AVAL

ASSESSMENT OF VULNERABILITY AND LETHALITY

A TRI-SERVICE VULNERABILITY / LETHALITY SIMULATION TOOL

GENERAL PRODUCT INFORMATION

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1. GENERAL INFORMATION

Development of the model AVAL started in Sweden 1995. Today AVAL is used by government agencies and private industry in several nations. AVAL stands for Assessment of Vulnerability And Lethality. AVAL was and continues to be developed in close cooperation between:

- FMV (Swedish Defence Materiel Administration).
- FOI (Swedish Defence Research Agency).
- BAE Systems Bofors AB.
- Dynamec Research AB.

AVAL is owned by the Swedish Armed Forces and managed by FOI, commissioned by the Armed Forces.

1.1. AVAL vision. The purpose of the model is to serve as an aid in assessment of platform vulnerability and weapon lethality. The Swedish national vision has been to achieve:

- Use of the same model by all parties involved in research, design, manufacturing, evaluation and use of ordnance projects.
- A model that handles all kinds of targets and weapons
- An object model, dealing with the product properties vulnerability and lethality and including all important phenomena for the product, capable of producing data for combat models and making use of data from technology models.

From 2002 the first goal is extended to include international parties.

AVAL is a commercially available, autonomous model designed for use with standard PC:s and standard office software. It is unclassified, but specific assessment data and simulation results are often classified according to user specifications.

1.2. Scope. AVAL primarily simulates end game events including results of fuze and conventional warhead function and components and target system damage.

Input data can be given to either calculate fuze function or describe final points of detonation.

In later years AVAL has expanded so that it now also simulates EM (electro magnetic) weapons and ballistics for both direct and indirect fire as well as target automatic hard kill protection systems.
2. AVAŁ - THE V/L ASSESSMENT TOOL

The core task for a V/L assessment software like AVAŁ is to calculate the consequences for a target when subjected to a weapon effect. The result can be for one specific hit, or for an average of a number of randomly distributed hits (lethality analysis) or as a map of the effect over the contour of the target (vulnerability analysis). In order to perform this task targets and warheads need to be described in appropriate detail, hit points must be generated and the warhead-target interaction is simulated repeatedly.

2.1. Basic AVAŁ objects.

- Warhead carrier with
  - Fuze system with sensors.
  - Warheads with warhead effects.
- Target with
  - Structural components.
  - Explosive reactive armor components (ERA).
  - Locally reactive armor components (LRA).
  - Vital parts.
  - Volumes.
  - Damage phenomena data and criteria.
  - System damage criteria - fault tree.
- Hit/burst points.

2.2. Warhead carrier. Figure 1 shows a simplified warhead carrier.

![Warhead carrier diagram](image)

**Figure 1.** Warhead carrier.

The fuze system needs to be specified only if the module built into AVAŁ should generate the hit points. It includes one or several of the following sensor types:

- Height sensor.
- Impact sensor.
- Laser sensor.
- Radar sensor (proximity fuze).
- Timer.
- Empirical infra red sensor.

The sensor properties and the fuze system location relative to the reference point are specified as input data. A warhead carrier contains one or several warheads with locations and orientations relative to the reference point that are specified as input data.

A warhead contains one or several warhead effects with locations relative to the warhead that are specified as input data. Presently there are models for the following types of warhead effects:
• Shaped Charge.
• Kinetic energy (KE) penetrator.
• Shaped Charge with a stiff, penetrating nose.
• Explosively formed projectile.
• Fragmentation warhead.
• High explosive warhead.

A penetrating object may generate secondary fragments (behind armor debris).

2.3. **Target.** All different types of targets are described with the same basic components.

Structural components, see figure 2, are specified as polyhedrons or plane plates and are used to define geometry, protection against penetration and conditions for generation of secondary fragments.

![Figure 2. Example of structural parts from an AFV.](image)

ERA and LRA components (hollow polyhedrons), if present, protect targets against penetrating objects according to special models.

Vital parts (vulnerable components), see figure 3, are specified as polyhedrons or plane plates and are the same capability of protecting against penetration as structural components. The main task for the vital parts, however, is to that they are subjected to damage caused by various phenomena. Therefore they are assigned a set of applicable damage criteria.

A volume consists of one or several of hollow polyhedron structural components. Volumes are used in the models of some of the damage phenomena, for example pressure, fire and water.

Damage criteria define how sensitive a vital part is when subjected to hits by penetrating objects, blast and overpressure, heat and smoke, structural damage and water submersion.

System damage criteria or fault trees define which consequences that vital part damage will cause to the entire target.

2.4. **Hit points.** Hit points are specified before warhead-target interaction simulation is started and read into AVAL as input data from a text file or a dialog box. They can be generated either within AVAL or by any separate trajectory and sensor simulation code. There can be either a single hit/burst point, or randomly distributed hit points or hit points that are regularly distributed in a grid over the target contour. A fuze system is used to find a hit point location along a trajectory. Figures 4 and 5 show examples of randomly and regularly distributed hit points.
FIGURE 3. Example of vital parts from an AFV.

FIGURE 4. Randomly distributed hit points. 200 rounds with a rotating warhead carrier and a laser sensor are fired against the front of a fighter aircraft. Red dots mark rounds with trigged sensors while blue dots with short lines mark misses and firing direction.
Figure 5. Regularly distributed hit points. Rounds with impact sensors are fired against the target’s (an AT missile) left hand side in a 10 x 10 mm grid. The total number of grid points is $130 \times 80 = 10400$. Red dots marks hit points and blue dots mark misses.
3. BASIC CHARACTERISTICS OF AVAL

3.1. **AVAL - one common model for all target types and all damage phenomena.** A goal for development of AVAL was to establish one common software package to be used for all different types of targets (ground, aerial and naval) and damage phenomena. This goal is achieved. All target types are described in the same way and damage phenomena to be used during simulations are specified as part of the target description. Some phenomena can be switched on and off by the user interactively.

![Diagram of AVAL models](image)

**Figure 6.** One common software that handles all conventional warhead effects, all damage phenomena and all types of targets.

3.2. **Different sources of information for damage phenomena models.** Since AVAL is an assessment model at systems level it is impossible to include all available models on a detailed technical level for the important phenomena. Instead the phenomena are described basically by parametric models where parameter values may be determined from different sources of information whenever available. Sources may be basic physics, hydro-codes, empirical models or test results. In this way models are flexible and new information can easily be implemented when it appears.

Model parameter values, which are required to calculate if and to which extent the different damage phenomena are generated by a warhead interacting with the target, are given as input data to AVAL partly as warhead data, partly as target data. In some cases interfaces to specific external software have been developed to transform data to a format suitable as input to AVAL. For example fragmentation data may be generated by the German code Split-X and transformed to AVAL-data by a module built into AVAL. A similar interface was developed for the Swedish code FRAGM. Another example relates to the problem of treating stability of naval targets with water leaking in. In this case tables are generated for the specific target by the stability calculation code TRIBON, read into AVAL and used...
for interpolation in an iterative scheme. In order to characterize fire development in different environments the target volumes are divided into classes and the time development parameters are assigned from corresponding NFPA[1] curves.

3.3. Description of targets and munitions made as realistic as possible. Examples:

- Target components are given realistic shape, size and material properties.
- Penetration e.g. by fragments is treated by generating and following individual fragments (ray-tracing), see figure 7.

![Ray-tracing of fragments from warhead to target.](image)

**Figure 7.** Ray-tracing of fragments from warhead to target. The black line above the aircraft represents the firing direction of the warhead carrier and the green triangle represents the trig point of the laser sensor.

This makes it easier to:

- Check for data and simulation errors.
- Verify software solutions.
- Validate models.

3.4. AVAL’s general fault tree. The basic properties of the fault tree are:

- Target component damages are combined into events via a set of operators.
- Events may be combined into new events in a hierarchy.
- Uncertainties (probabilities) may be included in the fault tree.
- The fault tree is based entirely on Monte Carlo technique (random choice).
- The final status of a target can be expressed as any combination of the events that are defined earlier in the fault tree.

3.4.1. Dependent and independent events. Monte Carlo simulation. In AVAL Monte Carlo Simulation is used instead of analytical calculations of probability. Warhead effects on all components are determined via phenomena descriptions, which include models for kill probabilities for components as consequences of these effects. Thereby random numbers are used to determine the status of every component (killed or not killed). The random number generator is also used in phenomenon descriptions when these involve statistical parameters. For instance, a projectile may be broken into several pieces when it perforates armour. The number of pieces, their masses, velocities and flight directions are determined

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via random numbers and distribution functions. The latter are obtained from theoretical models and experimental results.

Thus, when a warhead interacts with a target a Monte Carlo simulation yields the status for every component and every ability. A Monte Carlo simulation is carried out N times (typically $N > 1000$), every time with new (independent) random numbers, whereby an ability is found to be killed in $K$ of these $N$ simulations. Thus, the estimated kill probability for the ability is $P = K/N$. Several component kills can be required to achieve kill of a target ability. In figure 8, ability A is killed if at least one of components 1 and 2 is killed, or if both components 3 and 4 are killed.

![Figure 8. Example of fault tree.](image)

3.5. **Result presentation.** The results from AVAL simulations are presented in basically two ways:

- On-line color graphics.
- Text files formatted to fit standard software, e.g. EXCEL.

From single warhead analysis plots can be generated showing detailed results from the shot such as penetrator and fragment trajectories and hit points, vital parts that are damaged by different phenomena, pressure, temperature, smoke and water level as function of time.

Results from lethality or vulnerability analysis simulations can also be presented as graphic plots showing color representation of the level of effect on the target for the different hit points. The user may also order different types of result summaries to be written into text files for further analysis.
4. SIMULATION MODES AND TYPES

AVAL contains four simulation modes with one, two or three possible simulation types:

- Single target (standard).
  - Single simulation.
  - MC simulation Lethality.
  - MC simulation Vulnerability.
- Direct fire scene (not yet commercially available).
  - Single simulation.
  - MC simulation Lethality.
- Indirect fire map (optional).
  - MC simulation Lethality.


4.1.1. Single simulation. In single simulation a single warhead effect or a complete warhead can be simulated. The examples below show warhead effect.

   In the first example, figure 9 of a single warhead effect mode the explosive charge (100 kg TNT) from an Anti-Ship missile is located inside the hull of a frigate below the sea level causing large water leakage. The plot shows water content inside the ship and the floating condition 320 seconds after detonation.

   ![Figure 9](image9.png)

   **Figure 9.** Single shot example. 100 kg high explosive inside frigate, below sea level.

   In the second example, figure 10 a fragmentation charge is detonated in a position above the sea level. No critical water leakage occurs but fire is initiated. The plots show fragment hit points and temperature distribution in the different affected volumes at a late stage of fire development.

   The single warhead effect mode can also be used to simulate warhead interaction with simple targets, figure 11. In this way experiments may be reproduced and model input parameters can be adjusted to fit experimental results. Figure 11 shows the result from a simulation of a shaped charge jet penetrating a thick steel plate and generating a large number of secondary fragments. The hit pattern on the witness plates gives a good basis for parameter adjustments.
4.1.2. **MC simulation - Lethality.** In figure 12 a 40 mm Anti Aircraft round with a large number of tungsten fragments and supplied with a proximity fuze is fired against the front of a fighter aircraft. The firing is repeated 500 times (Monte Carlo cycles). Since this is Monte Carlo simulations each round will either lead to the current event (immediate crash) or not, therefore there are only blue and red dots in figure 12.

4.2. **MC simulation - Lethality with APS (Automatic Protection System).** Lethality simulations can be conducted taking the target’s APS (hard-kill systems only) into account. In order run a APS-Lethality simulation the automatic protection system of target must be described and the warhead carrier (the threat) must be described as a target as well as a warhead carrier.

4.2.1. **MC simulation - Vulnerability.** The vulnerability of an armoured vehicle to an EFP off-route vehicle mine is simulated in figure 13. The mine is fired in a 20 by 20 mm pattern, 360 x 150 points in all 54,000 points. For every point six mines are simulated to account for the random behavior of mine and target. The target is a generic armoured fighting vehicle with front mounted engine, a turret with gun and a rear troop compartment, see figure 14.

The plot in figure 13 shows the probability of putting gun firing ability and/or vehicle mobility and/or at least 3 soldiers out of action. The probability is related to target status 120 seconds after hit.
FIGURE 12. Lethality simulation example. 40 mm anti aircraft rounds against a fighter aircraft. The converging confidence interval as function of increasing number of Monte Carlo cycles is shown to the right.

FIGURE 13. Result plot from vulnerability simulation. The colour scale shows the probability of killing firing ability and/or vehicle mobility and/or at least three soldiers.

The purpose of a simulation should govern the ambition regarding number of points and firings in each point. This example represents a moderate ambition in finding vulnerable areas for the vehicle.

4.3. **Indirect fire map.** In this mode a combination of different targets and firing units is positioned on a map, figure [15]. The targets’ positions can be set to change with some delay after the first burst (soldiers changing from standing to laying or vehicles escaping out of the target area). In this mode 6 D.O.F ballistics calculations can be used. The ballistic calculations are capable of handling cargo grenades with separation of sub-munitions including a canister phase, according to figure [16]. This mode is preferable for lethality
evaluations. The example in figure 17 shows all fragments from the grenades fired against the target area and a sub-figure with presentation of fragment hits in one of the targets.

4.4. Direct fire scene. In this mode a combination of different targets is placed in an environment. The first intended environments were like the one in figures 19-21 but an environment can also represent a military camp, as in figure 18 or a civilian environment.
FIGURE 16. Different phases for ballistic calculations.

FIGURE 17. Indirect fire simulation example. All fragments displayed on the map and detailed presentation for one of the targets, which is hit by fragments from five different grenades.

The targets positions can be set to change a with some delay after the first burst in the salvo. In this mode 6 D.O.F ballistic calculations can be used. This mode is preferable for lethality evaluations.

4.4.1. Single simulation. In the example in figure 19 and 20 the Direct fire scene includes four standing soldiers and a light truck with another four soldiers, located at the edge of a forest. The flight direction and burst point of the warhead is set to be as shown in figure 19.

A 40 mm warhead with spherical tungsten fragments detonates 3 m above ground. One of the soldiers in the light truck is incapacitated (one of the upper legs is red). Two of the standing soldiers are hit in the torso by a fragment, but protection vests prevented them from being incapacitated, see figure 20.

4.4.2. MC simulation - Lethality. The 40 mm warhead (from the example above), supplied with a time fuze, is fired from a distance of 200 m. The firing is repeated 10 times (Monte Carlo cycles) in figure 21.
FIGURE 18. Direct fire scene example. Part of a military camp. Civilian environments can be treated in the same way.

FIGURE 19. Direct fire - Single shot simulation example. Firing direction and aim point.
FIGURE 20. Direct fire - Single shot simulation example. Effects from fragmentation warhead. The left hand figure presents the trajectories of the fragments. These trajectories are removed in the right hand figure.

FIGURE 21. Direct fire - Lethality simulation example. The dots to the left show the burst points, the lines show the flight directions and red dots indicate sensor trigging of the warhead. The red dots to the right show that the warhead was capable of incapacitating at least one of the soldiers.
5. Case Example - Defining and Running Single Target Lethality Simulation

5.1. Defining a simulation Case. The first step is to define a so called Case, figure 22. The case defines which warhead carrier that will be used against which target. It also specifies the aim point in the target co-ordinate system, the firing direction, warhead carrier velocity and rotation. Data for salvos are optional. These data are combined with input data about hit point distribution around the aim point in order to calculate burst points (hit and miss points). In the single target mode AVAL does not calculate the complete ballistic trajectory of the warhead carrier, instead parallel straight line paths is assumed. The resulting burst points are saved in a burst point file, readable with any text editor or EXCEL.

![Figure 22. Lethality case dialog box](image)

The burst points calculated in this example are presented in figure 23, where red dots represent hits and blue dots with lines represent misses and the firing directions.

This procedure gives the user possibility to replace the burst point calculation with one of the user’s own choice. The only requirement is that the user specifies the same type of data in the same way.

5.2. Defining the simulation. The second step is to define the actual simulation, figure 24.

This definition is based on the previously created case and adds information about which pheonomea that shall be included, figure 25, and at what time (after the first burst time) the
result shall be evaluated. Most often only one case is used in each simulation, but by adding several cases one can define an attack with, for example, two anti-tank weapons and one machine gun against the target. These weapons have their own case files with separate aim points, hit distributions, salvos and so on. The only requirement is that they all attack the same target and that the same number of Monte Carlo cycles are used.
5.3. **Running the simulation.** Running the simulation is the third step, figure 26. When the simulation is running the dialog box shows the current Monte Carlo number and results for one of the target’s fault tree top events at one of the evaluation times. There is also a simulation time clock. In this case, the 100 Monte Carlo cycles required 6 seconds of simulation time.

5.4. **Examining the results.** When the simulation is finished then all results are saved in result files. These files are readable by any text editor or EXCEL. In this case it is found that top event 3017 for this target (Firing ability and/or moving ability and/or 3 soldiers incapacitated) occurs with probabilities of 32% at \( t = 1 \) s, 34% at \( t = 10 \) s, 37% at \( t = 60 \) s and 37% at \( t = 300 \) s. The results can also be presented graphically in AVAL, as in figure 27, showing hit points leading to top event 3017 at \( t = 300 \) s.
FIGURE 27. Results from the example simulation. Red dots marks hit points leading to top event 3017.
6. AVAL - THE SOFTWARE AND HARDWARE

AVAL is developed to be a stand-alone system running under MS Windows XP. It is object oriented and written in the C++ language using MS Visual Studio environment. The program is operated interactively with an OpenGL graphic user interface used in all phases of operation - specifying input data and setting up simulations, control of simulation progress and presenting evaluation of the results.

The package includes separate modules for defining and testing warhead input data, generating hit and burst points based on chosen firing direction, trajectory distribution and fuze properties and displaying, checking and manipulation of target data.

Besides displaying the results graphically the user may also order different types of results to be documented in text files, formatted to suit as input data to standard analysis tools such as EXCEL.

Target descriptions used in AVAL consist of sets of text files defining geometry, protection properties, damage phenomena data, damage criteria and system properties. In order to support the work required to generate these data a separate module (AVALCAD) to the commercial AutoCAD software was developed and is included in the AVAL package, figure 28.

![Figure 28. Example of target description in AutoCAD.](image)

The AVAL package consists of:
- The AVAL executable including interactive modules for weapon data and hit point generation, weapon-target interaction simulation and result display and analysis.
- Input data for example warhead carriers.
- Input data for example targets.
- The AVALCAD module used in conjunction with the AutoCAD software to generate target geometric data and protection data.
- An USB-dongle hard lock device, used for license management.

The hardware requirements to run AVAL are moderate, a standard office PC will be appropriate.
7. FURTHER INFORMATION

For detailed information about AVAL usage, some of the AVAL manuals can be downloaded from the AVAL web page.

7.1. Contact information. For further information, please contact the AVAL development team via e-mail aval@foi.se or see the AVAL web site www.foi.se/aval. On the AVAL web site you will also be able to find the name of the current contact person at FOI.

7.2. International user group. All AVAL users are members of the International AVAL User Group. The current president of the user group is Mr. Martin Sjöberg, BAE Systems Hägglunds AB (located in Sweden).