8 gives an example of the results from the conducted simulations. The maximum kill probability, about 45%, is in the same range as the projected areas of the internal vital components as a mean value for each simulated attack direction, and thus a geometrical analysis should be able to give a similar result.

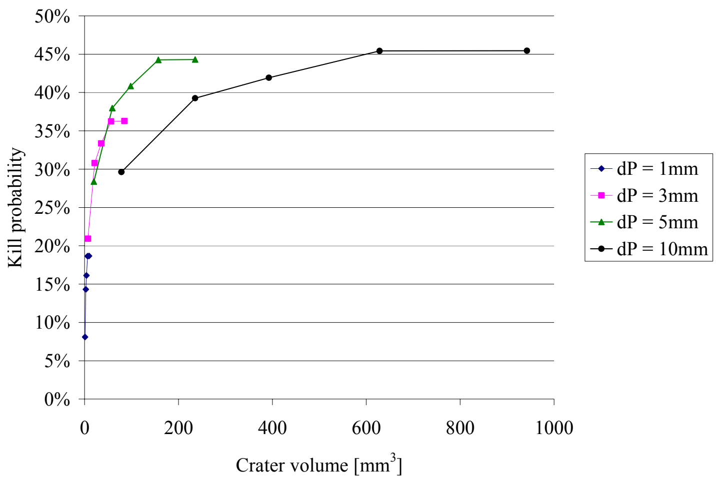

Figure 8. Kill probability (%) vs. crater volume (mm^3) with different penetrator diameters, dP, for the radio used in [18].

The same idea was used by Gustafsson and Karlsson [20] for an analysis of a gearbox. In this case it was obvious that the internal component had some ability to withstand penetration damage since it is all mechanical parts. The results were used in order to give kill criteria to two gearboxes that were not described in detail, one consisting of only one component and the other consisting of three components. They were able to get quite similar results from each description of the gearbox.

A similar idea is also described by Kinsler in [21], where he gives a historical view of various kill criteria. In [21] a concept of performing miniature vulnerability of each critical component to find the $P_{k|h}$s is mentioned, but unfortunately not described in detail.

One problem when components are described in detail as targets of their own, as in [18, 19, 20], is that ray-tracing with infinitesimal lines can pass between parts that should be impacted in a real situation [18].

Another example of work where two simulation tools are combined in order to estimate the performance degradation of a component is presented by Dunnebier and van Erkel [22]. They present a case study in which the operational degradation of a radar after the impact of 155 mm type shell fragments. The radar consists of an active phased array of individual radiators (2048 in total) which generates the radiation pattern. The radiators are so-called printed microstrips, which mean that they consist of a very thin layer of metal on a dielectric substrate. A radar simulation tool is used to simulate the performance of the undamaged and damaged radar, in which the gain is one of the most important characteristics. The gain determines how effective an antenna radiates its energy in the prescribed direction and therefore gives the distances at which it can detect its targets. The system performance is in the cumulative detection range of the system against a generic airborne target in absence and presence of a generic barrage noise jammer. The cumulative detection range is the parameter that indicates at what range a target is detected with a certain cumulative chance.

TARVAC (see chapter 8.30) was used to simulate the warhead and fragment distribution and this gave a statistical impact pattern on the radar. In order to determine the number of damaged radiators, the number of hits depicted in the hit pattern was divided by the number of radiators and gave a failure number of 2%. The fragments that were stopped in the radome should also disturb the radiators behind and this gave a failure number of 5% instead. This number is supposed to increase when considering the probability of one fragment hitting more than one radiator due to the closeness between them. It is assumed plausible that an average fragment will hit at least two radiators [22]. This finally gave a failure number of 10%.

The performance of the damaged radar was simulated in three ways; 10% randomly distributed failed radiators, 30% randomly distributed failed radiators and 10% failed radiators in one rectangular block. Table 6 presents some results from [22]. The performance is not dramatically reduced when the damage is randomly distributed, but if a rectangular block of radiators is damaged the cumulative detection range is significantly reduced if a jammer is used.

It is obvious that it would be very hard to set a realistic kill probability for this radar; a degradation criterion is probably needed. Otherwise the damage must be defined in a way like “the probability that the radar is unable to detect the target at 50 km distance”, which in turn can be related to a number of disabled emitters.

Table 6: Summary of system results from various damage cases [22].

System damage case	Gain (dBi)		Cumulative detection range (km)	
	Transmit	Receive	No jammer	Jammer
Undamaged	40	38	55	10
Random 10%	39	38	50	9
Random 30%	38	37	48	8
Block 10%	39	37	48	1,5 km (99% chance) 5,0 km (70% chance)

In the 1992 US workshop on component kill criteria [8], doubt was raised about the practicality of modelling many components at a high resolution level of detail, especially in those branches that require fast turn-around of foreign (unavailable) vehicles. It was, however, appreciated that the high resolution modelling may be an excellent supplement or even substitute for actual component testing, with a significant saving in time and money. It is also stated in [8] that ComputerMan (see chapter 8.6) may be the ultimate example of high resolution component modelling especially since the kill criteria are depth of penetration in the body and critical holes in various sub-components (organs).

4.2 Educated guesses (engineering judgement)

Verheij [23] gives an example of probably the most used method to set kill criteria when writing "*Indication of the damage tolerance of the other helicopter components (resistance to certain projectiles calibres, etc.) were obtained from numerous literatures sources or determined by "educated guesses"*".

4.3 Experimental studies

If possible it is of course tempting to define the kill criteria via experimental studies. One such study is presented by Ipson et. al. in [14], where single conductor wires, a coaxial cable and a multiple conductor cable are investigated.

The breaking velocity, V_{bw}, (the velocity for which there is a 0.5 probability of cutting the wire into two parts) was determined, and used to establish empirical equations. All cables were firmly clamped at the ends, normally with a distance of 6 inches, but also with 3 and 12 inches to study the possible influence of cable length. The breaking velocity was determined in the same way as the ballistic limit is determined for regular plate targets. In the case of coaxial cable tests, two malfunction criteria were observed. Tests were conducted to establish the breaking velocity and a velocity related to shortening of the centre conductor and the shielding. The shortening velocity was found to be lower than the breaking velocity, which means that using the breaking velocity gives a conservative estimate of the velocity required to cause malfunction.

Table 7. Breaking velocities determined for single conductor wires and a coaxial cable [14].

Type of wire	Fragment mass (grains)	Wire diameter (inches)	Length between fixed ends (inches)	Breaking velocity (feet per second)
Solid, soft copper	17	0.040	6	435
	17	0.102	6	615

Type of wire	Fragment mass (grains)	Wire diameter (inches)	Length between fixed ends (inches)	Breaking velocity (feet per second)
	17	0.128	6	875
	17	0.162	6	1005
	17	0.162	3	930
	17	0.162	12	930
	6	0.102	6	845
Stranded, soft copper	17	0.051	6	330
	3.75	0.051	6	500
RG 8/U coaxial cable	17	0.072	6	800
	6	0.072	6	1000

Experimental studies are crucial in order to define empirical relationships and to compare with other types of estimates. One such experimental study, which was used to define empirical equations, is presented by Schäfer et. al. [24]. In this study, spherical aluminium projectiles were fired at a few different types of components, arranged in a realistic way for use in a satellite. The impact velocities were quite high (ranging from 2.26 km/s to 7.79 km/s) since the study focused on space applications [24]. The empirical equations give the critical diameter of a spherical aluminium projectile as function of the impact velocity (impact at the protective shielding representing the outer surface of the satellite). There are different equations in the ballistic velocity regime, the shatter velocity regime and the hypervelocity regime, all including a number of adjustable parameters. The same equations are used for all combinations of satellite structure and type of component (e.g. pipes, battery and electronic boxes with aluminium casing) with different empirical parameters. The experiments with the electronic boxes are also reported in [25], with some more details and where it is concluded that perforation of the casing not necessarily leads to component failure. Schäfer is also involved in Putzar et. al. [7] where fuel and heat pipes are tested and empirical parameters are derived to the equations defined in [24] based on the same set of experiments. Some of these experiments are also used in [26, 27] but now focused on cables or harnesses. In addition to the ballistic limits reported in [7, 24-26] there is also a valuable discussion and description of the damage and failure modes of the different types of components. It should be noted that the generation of and the effects from the shield debris cloud behind an armour is included in these empirical equations. This must be considered when comparing them with other equations.

There are probably several classified experimental studies of component vulnerability. One Swedish example of this is [28] where fragments of different sizes and shapes were fired against parts of a Swedish aircraft J35 Draken. The aim of this study was primarily to gather more experimental data to verify input data in computer models.

5 Different types of criteria for different types of components?

In an arbitrary target there are numerous components of different types. Some are small electronic components crucial for different onboard systems; others are large and designed to transmit torque or other forces, like a drive shaft. The crew can be said to represent a third, completely different type of component. It does not seem unrealistic that different types of criteria for different types of components could give a better representation of the components' kill probability than using the same type of criteria for all components.

Bysh [29] presents a table of different component types and which criteria types, available in TARVIEW (see chapter 8.31), that were used in a land vehicle target description example.

Table 8. Example of different types of components and criteria [29].

Component type	Number of criteria	Type of criteria (used in TARVIEW)
Engine block	1	Punched area
Cables	2	Number of hits
Crew	1	Penetration depth
Ducting	6	Punched area
Tubes	1	Punched area
Motor	1	Penetration depth
Transformer	1	Penetration depth
Electronics	7	Penetration depth
Reservoir	7	Punched area
Pressurised tank	1	Penetration depth
Gearing	1	Penetration depth
Miscellaneous	4	Punched area

5.1 Electronics

Electronics are crucial for many systems in a target. It is quite common that the electronics are surrounded by some kind of casing, where parts of the casing also act as the user interface with buttons and displays. The small electronic parts inside the casing are probably quite sensitive for penetration damage but the result of the damage may vary between different types of components.

There are also larger electronic components, such as alternators and electrical engines, most likely less sensitive than the smaller components. When electronic components are damaged, the reaction on connected systems will normally be seen immediately.

5.2 Cables and wires

Cables and wires are very narrow components and often not very strong if hit. Breakage of a cable or wire may lead to lack of signal or electric power transmission, shortening of electric circuits and loss of the ability to control components attached to a wire (like the parking brake in most cars).

Broken cables and wires will often give a system response or even failure immediately.

5.3 Mechanical components

Mechanical components are often designed to transfer torque or momentum. In these cases it should be possible to calculate an absolute minimum cross section of the component in order to withstand the loads it is designed to withstand in order to operate. This will vary depending on the location of the damage and the shape of the component and maybe some components should have different criteria in different regions.

The system response of the damage will often be noticeable quite quickly after the component is damaged.

5.4 Pipes / hoses

Pipes and hoses can be considered as damaged when there is a leakage and the contained matter is lost. The size of holes is important in order to estimate the leakage rate. This will also depend on the internal (initial) pressure and the properties of the contained gas or fluid.

In some cases the system will response almost immediately to a broken pipe, e.g. as when a completely broken fuel pipe does not deliver fuel to an engine. In other cases it will take longer time, e.g. when an engine cooling hose loses the cooling liquid but the engine continues to run until it becomes overheated.

5.5 Crew / humans

Crew members are a very special type of component. This is exemplified in Table 8 and by the fact that tools like ComputerMan, see chapter 8.6, have been developed. Criteria often used for personnel (if tools like ComputerMan aren't available) are impact kinetic energy or impact kinetic energy per surface area. This review does not focus on kill criteria for the human body but such criteria must not be forgotten since the survival of the crew is an important factor.

One very often used kill/incapacitation criterion for humans is the 80 J criterion, which according to Neades [30] emanates from Rhone (1896 and 1906). It states: "*To remove a human from the battlefield, a kinetic energy of 8 kgm is sufficient according to the prevailing view in the German artillery community*". This criterion was given without any discussion about its validity [30]. For occasions when complete incapacitation of humans are unacceptable, Harling and Tyrberg present a number of threshold velocities for skin penetration [31]. This kind of criteria might be used when performing risk analysis unless it is deemed too high a risk if a person is hit at all. Two of the presented threshold velocities V_{th} are given in equations (16) and (17). Equation (16) is based on the work done by Sperrazza and Kokinakis [32] and equation (17) is based on the work done by Tausch et. al. as presented by Harling and Tyrberg in [31].

$$V_{th} = \frac{1.25}{S_{frag}} + 22 \tag{16}$$

$$V_{th} = 277.7e^{-0.482\sqrt{S_{frag}}} \tag{17}$$

In both cases, S_{frag} is the fragment sectional density (g/mm^2). As always there are a number of varying criteria. The 80 J criterion presented above is quite close to the 100 J fragment impact energy criterion for light damage of a human ($P_k = 0.1$) presented in [33]. This is said to be the minimum lethal impact energy. In [33] 1 kJ is required to achieve moderate damage ($P_k = 0.5$) and 4 kJ gives heavy damage ($P_k = 0.9$).

In [34] van der Horst et. al. present an idea about a four layer human effect taxonomy, see Figure 9. The taxonomy is based on a top-down in combination with a bottom-up approach. Incapacitation criteria have been defined for specific cases and tasks, for instance infantry assault, truck driver etc. This link with the operation context is indicated with objectives.

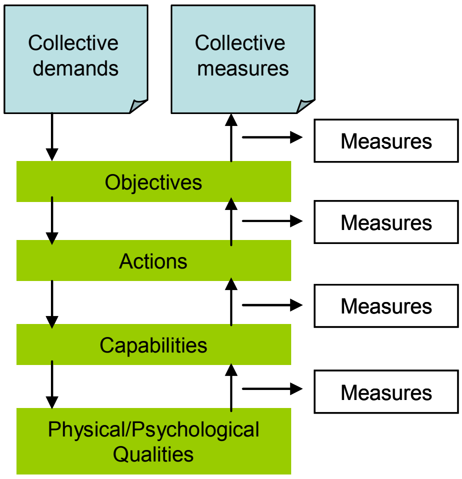

Figure 9. The four layer human effect taxonomy according to van der Horst et. al. [34].

The physical state of the soldier after an injury governs the severity of the casualty. Injury biomechanics is the base of the physical state layer.

This taxonomy enables users to grasp the meaning of complex research topics and literature as well as to use the available knowledge in new and concrete situations realizing synergy and consistency over various studies [34].

The crew has not always been considered as a critical component in a vehicle, but their influence on vehicle mobility and other abilities was considered [35]: "*In any vehicle vulnerability assessment the crew must be considered as a factor. The crew of a soft (unarmored) vehicle, unlike an aircraft of armored vehicle crew, are not normally considered to be a vulnerable part of the vehicle, because replacements should be available from the other parts of the vehicle convoy. On the other hand, it might be possible to immobilize an armored vehicle simply by incapacitating the crew*". The survivability of the crew would probably be rated higher today.

The effect of crew injuries on a system level will vary greatly in time, depending on the crew training, injury severity, tactical situation, the number of uninjured crew members etc.

6 Influence of kill criteria

The reason to work with kill criteria for components is that one assumes that the criteria have a significant impact on the vulnerability/lethality results. With this in mind, surprisingly few sensitivity analyses with criteria alternations have been found during this review.

Durfee et. al. [17] used a modified version of PKHDOC (see chapter 3.2) to study the influence of the kill probability $P_{k|h}$ from different attack directions compared to the averaged probability $P_{k|h}$. Based on the results from their example component (an engine/transmission cooler for the M48A1 tank) they concluded that face-to-face $P_{k|h}$ variations can be considerable for non-homogenous, non symmetrical type components. The computed averaged $P_{k|h}$ over all faces can result in decreased vulnerability for some faces and an increased vulnerability for others. This will in turn lead to a significant misrepresentation of the component's vulnerability to certain mass/velocity combinations for specific attack directions. One example gave a kill probability of 92% for one face and 0% for the others, represented by an average probability of 15% irrespective of attack direction.

They continued the sensitivity analysis by studying the influence of fragment shape, defined in equation (18) where K is the fragment shape factor, A_f the fragment's average presented area and M_s the fragment mass.

$$A_f = KM_s^{2/3} \tag{18}$$

From this part of the analysis they concluded that the average computed step function for $P_{k|h}$ (for the example component) exhibits significant sensitivity to variations in K for many of the mass- and velocity combinations considered. However, the post processed (from genreg and genmax) curves are not only poor representations of the average $P_{k|h}$ step functions, but show also very little sensitivity to variations in K [17].

The third part of the Durfee [17] analysis considers the influence of "engineering judgements" used to define the components. Inputs from the component evaluator are:

- component kill criteria (minimum hole size in sensitive area required to kill the component),
- material thickness (thickness of material barriers between the striking fragment and the sensitive area) and the
- sensitive area (that part of the total component which, if damaged to a predefined degree, will cause failure).

The sensitive area, A_k, and the total presented area of the component, A_p, is used to calculated the $P_{k|h}$ according to equation (19).

$$P_{k|h} = \frac{A_k}{A_p} \tag{19}$$

A_k is dependent on the mass and velocity of the impacting fragment. If a fragment's velocity is increased it might be able to kill the component also in an additional sensitive area. Also the material thickness was varied in this study. Changes in material thickness and sensitive area with ±50% result in significant variations of the generated $P_{k|h}$ curves. There is little variation in these for the ±50% variation in kill hole requirement [17].

Based on the results presented by Durfee et. al. [17] it can be concluded that there might be a need for different kill criteria for different faces of a component and that the kill criteria are (at least partly) dependent on the geometrical description of the component. This will also be important for V/L-codes in deciding when the kill probability should be calculated. It can be either upon hit of the component or after perforation of a possible enclosing structure.

Eriksson and Hartmann [19] present another, much smaller, study on the influence of variations in kill criteria, related to the simulation method described in chapter 4.1. The kill criteria for the components in the radio varied by multiplication by four and by setting the equal with a $P_{k|h}$ of 1 for a crater volume of $1 \cdot 10^{-8}$ m^3, according to Table 9.

Table 9: Kill criteria used in [19].

Vital parts	**Original criteria**		**Equal criteria**		**Original criteria x 4**	
	Penetration crater volume [m^3]	Kill probability	Penetration crater volume [m^3]	Kill probability	Penetration crater volume [m^3]	Kill probability
Small electronics	0	0	0	0	0	0
	$2 \cdot 10^{-9}$	1	$1 \cdot 10^{-8}$	1	$8 \cdot 10^{-9}$	1
Larger electronics	$1 \cdot 10^{-9}$	0	0	0	$4 \cdot 10^{-9}$	0
	$8 \cdot 10^{-9}$	0.9	$1 \cdot 10^{-8}$	1	$32 \cdot 10^{-9}$	0.9
Batteries	0	0	0	0	0	0
	$1 \cdot 10^{-8}$	1	$1 \cdot 10^{-8}$	1	$4 \cdot 10^{-8}$	1
Printed circuit board	0	0	0	0	0	0
	$1 \cdot 10^{-9}$	0.5	$1 \cdot 10^{-8}$	1	$4 \cdot 10^{-9}$	0.5
	$4 \cdot 10^{-9}$	1	-	-	$16 \cdot 10^{-9}$	1
Transformer, Antenna amplifier	$4 \cdot 10^{-9}$	0.05	0	0	$16 \cdot 10^{-9}$	0.05
	$6 \cdot 10^{-8}$	0.9	$1 \cdot 10^{-8}$	1	$24 \cdot 10^{-8}$	0.9
Battery lock	$1 \cdot 10^{-8}$	0.05	0	0	$4 \cdot 10^{-8}$	0.05
	$1 \cdot 10^{-4}$	0.5	$1 \cdot 10^{-8}$	1	$4 \cdot 10^{-4}$	0.5

It is assumed that the component would be tougher with both the equal criteria and the criteria multiplied by four, since in most cases the variants require a smaller crater volume in order to get a $P_{k|h}$ of 1 or close to 1. This is also the case in [19], here exemplified by Figure 10 and Figure 11, where two more sensitive equal criteria ($1 \cdot 10^{-9}$ m^3 and $1 \cdot 10^{-10}$ m^3) are introduced.

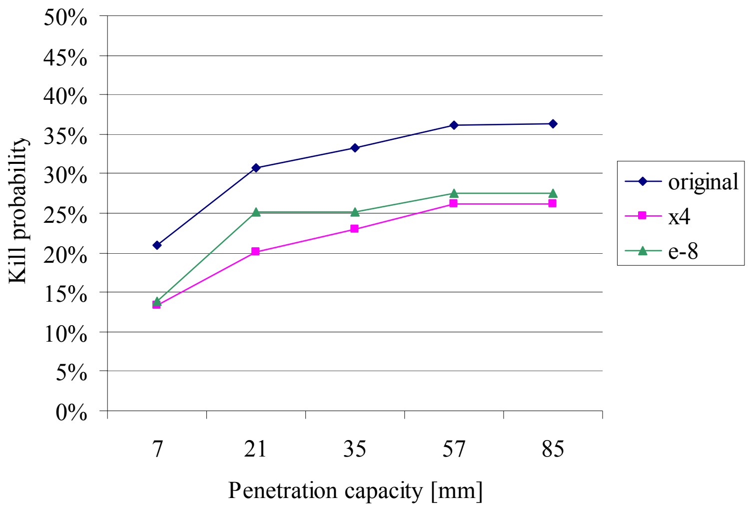

Figure 10. The kill probability dependency of criteria. In this case a 3 mm penetrator is used and the penetration capacity is given as penetration depth instead of crater volume [19].

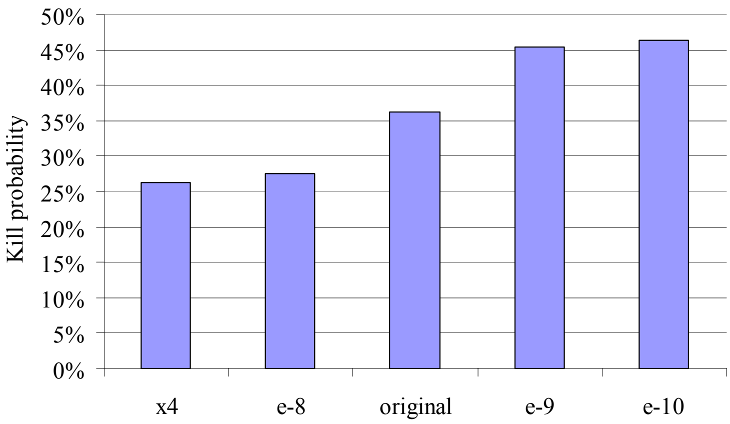

Figure 11. A comparison of the kill probability of the radio when impacted by a 3 mm penetrator with a penetration capacity of 12 mm and different kill criteria [19].

In Figure 11 it can be noted that when the criteria are sensitive enough, i.e. very close to a killed if hit criterion, the result does not change significantly. It can also be noted that the variations in component kill criteria do influence the kill probability of the radio.

Bysh [29] presents an analysis of the influences of changes in the damage algorithms available in Tarview (see chapter 8.31). He concludes that the result for the whole target is not so sensitive for changes in the damage parameter of single components. This is probably because the target has a lot of very vulnerable components in it, and changing the sensitivity in a subset of them does not have a significant global effect. Though, subsystem results vary considerable, although the effect of changes varies from parameter to parameter. The trigger point has the greatest influence of component vulnerability, with Tarview's damage algorithms.

7 Storage and reuse of criteria

Since it is hard and expensive to estimate the kill criteria, it is crucial that the information is saved in a way that makes it accessible and reusable.

The component $P_{k|h}$ is a function of the component design, whilst the target $P_{k|d}$ (probability of target kill given damaged component) is unique to the component installation in the target [36]. This implies that one has to consider the component "out of context" when estimating the $P_{k|h}$ in order to be able to reuse the criterion in other targets.

CVAA (Component Vulnerability Analysis Archive) [36] is a US example of a database designed to archive component vulnerability data and associated methodologies. The creation of CVAA is a part of the work done by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME). Another US example is SDAL (Standard Damage Assessment List) [37]. SDAL is a listing of approximately 120 major systems and components of an armoured fighting vehicle. It represents the best estimates of the relative combat utility of a vehicle given the loss of each specific system, component or group of components.

Van der Horst et. al. present an illustration of the user interface to a database with injury criteria for humans [34]. They use one block with fields for name, formula (physical parameter of function) and reference to standards. The next block defines the body region to which the criterion is related, the loading range for which the criterion is valid and available tolerance levels. Another block gives remarks as well as literature references. These criteria can also be associated with a selection of threats. Similar approaches might very well be useful for other types of components as well.

Another idea of the content of a database for kill criteria is presented in [38]. The most important subjects are:

- component name,
- references,
- log of changes and
- one or several kill criteria.

In addition to the subjects listed above the database should also include [38]:

- a list of the targets in which this component is used,
- the geometrical shape of the component,
- the internal protection of the component,
- a "Notes" section,
- a possibility to reuse (parts of) earlier defined criteria,
- a printing function, which is able to print both readable information on paper and files formatted for one or several V/L-tools,
- automatic logging of changes and
- a search functionality.

The 1992 US workshop on kill criteria [8] also listed what should be included in a criteria database. This list is in many ways similar to the ones already described.

- component description - including dimensions,
- component function being disrupted,
- the failure mode, which also include the time-to-failure,
- target containing the analyzed component,
- target description/version containing the component,
- the study for which the criteria was derived,
- the person who did the criteria determination,

- how the criteria determination was done (calculation, experiments, engineering judgement),
- mechanism causing the component failure and
- references to cad models, pictures, publications etc.

They also expressed a need for a museum of actual damaged components and description of the threat that produced the damage [8].

8 The use of penetration kill criteria in different V/L-codes

This chapter gives a short description of various V/L-codes, in most cases with respect to their penetration kill criteria on a component level, if such information has been found. The list of codes is far from complete and the description of the codes varies in scope. This is to a large extent due to classification of codes [39] and the lack of scientific sharing of models and input data. There are quite many Swedish models in this list, which is natural with respect to the nationality of the author and the fact that Sweden was a neutral nation during the cold war era and relied on national competence and tools.

8.1 AFVKILL

AFVKILL is a successor to TANKILL [40]. The kill probability of components is probably handled in a similar way as in TANKILL, see chapter 8.29.

8.2 AJEM

AJEM (the Advanced Joint Effectiveness Model) is a US model that is said to give both the platform vulnerability analyst and the munitions lethality analyst a new tool with new capabilities that can provide a more realistic estimate of weapon effectiveness against platforms [41]. The heart of AJEM is the Vulnerability/Lethality module, which actually is the code Muves, see chapter 8.19.

8.3 An Anti-Ship simulation model

In the description of this model the authors did not present a name for it [42]. The authors come from Taiwan and Sweden so the model is probably the result of some kind of cooperation between Taiwan and a private Swedish company.

The target ship is defined by many components. If any damage mechanisms inflict with the vital components, their function degradation depends upon the intensity of the damage mechanism. The penetration capability is the defining damage mechanism for fragments.

8.4 APAS

APAS (Analys av Pansarbrytande Ammunitions verkan mot Stridsfordon) is an outdated Swedish V/L code designed to analyse armour piercing munitions effects in armoured vehicles [43,44,45]. It was used from the mid seventies until the early nineties.

The kill criteria for components are given as tables with kill probabilities as function of penetration capacity, for penetrators of two types. Linear interpolation was used between the tabulated values.

8.5 AVAL

AVAL (Assessment of Vulnerability And Lethality) is the current Swedish V/L-tool. It is commercially available[1] in contrary to most other codes.

The kill criteria for components are given as tables with kill probability as function of either penetration capacity or crater volume caused by the penetrator. If the criteria are

[1] With some restrictions of export of military equipment.

based on crater volume it is optional to choose if hits in the component shall be evaluated individually or if the accumulated damage volume shall be used. It is also possible to give the crater volume values in the table as either the absolute volume or the relative volume of the component [46]. The way AVAL checks the kill criterion in order to find out whether a component is killed or not is presented in Table 10..

Table 10. Incapacitation of single components due to penetration damage in AVAL.

Criteria \ Geometry	Plane surface	Massive polyhedron	Hollow polyhedron
Penetration capacity	If and after the component is penetrated.	When the component is hit.	If and after the entrance side is penetrated
Absolute volume	If and after the component is penetrated.	When penetration stops or the penetrator leaves the component.	If the entrance side is penetrated and either when penetration stops or the exit side is reached.
Relative volume	If and after the component is penetrated.	When penetration stops or the penetrator leaves the component.	If the entrance side is penetrated and either when penetration stops or the exit side is reached.

All penetration criteria in AVAL also contain a time dependency. The point in time when the component is killed is randomized (rectangular) between two moments T_1 and T_2 after impact and the function is restored somewhere between two moments T_3 and T_4 ($T_1 < T_2 < T_3 < T_4$). In most cases T_3 and T_4 are given large values in order to not restore the functionality of the component during the simulation's time span. Linear interpolation is used in the tables.

8.6 ComputerMan

ComputerMan is a US model designed to simulate wounding, the resulting performance degradation, and threat to life caused by fragment impacts [47]. The human anatomy is represented by 167 horizontal cross sections, each of which is further subdivided into 5 mm by 5 mm cells. There are 290 different tissue types identified, at a level so that nerves and blood vessels are included.

The model draws upon an empirical database which includes data on 14 different projectiles ranging in mass from 0.5 grain to 225 grains, with four shapes and three densities. Projectile parameters include mass, velocity, density and a shape factor.

8.7 COVART

COVART (Computation if Vulnerable Area and Repair Time) is the successor of VAREA and HART and has been in use in the US since the late seventies [48]. The $P_{k|h}$ functions used in COVART are obtained from a library of existing $P_{k|h}$ function or by defining new ones [49]. A component's $P_{k|h}$ is calculated using the impact penetrator conditions by interpolating between the available data of the piecewise linear or exponential component $P_{k|h}$ functions. These damage functions can be based on penetrator impact mass and velocity relationships or hole size for liquid filled containers [50], and can also be given as input for a given aspect or averaged [51].

8.8 GVAM

GVAM (General Vulnerability Assessment Model) is a Canadian low-resolution box model, initially designed for ship vulnerability assessments [52]. The development of GVAM started 1980. In GVAM, a subprogram called DAMAGE is used for assessment of component damage based on lists of characteristics of the fragments having penetrated each component-box.

8.9 HEIVAM

HEIVAM is a US model to compute vulnerable areas and damage caused by detonation of HEI (High Explosive Incendiary) warheads. The functionality of HEIVAM has been incorporated in COVART [51].

8.10 HEVART

HEVART is a US model to compute vulnerable area and repair time associated with damage caused by detonation of small HEI projectiles. The functionality of HEVART has been incorporated in COVART (ver. 4.1) [51].

8.11 INTAVAL

INTAVAL (Integrated Air Target Vulnerability Assessment Library) is the main UK tool for assessing the vulnerability of air targets [53]. Each component is modelled with its physical dimensions, location within the target and material composition. Damage algorithms are assigned to each vulnerable component, expressing the degradation to its functionality as a result of impacting fragment mass and (typically) impact velocity [48].

INTAVAL has also been given a capability to simulate intercept of ballistic missiles [54]. The ballistic missiles may carry a payload of chemical or biological bomblets, contained in a volume significantly larger than the intercepting projectile. A model gives the crater dimensions in the missile. The affected volume is divided in to three parts;

- the crater or swept damage zone, where all components are destroyed,
- the fragment effect zone, where a probability gradient may be applied and
- the forward damage zone, where a probability gradient may be applied.

8.12 ISAAC

ISAAC (Integrated Survivability Analysis and Assessment Code) is a UK model developed in the context of land systems but it is based on generic principles, which makes it applicable to all defence systems [55]. According to [55] it seems as if ISAAC is more of a scenario level assessment tool and thus there is no need for component kill criteria. The performance of weapons is defined by among others the probability of kill, P_k, and penetration capacity. An increased armour performance will relate to a reduced residual penetration capacity which in turn gives a reduced P_k on the target level.

8.13 INVLWP

INVLWP (Integrated Vulnerability and Weaponeering) was written in the early nineties to replace COVART for applications where repair time was not needed [56]. INVLWP is intended to assess the effectiveness of small arms and other direct fire weapons against targets. A $P_{k|h}$, kill probability given a hit, table is associated with each vulnerable component. The table generates a family of piecewise linear curves, representing $P_{k|h}$ as a function of threat velocity for a given threat mass, according to Figure 12.

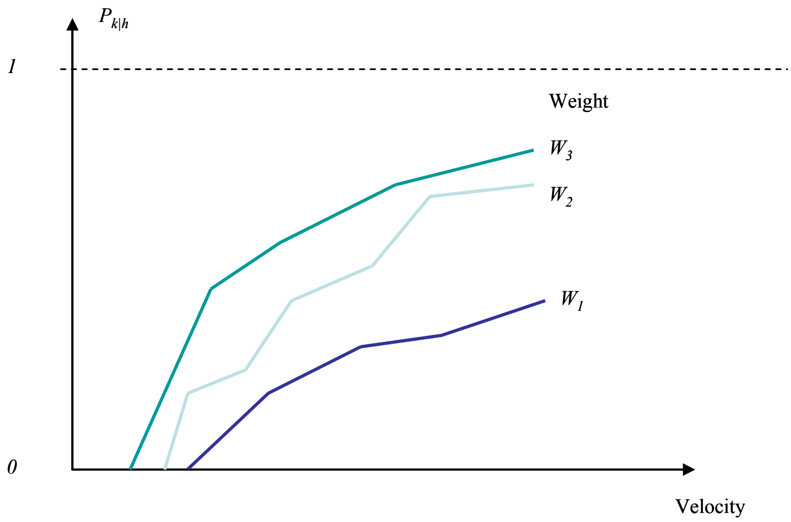

Figure 12. Examples of the shape of $P_{k|h}$ curves for vulnerable components in INVLWP [56].

8.14 LIBRA

LIBRA was the original name of the Swedish V/L code now called AVAL, see chapter 8.5 for further information.

8.15 LMP3

LMP3 (Luftmålsprogram 3) in an older Swedish V/L code for air targets, used from the early seventies to the nineties. Components are killed if the fragment impulse is high enough to penetrate the components' outer casing (protection defined as a thickness of dural) [57].

8.16 MAVKILL

MAVKILL (Multiple Attack Vehicle KILL) is a successor to AFVKILL, which also can handle evaluation of multiple strikes on the target [40]. The kill probability of components is probably handled in a similar way as in TANKILL, see chapter 8.29.

8.17 MEVA

MEVA-GF (The Modular Effectiveness Vulnerability Assessment- Ground Fixed) is a US engineering tool for assessing the vulnerability of fixed ground target to conventional weapon attacks [58]. Target damage is modelled as a function of time. It is not described how components are killed by penetration damage, but it is obvious that they are treated individually.

8.18 MINERVE

MINERVE (Modéle INformatique pour l'Evaluation et le Réduction de la VulnérabilitE) is a French vulnerability code for ships [59]. The postprocessor enables a probabilistic and functional analysis on the ships' operational capabilities including; damaged components, residual aggression on those components (projectile mass and velocity) and a database that provide failure thresholds for components.

8.19 MUVES

MUVES (Modular Unix-based Vulnerability Estimation Suite) is an US-V/L code [51]. Components can be damaged by e.g. penetrator mass, penetrator velocity or hole size [60].

8.20 ORCA

ORCA (Operational Requirement-based Casualty Assessment) is the US premier personnel vulnerability model [61]. The penetration part is to a large extent based on ComputerMan, see chapter 8.6. Orca has also been imbedded in MUVES [61].

8.21 PUMA

PUMA is an outdated V/L code developed by the Swedish defence research agency in the late eighties [62]. For penetrative warhead effects, the deposited energy in the vital components is the basis in deciding whether the component is killed or not.

8.22 PLEIADES

PLEIADES is a French V/L-code suite for land, air and space targets [63, 64]. In PLEIADES/A (air targets) components can be damaged by penetrators based upon the penetrator's mass and impact velocity [figure 4 on page 5 in 65]. Components can be killed or degraded.

PLEIADES/I (I is for Infrastructure) is another version of PLEIADES used for conventional air to ground warfare [64, 66, 67]. PLEIADES/T is used for vehicle studies and PLEAIDES/TBM for tactical missile studies [68].

8.23 RESIST

RESIST is the result of a tailor made development of TARVAC for a specific frigate related design task [69].

8.24 Robin Hood

Robin Hood (ROBotar I Närförsvar, Huvudprojekt luftförsvar och nymOOD) is an outdated Swedish V/L code for missile targets [70,71].

The kill probability of a component, P_k, is defined via a quotient, K, defining the relationship between fragment properties and the sensitivity of the component. Two types of components are defined. For so called "area components" K is defined by the total hole area caused by the fragments and a largest defined hole area for the component. For "penetration components", the fragments' impulse is divided by the components protection and the penetration depth is divided by an effective depth. These two quotients are multiplied to give K.

The relation between P_k and K is described by a Gaussian distribution. By defining a confidence interval with the confidence level $1\text{-}\alpha$ according to equation (20),

$$P_k\left(\mu - \lambda_{\alpha/2}\sigma\right) \le K \le P_k\left(\mu + \lambda_{\alpha/2}\sigma\right) \quad (20)$$

where μ is the mean value and σ the standard deviation, it should be possible to define the relationship between P_k and K.

8.25 SLAMS

SLAMS (Survivability and Lethality Assessment Modelling Software) is a V/L tool developed in Canada. SLAMS is the successor to GVAM [52]. Component damage algorithms are used to assess the kill probability of components, P_k. These algorithms are provided as families of curves i.e. P_k vs. kinetic energy of impact or momentum [52, 72]. Families of curves such as P_k vs. velocity for a given mass are also used. Experimentally fitted curves, without any clearer description in [72], are used for shaped charges.

8.26 SLAT

SLAT (Survivability Level Assessment Tool) is a French simplified tool based on a probabilistic approach [73]. It is a higher level tool and thus kill criteria for components are not used. In order to calculate the survivability of a vehicle, the kill probability given a hit is used, among other things.

8.27 SURVIVE

SURVIVE is a UK code developed by QinetiQ. Each equipment component is allocated to a category to allow SURVIVE to look up failure criteria for the item's response to each damage mechanism [74, 75]. There is also a reduced version of SURVIVE called SURVIVE Lite.

The trajectory of kinetic energy warheads is calculated through the target until the projectile cannot penetrate any further or the fuze detonates the warhead. Fragments are treated in a hybrid deterministic/probabilistic manner accounting for actual fragment penetration. The actual fragments produced by the warhead are the assigned pre-calculated trajectories to give the average number of each type of fragment that might be expected to hit or penetrate each component or structural element. [75]. No information on how SURVIVE defines components as killed or not has been found.

8.28 SQuASH

SQuASH (Stochastic Quantitative Assessment of System Hierarchies) is an American (Ballistic Research Laboratory, BRL) Monte Carlo vulnerability code for burst point modelling [76, 77]. SQuASH identifies each component with respect to whether it has survived or has been rendered non-functional by the action of the damage mechanisms, primarily penetration and spall. No information of how SQuASH defines component as killed or not has been found.

8.29 TANKILL

TANKILL is the oldest and probably best known component based vulnerability model in the world, according to [40]. It is (or was in 1992) commercially available to industries in the UK and other foreign governments [40]. Component kill is based on curves describing the likely component response to various levels of threat performance. These curves were established using the CARDE derived damage algorithms.

The CARDE trials are a set of firings performed in Canada 1959, where approximately 400 antitank rounds were fired against armoured vehicles [37].

8.30 TARVAC

The development of TARVAC (TARget Vulnerability Assessment Code) started in the late seventies at TNO to support the Netherlands Defence organisation [69, 78]. The physical state of the target's components is made up by the parameters describing the geometry, the material and other physical properties. The altered physical state is described in a direct as well as an indirect way, where parameters based on threat characteristics or exposure of the component such as the mass, velocity, energy, momentum of the penetrator at impact as well as residual metrics are used. Also parameters based on the state of the component after exposure such as penetration hole size, volume and depth are used. The physical state parameters are filtered with respect to typical, component dependent, threshold values and aggregated using physical principles. In the end, the physical state of the component is dealt with by a limited number of aggregated parameters. The functional state of a component is derived from interpretation of the aggregated physical state of the component.

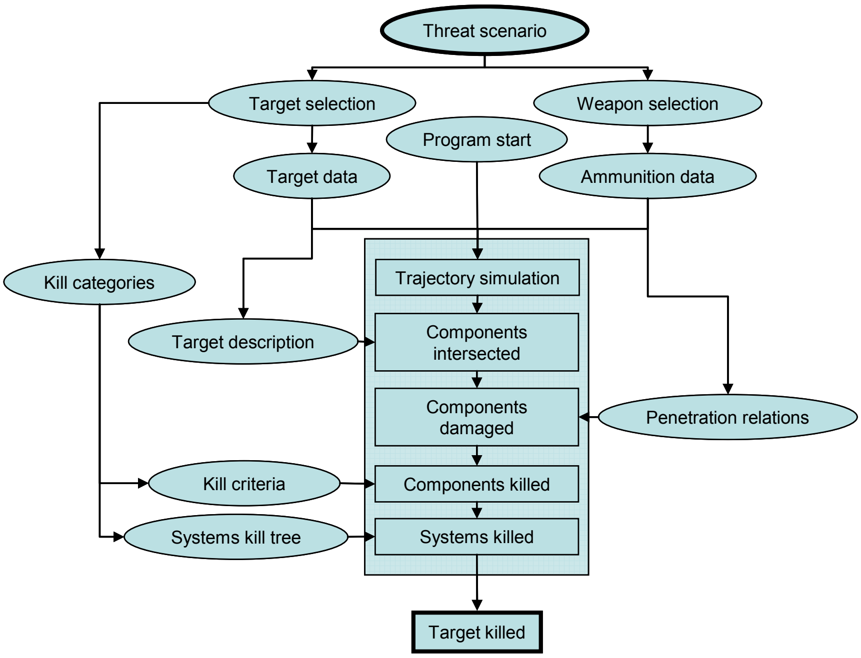

Figure 13. Block diagram of the TARVAC code [79].

The importance of kill criteria is indicated in Figure 13 where it is defined as a unique part in the block diagram.

8.31 TARVIEW

TARVIEW is a lethality software developed by ATKINS in the UK to model the effect of fragmenting warheads on various targets [29]. TARVIEW uses three types of damage algorithms, based on;

- the penetration depth into a component,
- the number of fragments hitting a component and
- the punched area of fragments striking a component.

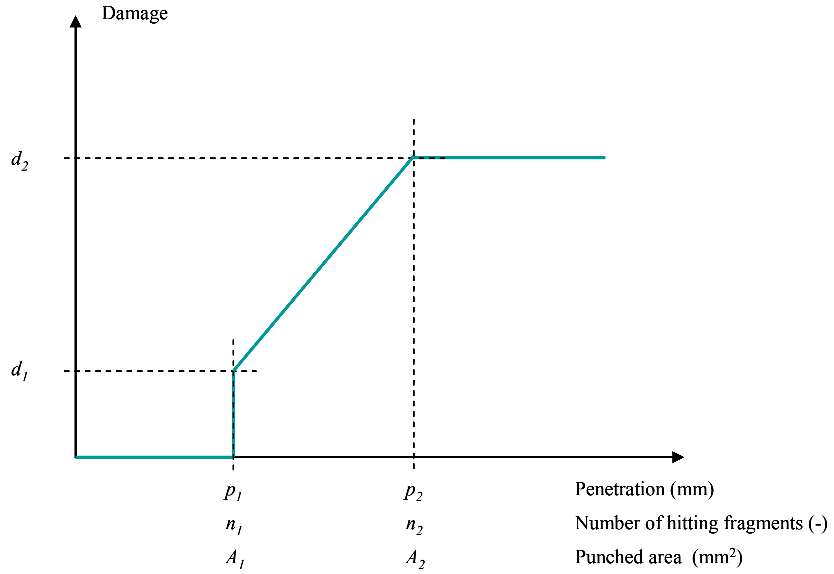

Figure 14. Evaluation of damage in TARVIEW [29].There are three possible phenomena causing damage, penetration depth, number of hitting fragments and punched area, all treated similarly.

The damage algorithms are defined by four parameters, describing two points according to Figure 14. The evaluation of damage is performed in the same way for all three different types of damage, with the exception that damage by penetration is treated independently for each hit whilst damage based on number of hits and punched area is defined by the accumulated number of hitting fragments or punched area [29].

8.32 TBM-Xpert

TBM-Xpert is developed by TDW in Germany in order to simulate intercept of tactical ballistic missiles (TBM) [80]. One of the focal points in this is to destroy the payload of the TBM, before it reaches its designated target area. The payload may consist of conventional explosives, chemical or biological bomblets, where each bomblet could be modelled individually as a component.

There are, at the moment, two models in TBM-Xpert to handle the effect of impacts with extended bodies, hit-to-kill missiles equipped with a lethality enhancer [80].

In the crater model a submunition component is considered damaged and possible killed when its volume overlaps the volume defined by elliptical effective craters. The level of damage can be related to the total volume fraction of a component overlapping with the craters. In the momentum flow model, eroded material strike the components and transfer energy. The amount of transferred energy is compared with a damage threshold energy level in order to see whether the component is damaged or not.

8.33 THETIS

THETIS is a French code for ship vulnerability, which was in a prototype state in 1998 [81]. In the geometrical and physical description of the target, each component is given kill criteria for different types of damage. The Thor equations are used to calculate the kill probability caused by fragment impacts and an energy balance model is used for small calibre projectiles. Then the actual kill probability of the component is calculated by a simple integral method in order to combine the individual kill probabilities based on different damage mechanisms.

8.34 UniVeMo

UniVeMo (Universelles Verwundbarkeits-Modell) is developed by IABG mbH on behalf of the German government [82, 83]. There are two classes of functional modules; the first one comprises phenomena from weapon deliver to target. Examples of output are: number of hits, impactor mass and velocity on a given component. The second class provide the level and probability of damage caused by the physical loads determined by the first class based on; mass and velocity, energy, momentum, damaged area, damaged volume, number of hits or synergistic effects. The individual contributions from single events are determined and cumulated to a kill probability and/or performance degradation [83, 84].

8.35 Unknown TNO(?) code

Verheij [23] describes the development of two generic helicopters, but does not give a name of the V/L-code the helicopter models should be used with. In the example given in [23] component kill criteria are defined for both "K-kill", damage that causes loss of manned control over the helicopter within 30 seconds after hit, and "A-kill", damage that causes loss of manned control over the helicopter within 5 minutes after hit. This means that the effects of damaged components are partly incorporated in the kill criteria.

The kill criteria can be selected from the following types:

- Complete penetration
- Minimum required penetration capability, with the subgroups;
    - Minimum thickness that has to be penetrated, given as a minimum plate thickness of the specific material that has to be penetrated.
    - Minimum required mass and velocity of the penetrator, given as M_{min} and V_{min}.
    - Minimum kinetic energy of the penetrator
- Personnel, divided into different tactical situations.

To include the hole area in the penetrated components, a minimum and maximum weighing factors, W_{min} and W_{max}, are available (see Figure 15). This weighing factor gives the kill probability of the hit component, provided that the penetration criterion, according to the types above, is satisfied.

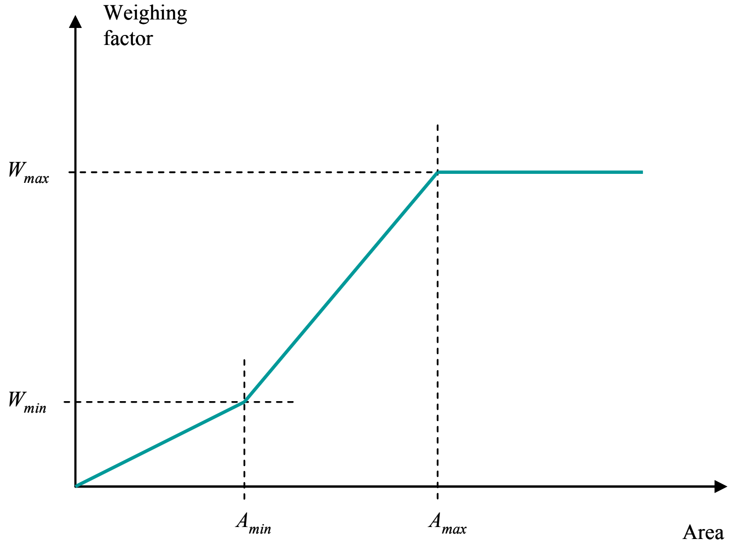

Figure 15. Weighing factors as used in [23].

8.36 UWM

UWM (Unified Weapon Model) is an integrated framework that can exploit existing software models, developed in the UK [85, 86].

The part of UWM liable to calculate the interaction of penetrators with component is the "Interaction handler" in the Weapon Target Interaction (WTI) module. WTI is also responsible for being able to connect different existing V/L codes. The calculations include the physical damage to the target components, e.g. size of holes, energy deposited etc. Example methods to calculate damage are individual target component lethality limits and scoring rules, including time features [85, 86].

8.37 VAREA

VAREA (Vulnerable AREA) is a US code from the early seventies that computes the vulnerable area for targets [87]. The modelling and methodology involves positioning all vulnerable components and shielding parts of the target in space and evaluating damage to those components. VAREA treats the target/penetrator interaction with the Thor penetration relationships.

The kill contribution of each vulnerable component is computed using either a curve or a step-function which relates a penetrator's striking velocity and weight to a conditional kill probability. Once the $P_{k|h}$ along a shot line (fragment trajectory) is developed, the vulnerable area for that shot line is found by taking the product of the $P_{k|h}$ and the grid cell area.

8.38 VAST

VAST (Vulnerability Analysis for Surface Targets) is another US code [49]. Two- or four-step functions are typically used to provide the $P_{k|h}$ by a fragment of a specified weight and velocity. The impact conditions of the penetrator are used to calculate the $P_{k|h}$.

8.39 VeMo-S

VeMo-S (Verwundbarkeits Modell - Schütze) is developed by CONDAT and DIEHL in Germany aiming to assess the vulnerability ($P_{k|h}$) of soldiers both under the threat of fragments and small arms ammunitions [88]. The soldiers can also be equipped with body armour. Due to the injury levels of the hit body elements (totally about 400 elements) a failure assessment is carried out which refers to incapacitation of the soldier. This incapacitation is defined as "Bio-Mechanical Failure" *(BMF)*, defined in events *E(BMF)* as;

- failure of the soldier, including incapability to perform any tactical mission, if elements of the central body region *(CBR)* were injured,
- failure of the extremities *(EXT)* if elements of arms or legs were injured.

A probability for the failure event *P(BMF)* is generated for each simulated shot line. The failure of *CBR*-elements is equivalent to "kill probability given hit" $P_{k|h}$ which refers to a defined tactical mission, whereas in the case of extremity failure a weighting factor, $0 \leq G \leq 1$, is multiplied to *P(BMF)*. The factor *G* is called "Mission reduction number". This is illustrated in equation (21) for hits in *CBR* respectively *EXT*.

$$P_{k|h} = \begin{cases} P(BMF)_{CBR} \\ P(BMF)_{EXT}\, G \end{cases} \tag{21}$$

In the event that a penetrator injures elements of CBR and EXT, a "Survivor rule" is used to calculate the combined kill probability, according to equation (22).

$$P_{k|h} = 1 - \left(1 - P(BMF)_{CBR}\right)\left(1 - P(BMF)_{EXT}\,G\right) \qquad (22)$$

The damage functions for *P(BMF)* are given in equation (23), where the limits x_1 and x_2 are based on expert judgement from wound evaluations. These values are primarily related to the soldier's failure within 30 seconds.

$$P(BMF) = f(x_1, x_2) = \begin{cases} 0 & x \le x_1 \\ \dfrac{x - x_1}{x_2 - x_1} & x_1 < x < x_2 \\ 1 & x \ge x_2 \end{cases} \qquad (23)$$

The penetration algorithms in VeMo-S enable the processing of shotlines through the soldier until the penetrator's kinetic energy is used up or until the soldier is perforated. In this way all hit elements are noted with impact performances and injury levels.

$$P_{k|h} = 1 - \left(1 - P(BMF)_{CBR}\right)\left(1 - P(BMF)_{EXT}\,G\right) \qquad (24)$$

Five different types of criteria are used in the different parts of the soldier body as listed in Table 11.

Table 11: Types of criteria used for different parts of the soldier body [88].

Body part	**Criteria**	**Unit**
Tissue	Loss of energy / path length	J/cm
Arteries, Veins, Nerves, Sinews, Eyes	Energy density at impact	J/cm^2
Tubular bones, Spinal column	Impulse	Js/m
Face region: nose, mouth, ears	Impact hole diameter	cm
Brain, Spinal marrow	Penetration depth	cm

8.40 Verksam

Verksam is an outdated Swedish naval target vulnerability code from the early seventies [89, 90]. Each vulnerable component is given a probability of kill if the component casing is perforated, regardless of the residual penetrator properties. The penetration calculations are performed using a set of equations and the number of hits in a component is defined via the protection and an area relation between the component and one warhead fragment ejection portion.

9 Discussion

Even if kill criteria only is one of many topics that has to be considered when describing a target for a V/L-tool, there are many different parts of this topic that have to be considered. Some of these are discussed below.

Well described and well presented (unclassified) methodologies, metrics, geometrical formats could be of great help in order to facilitate international cooperation and sharing of information on kill criteria and V/L-assessments in general. This will become more important in the future since common equipment are used by collaborating nations, i.e., the same components will appear in several different platforms and sharing of this type of information will give reduction in cost of producing target descriptions for V/L-codes.

9.1 Methodologies

Detailed vulnerability simulations and studies of single components seem to be feasible way of work. It is thus quite demanding work, with respect to time and need of knowledge about the functionality of the components. If the component is considered extremely sensitive, a geometrical analysis of the vulnerable projected area compared to the total projected area for a number of attack directions will give a kill probability, i.e. killed if hit.

Experimental studies should, whenever possible, support the detailed component vulnerability studies. In some cases it might even be possible to find components that can be experimentally tested in such magnitude that empirical relationships can be established. These empirical equations can then be used also for similar components even if some limited number of experiments and/or detailed vulnerability assessments is needed.

Engineering judgement can be a very effective and a quick way to set the criteria, but the experience of the analyst will decide whether the criteria turn out to be reasonable or not. A criterion based on engineering judgement is probably more difficult to document and therefore also harder to reuse later.

9.2 Metrics

Preferably, the performance of the penetrator should be described with a combination of physical properties, such as mass, velocity, size and shape. This is however not always possible, as in the case of SC- or EFP warheads. Therefore, some kind of calculated metrics such as penetration capacity, change in penetration capacity or hole volume is needed.

In order to have only a few ways of describing the kill criteria, the calculated penetrator performance is preferred. If there are reasonably good penetration capacity algorithms available, there should be no major problem of translating the physical properties of fragments and projectiles to the calculated metrics.

9.3 Criteria, P_k or $P_{k|h}$

Component kill criteria should be defined with the condition that the component is hit, i.e. as $P_{k|h}$. Influences of the hit probability can be handled later on when it is time to decide if a specific attack will kill the component or not, i.e. when deciding P_k. This is clearly illustrated in Figure 1 on page 10 and contradicts some of the so called kill criteria exemplified in chapter 2.2. If the hit probability is included in the kill criteria, one would probably have to define criteria for each possible attack situation and then it is not a component property.

9.4 Kill or degradation criteria

If the component is able to perform its tasks satisfactory after being damaged, it can be regarded as undamaged and damaged or killed otherwise. This gives a clear definition of the damage and makes it easy to use the result in a fault tree.

In most cases it is probably possible to define fault tree events in such a way that they represent a satisfactory level of system function, and then the components should only be killed or not killed. A main battle tank that has lost its sight systems would in most cases be given a “Firepower kill” designation, but for those standing right in front of the gun, this is not obvious. The definition of the results on the system level has to be clearly defined in order to let someone else interpret and use them.

The criteria are probably easier to understand if they describe kill or no kill rather than degradation.

9.5 Geometrical description

One important thing is that the kill criteria should not be separated from the geometrical description of the component. It is also stated in [8] that the $P_{k|h}$ analyst should be included in the target description loop. When calculating or estimating the $P_{k|h}$ one has to know the parts that are included in the component description. This is quite clear in the case of an engine, but should the criteria include externally mounted high pressure diesel fuel lines or are they described separately in other components? If the latter is the case those components should be quite sensitive, whilst, in the first case, that sensitivity has to be smoothed-out over the complete surface of the component describing the engine, which in some areas should be quite tough.

This makes it natural to prefer that it is the same person who does both the geometrical description and assess the kill criteria for the component.

A V/L-tool that allows sub grouping of components in order to accumulate the effect of several hits would be interesting. The outcome might differ if a soldier is described with one component representing his or her right leg. If this “leg” component is hit twice, the kill criteria can either be evaluated based on each hit individually or with the accumulated damage. If the leg instead is described with three components, upper leg, knee and lower leg, and the two hits are in separate parts there will be no chance to evaluate the accumulated damage if the tool does not allow sub grouping of components. It is also possible, depending on the attack direction, that the penetrator enters one part and then also enters the second or even the third part. In this case evaluation of individual hits will give three separate kill probabilities and this might increase the overall leg kill probability. The sub grouping of components should then only be used in order to combine components to allow kill evaluation based on accumulated damage, whatever metrics chosen, in order to overcome problems such as the one exemplified with the soldiers leg above.

Since computer performance increases, it might be possible to directly use component target descriptions (used for detailed vulnerability analyses) as part in a vehicle target description. When this is possible it will be easier to reuse components and hopefully also to define kill criteria.

9.6 Time

Time to kill has to be considered in some way. A fuel tank with a small hole is regarded as broken, but the engine will continue to run until fuel starvation. This can be accomplished in several ways; one is to set an “effect time after damage occurrence” and another is to actually calculate the fuel consumption and leakage and identify the fuel tank as killed when it is empty. Unfortunately this time to effect might differ from target to target for the same component, depending on the target system design. Nevertheless, the component response at $t=0$ (time of impact) should be the same and that is the main part of the criterion.

9.7 Documentation

There is an unambiguous need of documentation on how the kill criteria are estimated. Otherwise they cannot be reused with any credibility that the kill probability is realistic in the new case. The documentation would also be an invaluable source of knowledge for new $P_{k|h}$ analysts and would also give possibilities for continuous improvements of the criteria. Documentation of criteria, and continuous or incremental improvements, will also lead to a need of updated documentation of the target descriptions using the components and criteria. This will in turn naturally give a revision control of the targets, which is in accordance with different quality control systems.

9.8 Scientific sharing - standard format

The V/L-community would probably benefit from increased scientific sharing of methodologies of component kill criteria assessment and experimental results. This might be hard to accomplish due to limited availability of both input data and information about the V/L-tools. Nevertheless, general descriptions of methods and metrics should be possible to share to a greater extent than today. Some experimental findings and empirical models can be found in peer-review scientific journals, but they are too few.

A more standardised format of kill criteria as well as a common terminology would greatly simplify sharing of information on a user to user level.

Initiatives as the European Survivability Workshop (every other year since 2004) and NATO RTO AVT-153 Specialist meeting on Weapon/Target interaction Tools for Use in Tri-Service Applications (2008) are important steps in this direction.

9.9 The future for V/L-analysts working with component kill criteria

There is no doubt that there is and will be a need for continued research on component kill criteria and other things related to vulnerability and lethality assessments. V/L specialists can always refer to a statement by Goland 1989 [37], if their contractors believe that no more development is needed: "*Thus, it is seen that vulnerability assessment for combat vehicles, even if all the required data were available, is a most complex issue*". This is still true, especially since there is a lack of the required data.

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