SYSTEMA
Debris

Version 4.9.4

User Manual

September 2024
Ref: UM.000254385.AIRB

Document issue: 2

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I. Introduction

Due to their high velocity, micrometeoroids and small orbital debris represent a threat to spacecraft or its components. Larger on-orbit objects are tracked and orbit changes manoeuvres are performed to avoid a collision. For non-trackable objects, shields or other means are used to control risks. The amount of debris in space is continuously increasing. The prevention of critical damages on sensitive surfaces that might compromise mission and lifetime, interest more and more the satellite design engineers. In order to improve the design of the spacecraft, impact risk assessment tools Systema-Debris was developed.

The aim of a risk assessment is to identify the spacecraft components sensitive to MMOD, provide inputs to assess the spacecraft reliability and, if necessary, support the implementation of shielding to improve spacecraft survivability.
In order to perform a risk assessment analysis under a specific environment, it is necessary to evaluate whether or not the impacting particle will penetrate the sensitive target. A variety of ballistic limit equations have been implemented for many types of structural wall configurations to identify the minimum critical particle diameter that can penetrate the target. These equations depend on several parameters like the size and the density of the particle, the material type and thickness of the impacted target, and the speed of the impacting particle, which makes the analysis difficult to perform without the support of dedicated software like Systema-Debris.
The Whipple shield equation [4] allows computing the critical particle diameter, and it is assumed that the bumper shield is well designed which means its thickness is sufficient to fragment the impacting particle. Some elements like MLI, already present on the spacecraft design, can act as a bumper to the sensitive components. As they are designed for thermal needs, they are most of the time undersized. Reimerdes [2] modified the Whipple shield equation to take into account the bumper thickness. This methodology has been implemented into Systema-Debris to help the user to find mass effective protection concepts with undersized bumpers.

The purpose of this document is to provide a user tutorial in order to handle Debris module and to correctly conduct a MMOD risk assessment analysis on Systema-Debris. MMOD risk assessment theory is not detailed in this document.

II. Debris analysis description

The following figure summarizes the whole MMOD risk assessment analysis process which has to be conducted to perform a simulation on Systema-Debris.

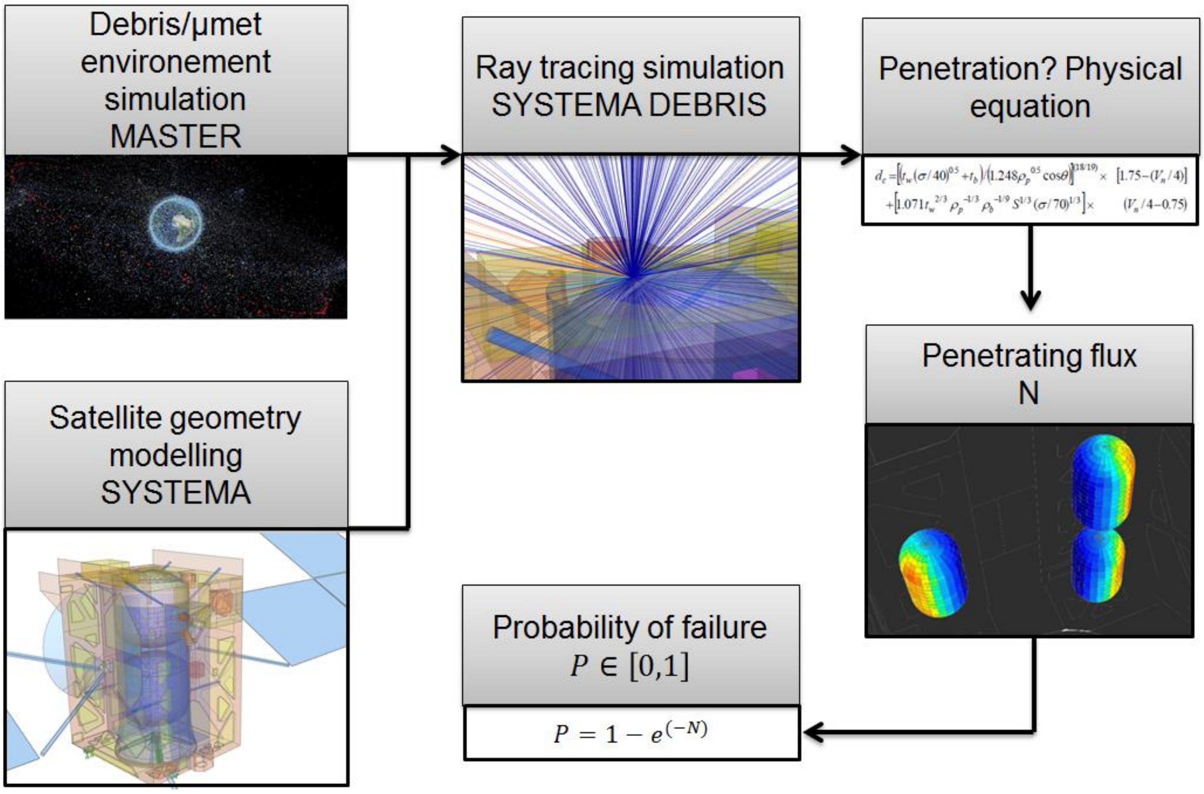


Figure II.1: Systema Debris analysis process

The different parts of the analysis are presented in the next chapters.

1. Generation of a realistic satellite model and meshing

The generation of a realistic model is done in Systema-Debris 3D graphical user interface allowing an adapted modelling from CAD files. During this step, BLE are chosen and adapted to the considered geometrical shielding configurations, material and mechanical properties are assigned to the geometries. The model is then used to generate a meshing.

Refer to SYSTEMA User Guide (Chapter 4: “Geometrical Model Management”) for more details on the modeller Systema.

1. 1 Model

Figure II.2 shows an example of a spacecraft configuration modelled with Systema-Debris.

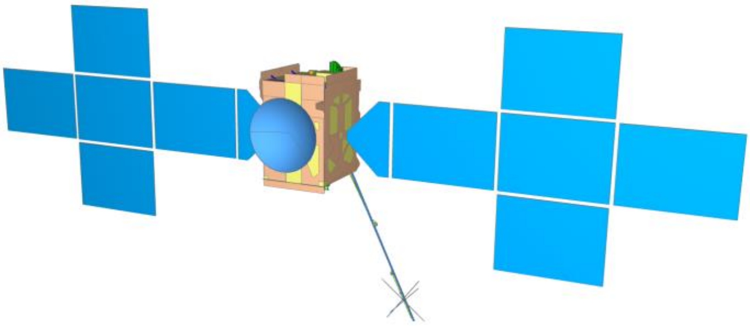
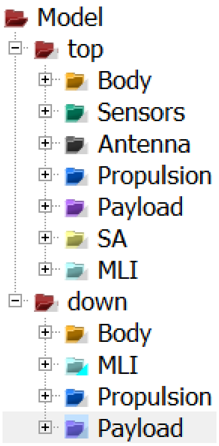


Figure II.2: Geometrical example model

Some good practice:

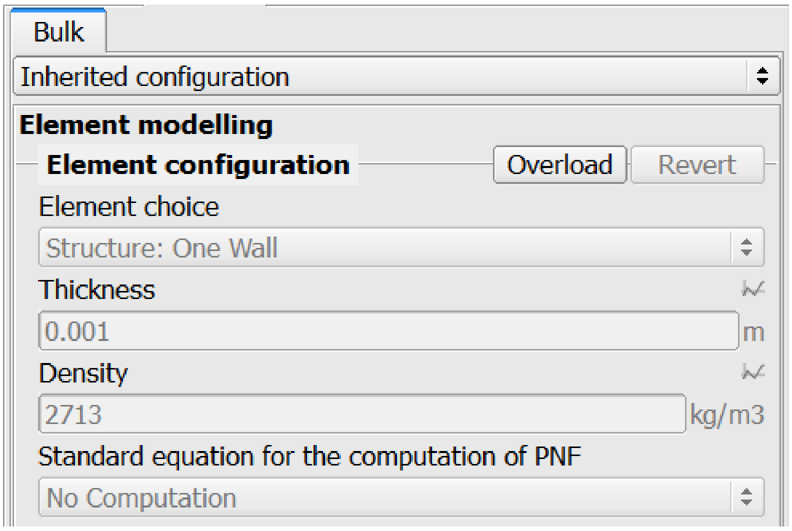
- Modelling pieces such as bolts, screws etc. are not necessaries.
- Debris compute results only on positive side. Check on 3D view configuration/shape orientation the orientation of the shapes.
- Quadrangles and triangles shapes are recommended to ensure the surfaces enclosure.
- Cutters (to cut holes in shapes) are very convenient to model complex geometries.
- To make a cleaner model and to make it more readable, it is preferable to create as many object as possible to detail the model tree especially if those includes several shapes. A random example of model tree organization is given Figure II.3 .
- It is recommended to group every sensitive item in the same object to make the analysis easier (apply properties to a group of shapes, create a group on the mesh tab for a sensitive element composed by a group of shapes).



- Model
  - ⊟ top
    - ⊞ Body
    - ⊞ Sensors
    - ⊞ Antenna
    - ⊞ Propulsion
    - ⊞ Payload
    - ⊞ SA
    - ⊞ MLI
  - ⊟ down
    - ⊞ Body
    - ⊞ MLI
    - ⊞ Propulsion
    - ⊞ Payload

Figure II.3: Model Tree

Applicative properties on shape or group of shapes are defined on debris tab (Figure II.4).



Inherited configuration

Element choice: Structure: One Wall

Thickness: 0.001 m

Density: 2713 kg/m3

Standard equation for the computation of PNF: No Computation

Figure II.4: Debris tab

The user can choose 3 configurations on the Debris tab for an object:

- No computation

There is no computation of the numbers of penetrations on this object. However the element is taken into account in the overall computation as a shadowing surface.

- Custom parameters

There is a computation of the numbers of penetrations on this element. The ballistic limit equation used by default for all the configurations encountered is a user-defined parametric equation based on the SRL equation.

- Implemented equation

There is a computation of the numbers of penetrations on this element. Standardized ballistic limit equation are implemented on Debris and the user can change the material and thickness properties of the element (see §3) and the coefficients.

- Custom equation

There is a computation of the numbers of penetrations on this element. Custom equation defined in Python will be used to perform the critical diameter computation (see §3).

If the user chose **implemented equation**, he can use standardized equations with pre-defined or customized coefficients. See §3 for more details on the ballistic limit equations.

The user can choose what standardized equation he wants used depending on the configuration: one, two or three wall or if he wants to compute the crater size.

- One wall cases
    - Standard equation

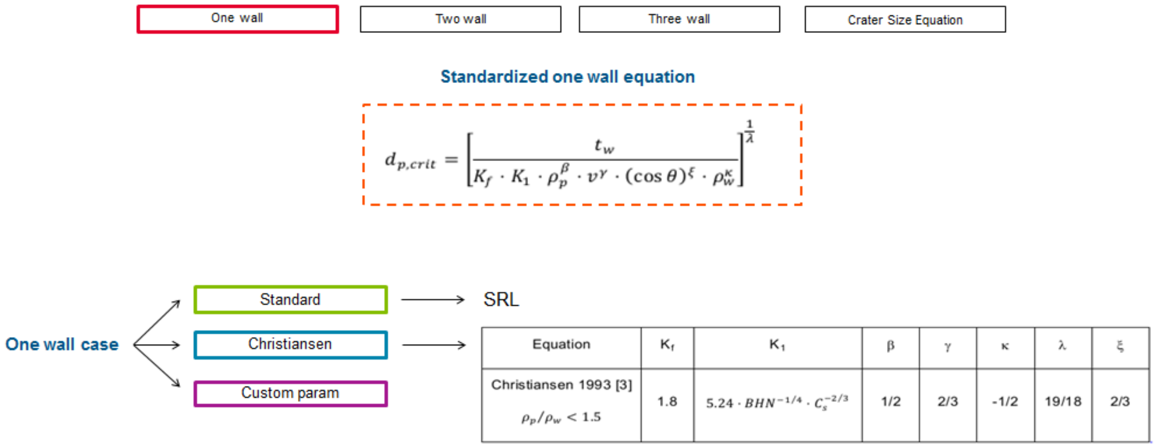
The equation used to compute the critical diameter in the one wall configuration (direct impact) is the SRL equation [6].

- Christiansen 1993

The equation used to compute the critical diameter in the one wall configuration (direct impact) is the Christiansen equation [4].

- Custom parameters

The equation used to compute the critical diameter in the one wall configuration (direct impact) is a user-defined parametric equation for single wall.



$$d_{p,crit} = \left[\frac{t_w}{K_f \cdot K_1 \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\theta)^{\xi} \cdot \rho_w^{\kappa}}\right]^{\frac{1}{\lambda}}$$

Equation	K_f	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1.8	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Figure II.5: One wall standardized equation

- Two wall cases
    - Standard equation

The equation used to compute the critical diameter in the two wall configuration (direct impact) is the SRL equation [6].

- Christiansen 1993

The equation used to compute the critical diameter in the two walls configuration is the Whipple shield equation given in Christiansen [4].

- Custom parameters – 1 velocity domain

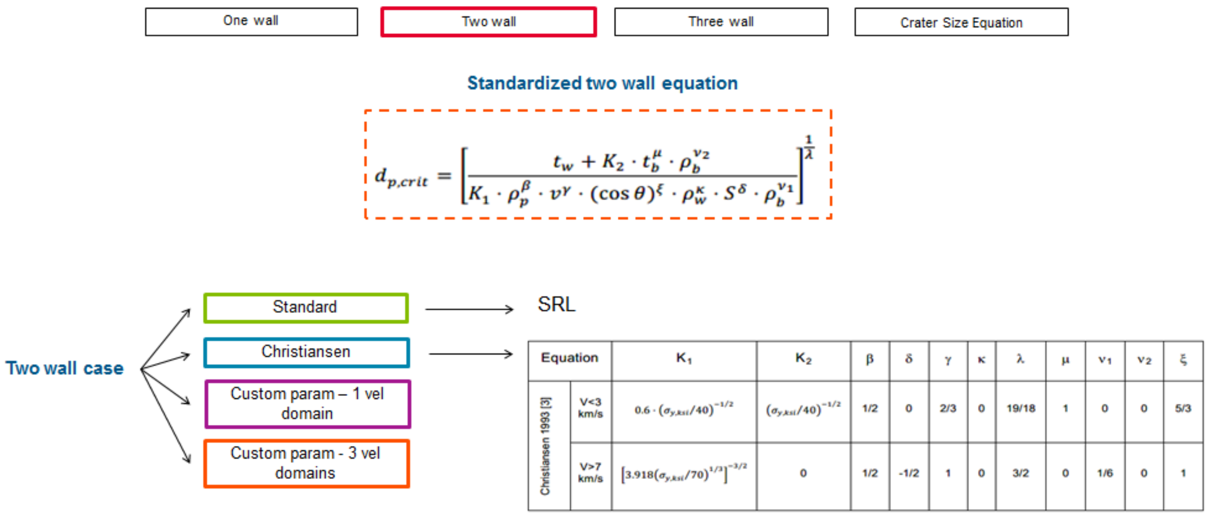
The equation used to compute the critical diameter in the two walls configuration is a user-defined parametric equation for multiple walls taking into account only one velocity domain. The limit angle has to be given. For oblique impact over the limit angle, the critical diameter is set for the critical diameter at the limit angle:

$$d_c(\theta > \theta_{lim}) = d_c(\theta = \theta_{lim})$$

- Custom parameters – 3 velocity domains

The equation used to compute the critical diameter in the two walls configuration is a user-defined parametric equation for multiple walls taking into account three velocity domains (ballistic, hypervelocity and transition regions).

The limit angle and the normal component limit velocities of the velocity domains (ballistic v_{t1n} and hypervelocity v_{t2n}) have to be given.



$$d_{p,crit} = \left[\frac{t_w + K_2 \cdot t_b^{\mu} \cdot \rho_b^{\nu_2}}{K_1 \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\theta)^{\xi} \cdot \rho_w^{\kappa} \cdot S^{\delta} \cdot \rho_b^{\nu_1}}\right]^{\frac{1}{\lambda}}$$

Equation		K_1	K_2	β	δ	γ	κ	λ	μ	ν_1	ν_2	ξ
Christiansen 1993 [3]	V<3 km/s	$0.6 \cdot (\sigma_{y,ksi}/40)^{-1/2}$	$(\sigma_{y,ksi}/40)^{-1/2}$	1/2	0	2/3	0	19/18	1	0	0	5/3
	V>7 km/s	$\left[3.918(\sigma_{y,ksi}/70)^{1/3}\right]^{-3/2}$	0	1/2	-1/2	1	0	3/2	0	1/6	0	1

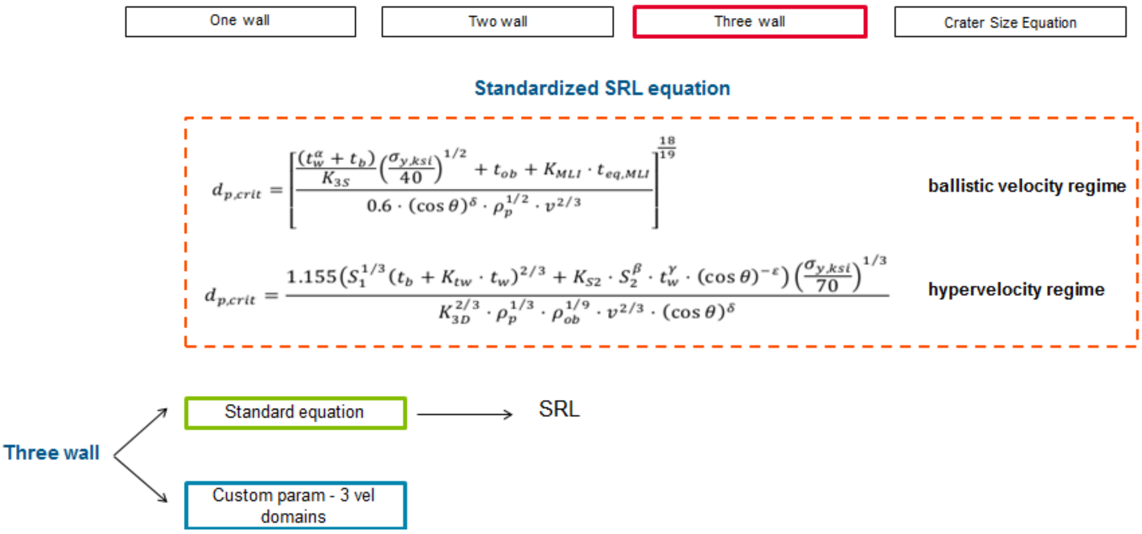
Figure II.6: Two wall standardized equation

- SRL case
  - Standard equation

The equation used to compute the critical diameter in the three walls configuration is the SRL equation [6].

  - No computation

There is no computation of the numbers of penetrations in the three walls configuration for this element. If this configuration is encountered by the element, it is considered shadowed.



$$d_{p,crit} = \left[\frac{\frac{(t_w^{\alpha} + t_b)}{K_{3S}}\left(\frac{\sigma_{y,ksi}}{40}\right)^{1/2} + t_{ob} + K_{MLI} \cdot t_{eq,MLI}}{0.6 \cdot (\cos\theta)^{\delta} \cdot \rho_p^{1/2} \cdot v^{2/3}}\right]^{\frac{18}{19}}$$

$$d_{p,crit} = \frac{1.155\left(S_1^{1/3}(t_b + K_{tw} \cdot t_w)^{2/3} + K_{S2} \cdot S_2^{\beta} \cdot t_w^{\gamma} \cdot (\cos\theta)^{-\varepsilon}\right)\left(\frac{\sigma_{y,ksi}}{70}\right)^{1/3}}{K_{3D}^{2/3} \cdot \rho_p^{1/3} \cdot \rho_{ob}^{1/9} \cdot v^{2/3} \cdot (\cos\theta)^{\delta}}$$

Figure II.7: SRL standardized equation

- Crater standardized equation
    - No crater computation

There is no computation of the numbers of craters on this element.

    - Christiansen

The equation used to compute the crater size is the single wall equation given by Christiansen [4].

The required crater size [m²], the Brinell hardness, the sound speed [km/s] in the material and the crater factor kc (ratio of the crater radius to the crater depth) have to be given.

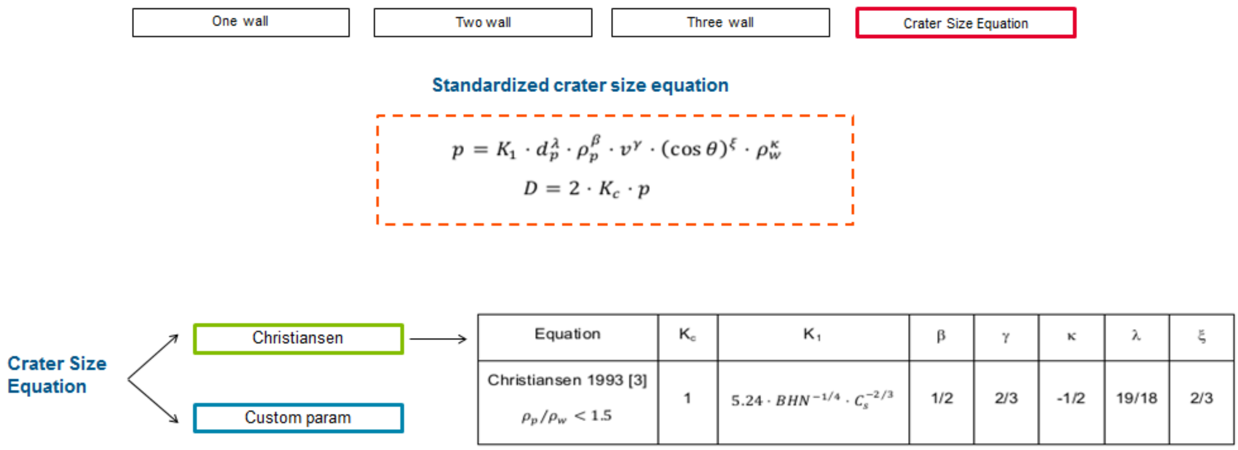
    - Custom parameters

The equation used to compute the crater size is a user-defined parametric equation for single wall.

    - Custom Python equation

The equation used to compute the crater size is a user-defined Python function.

The required penetration depth [m] has to be given.



$$p = K_1 \cdot d_p^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\theta)^{\xi} \cdot \rho_w^{\kappa}$$

$$D = 2 \cdot K_c \cdot p$$

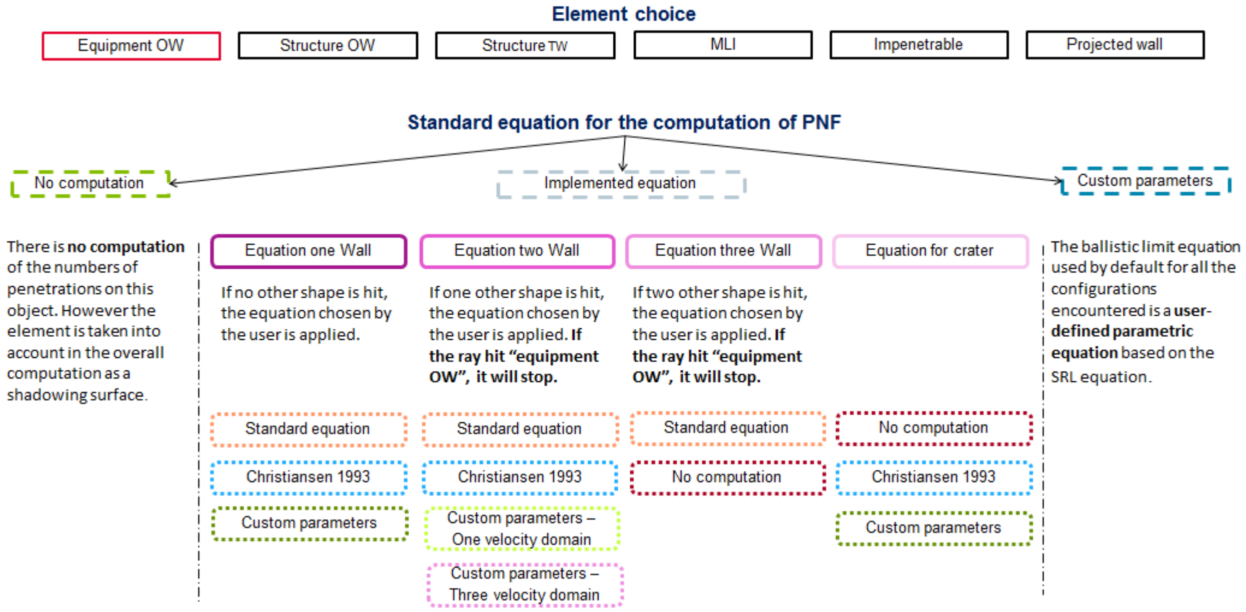
Equation	K_c	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Figure II.8: Crater standardized equation

The user starts choosing it element choice: equipment, structure, MLI, impenetrable and projected wall (see below). On equipment and structure elements, user needs to choose an equation for one, two, three and crater case. See §3 for more details on the ballistic limit equations.

a. Equipment: One Wall

The **equipment one wall** elements behave as the structure ones to the exception that they are considered as shadowing surfaces for others elements. It is assumed that a particle cannot impact another element if it has already encountered an equipment.



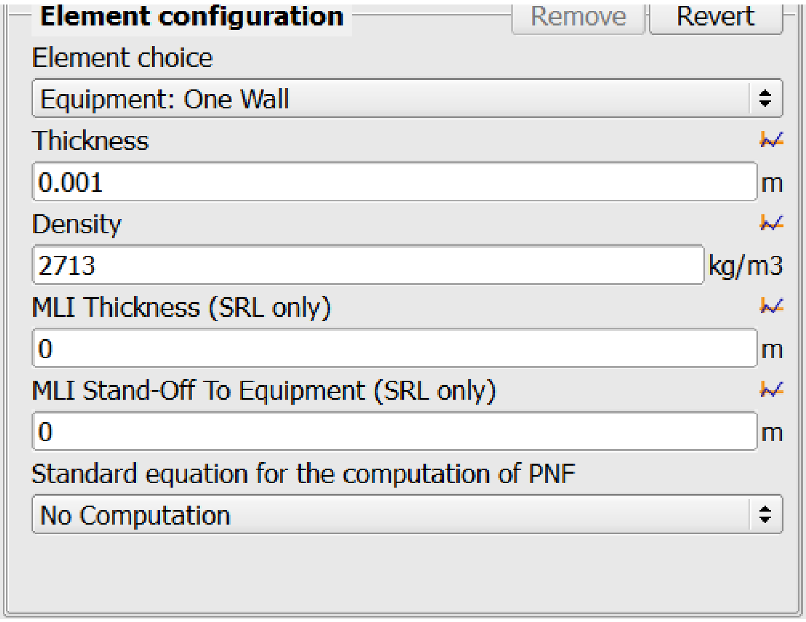
There is **no computation** of the numbers of penetrations on this object. However the element is taken into account in the overall computation as a shadowing surface.

If no other shape is hit, the equation chosen by the user is applied.

If one other shape is hit, the equation chosen by the user is applied. **If the ray hit "equipment OW", it will stop.**

If two other shape is hit, the equation chosen by the user is applied. **If the ray hit "equipment OW", it will stop.**

The ballistic limit equation used by default for all the configurations encountered is a **user-defined parametric equation** based on the SRL equation.



Element choice: Equipment: One Wall

Thickness: 0.001 m

Density: 2713 kg/m3

MLI Thickness (SRL only): 0 m

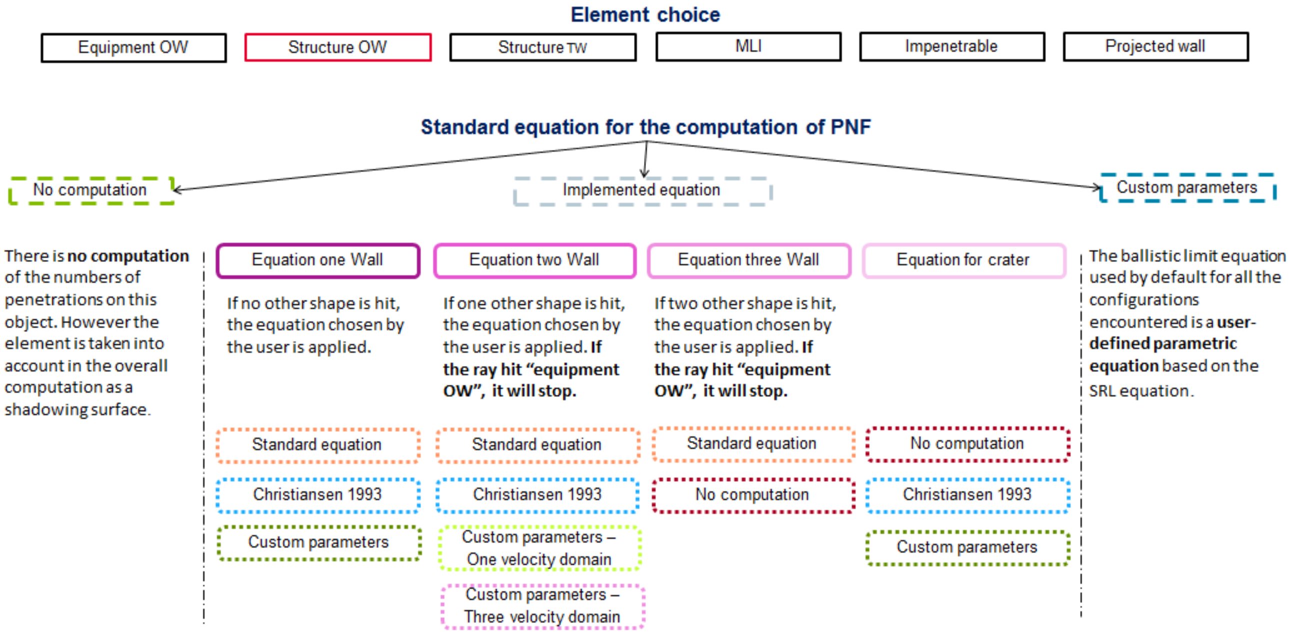
MLI Stand-Off To Equipment (SRL only): 0 m

Standard equation for the computation of PNF: No Computation

Figure II.9: Equipment one wall

b. Structure: One Wall

The **structure one wall** elements have no particular behaviour attached and can be used to describe the spacecraft at a structural level for example.



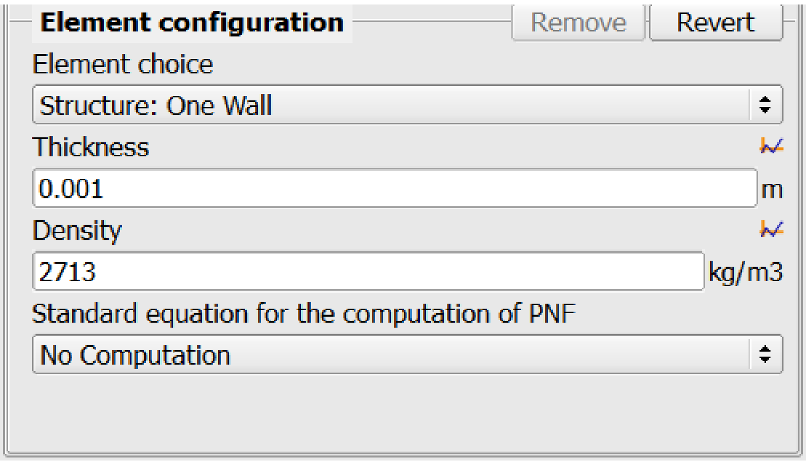
There is **no computation** of the numbers of penetrations on this object. However the element is taken into account in the overall computation as a shadowing surface.

If no other shape is hit, the equation chosen by the user is applied.

If one other shape is hit, the equation chosen by the user is applied. **If the ray hit "equipment OW", it will stop.**

If two other shape is hit, the equation chosen by the user is applied. **If the ray hit "equipment OW", it will stop.**

The ballistic limit equation used by default for all the configurations encountered is a **user-defined parametric equation** based on the SRL equation.



Element configuration

Element choice: Structure: One Wall

Thickness: 0.001 m

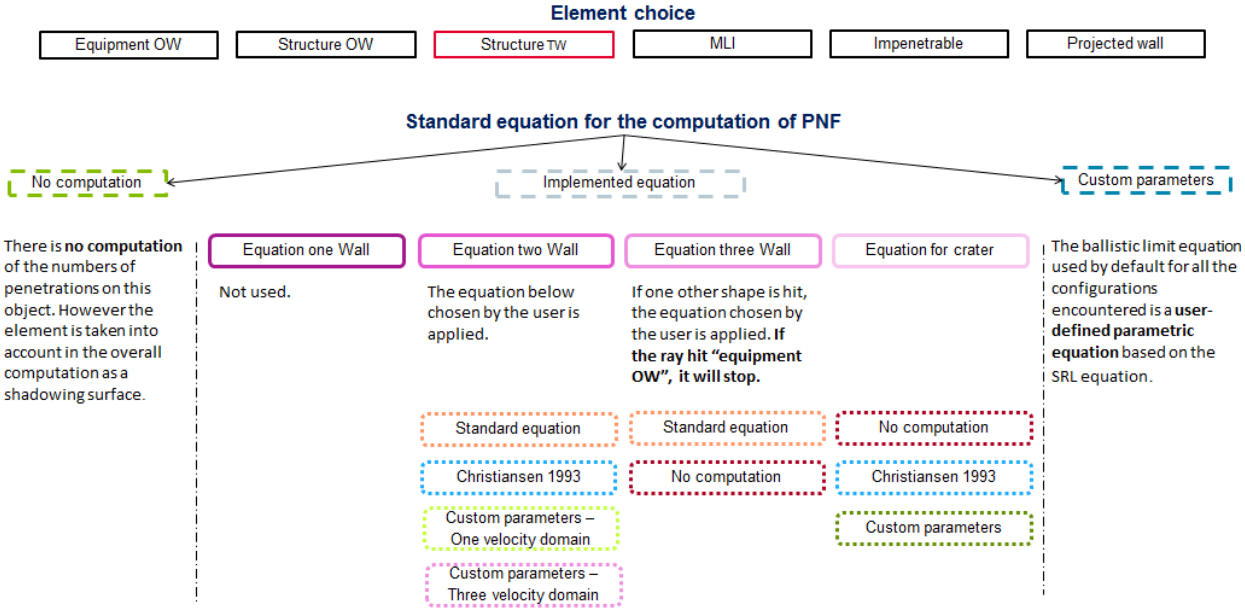
Density: 2713 kg/m3

Standard equation for the computation of PNF: No Computation

Figure II.10: Structural one wall

c. Structure: Two Wall

A **structure element two walls** are composed of two shapes; one modelled shape and one fictive shape defined by the user parameters in terms of spacing from the modelled shape, thickness, density, etc. It can be a honeycomb panel, for example.



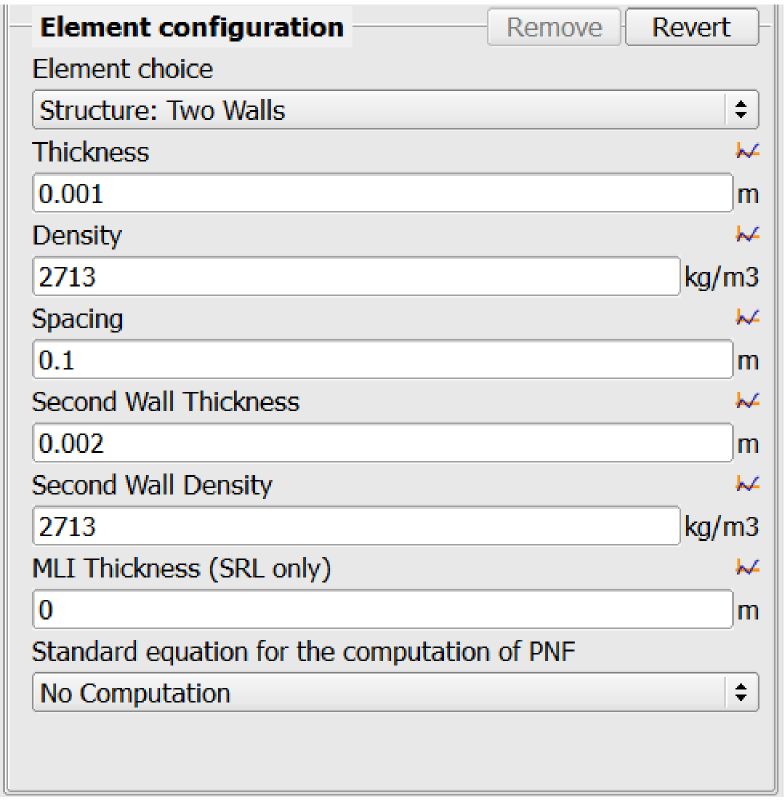
There is **no computation** of the numbers of penetrations on this object. However the element is taken into account in the overall computation as a shadowing surface.

Not used.

The equation below chosen by the user is applied.

If one other shape is hit, the equation chosen by the user is applied. **If the ray hit "equipment OW", it will stop.**

The ballistic limit equation used by default for all the configurations encountered is a **user-defined parametric equation** based on the SRL equation.



Element choice
Structure: Two Walls

Thickness
0.001 m

Density
2713 kg/m3

Spacing
0.1 m

Second Wall Thickness
0.002 m

Second Wall Density
2713 kg/m3

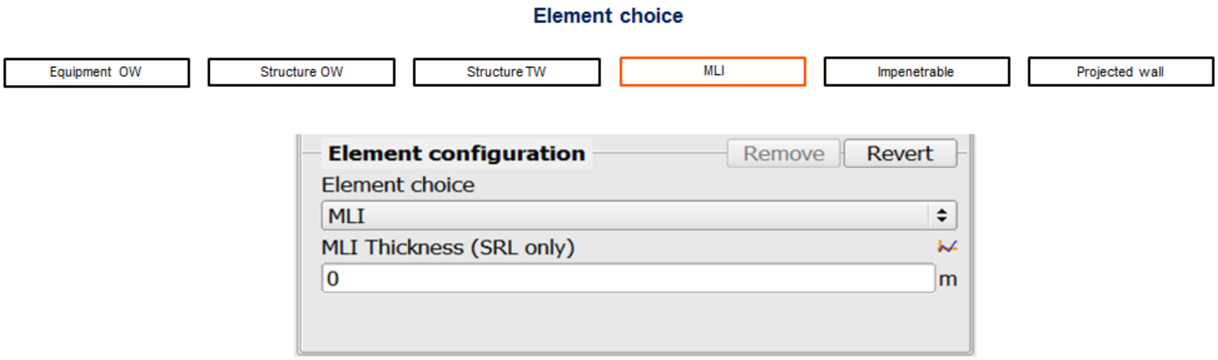
MLI Thickness (SRL only)
0 m

Standard equation for the computation of PNF
No Computation

Figure II.11: Structural two walls

d. MLI

The **MLI** elements can only be used associated to the SRL equation in the case of stand-of MLI. If the **MLI** element is associated with an element which is not using the SRL equation, it will be considered as a shadowing element.

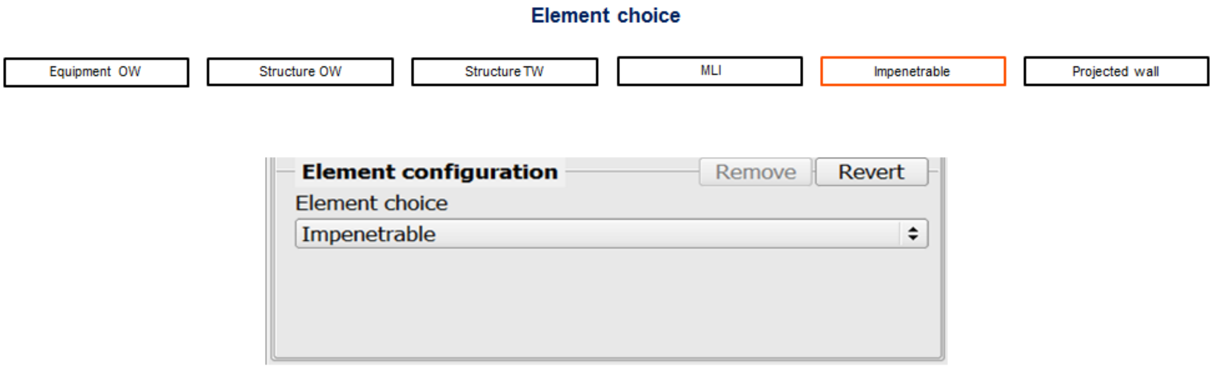


Element choice
MLI
MLI Thickness (SRL only)
0 m

Figure II.12: MLI wall

e. Impenetrable

If a ray hit an **impenetrable** element, it stops.

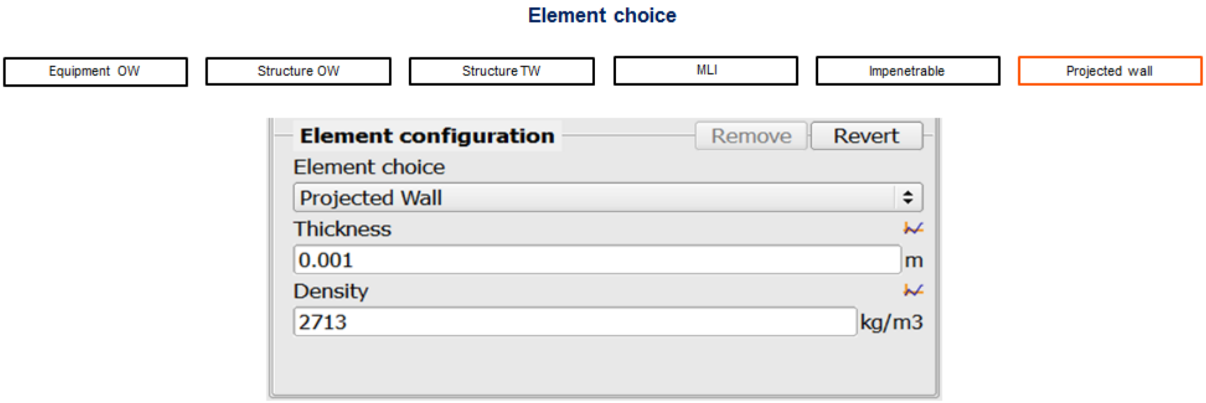


Element choice
Impenetrable

Figure II.13: Impenetrable wall

f. Projected wall

If a ray hit a **projected wall** element, it will add it thickness to the emitted surface thickness.



Element choice
Projected Wall
Thickness
0.001 m
Density
2713 kg/m3

Figure II.14: Projected wall

1. 2 Meshing

The entire geometrical model does not have to be meshed to perform a debris analysis. The impact/penetration computation is only performed on the meshed elements, however non-meshed elements are considered in the computation with their properties defined in the model tab. A group of shapes can be stored in a group-specific item. It allows obtaining results on the output file.

a. Meshing choice

The meshing of shapes consists in splitting the surfaces according to a certain number of meshes in each principal direction: this is the “a, b & c” meshing library.

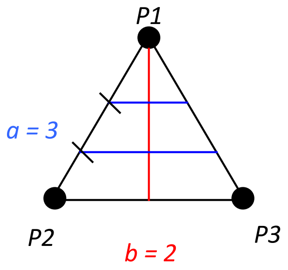
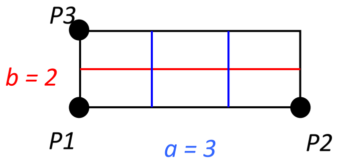
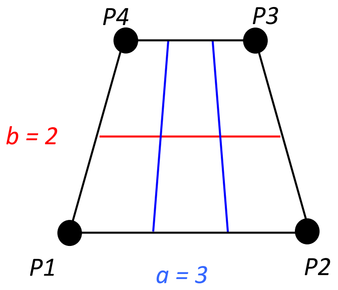
For the debris application, there is two ways of setting the “a, b & c” parameters: either directly, or by choosing a Length. In this case, the “a, b & c” parameters will be adjusted so that the characteristic size of the meshes correspond to the chosen length. For revolution shapes, a second parameter is available: the maximum angle which allows defining a minimum angular sector to mesh with (“a” parameter).

The three parameters: “a”, “b”, “c” define the number of desired intervals in a specific direction.

- Parameters “a” & “b”: refer to all two-dimensional elemental surfaces.
- Parameter “c”: refers to three-dimensional surfaces.

The following shapes may be distinguished:

- Triangle, rectangle, quadrangle

Triangle	Rectangle	Quadrangle
		

- Disk, cylinder, cone, parabola, antenna, sphere

Parameter	Segmentation based on:
a	angular sector

Parameter	Shape	Segmentation based on:
b	disk	radius
	cone, cylinder	height
	sphere, parabola	curvilinear abscissa in iso
	antenna	radius

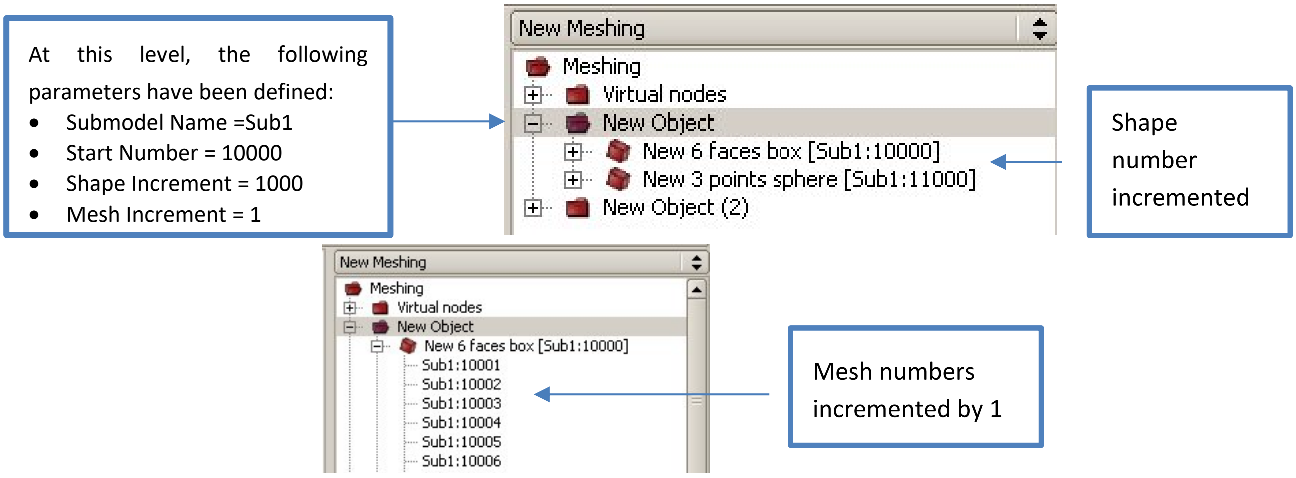
- Polygons

The meshing corresponds to the number of desired intervals in a specific direction. This does not apply to the polygon which is a particular case because it is divided in triangles and, consequently, only the "a" parameter will have an impact as regards the detail of surface triangulation.

b. Meshing numbering

It consists in numbering the surfaces for assigning a number to meshes and defining an increment value. Actually, it is an increment used for the global numbering of the model or a sub-part of the model to obtain a mesh network with a meaningful numbering system.

Example:



At this level, the following parameters have been defined:

- Submodel Name =Sub1
- Start Number = 10000
- Shape Increment = 1000
- Mesh Increment = 1

Shape number incremented

Mesh numbers incremented by 1

Figure II.15: Inheritance principle for numbering example

c. Meshing groups

During the computation, the different quantities are cumulated on meshes. If the user wants to have integrated quantities on a reduce part of the spacecraft, the mesh level or even the surface level may be too fine. That is why the concept of groups has been naturally introduced. A group is thus a set of surfaces on which integrated quantities are cumulated (by cumulating the integrated quantities on the corresponding surfaces). The corresponding group quantities are stored in spread sheet report file for direct text access.

Two types of groups exists, the standard group will compute the cumulated probability of failure and the Craterized group will compute the cumulated craterized area inside the group.

The Probability of No-Failure is only computed on a group level.

To create a group from selection:

1. Open the meshing model
2. Select one or several shapes of the geometrical model representing the set of shapes of the group to account for.
3. Via the right click menu, select **Create specific meshing item -> Group or Caterized group**.
4. A window opens (see Figure II.16). In the General Tab, it can be checked that the correct shapes are referenced.

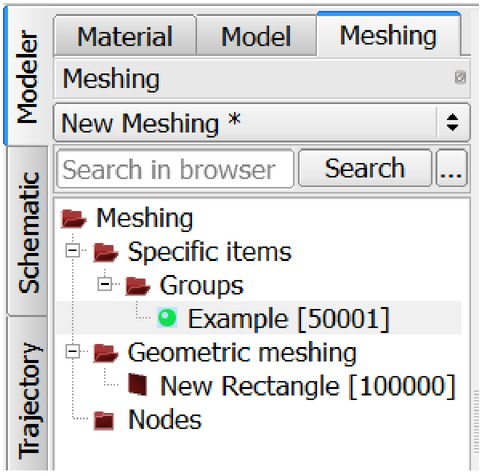


Figure II.16: Meshing group

Parameters need to be provided for Caterized groups:

- Maximal caterized surface – This is the maximal acceptable caterized surface on the shapes inside the group, if this value is set too high the resolution of the distribution function computed will not be acceptable.
- Number of bins – This is the discretization of the distribution function that will be outputted. If this value is too low the computation will not be accurate, 1000 is the recommended value.

For example if the maximal caterized surface is set to 0.02m² and the number of bins to 1000 the distribution function will be computed with a resolution of 0.02/1000 = 2e-5m².

2. Backward ray tracing as a support to physical equation

The fluxes from the environment model are projected onto the satellite geometry allowing tracing the trajectory of each particle through the satellite structure. It tracks which layer of which material have been impacted by the particle before hitting the equipment. On each ray, application of standards IADC and ECSS recommended ballistic equations allows the software to check whether or not the particle being traced penetrates the sensitive element. Shadowing effects are captured by Systema-Debris.

Figure II.17 shows an example of the backward raytracing of Systema-Debris.

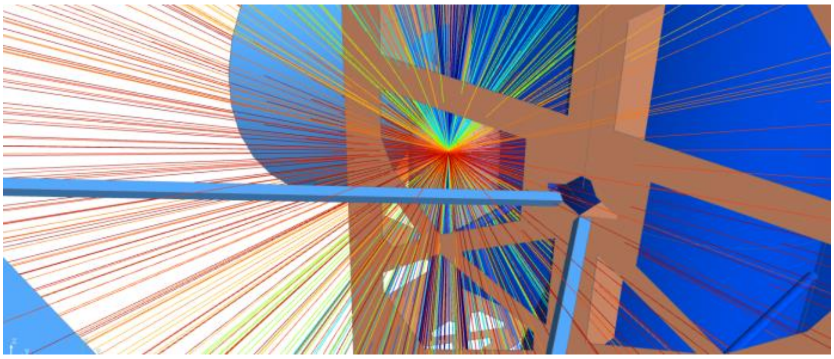


Figure II.17: Backward ray tracing example

3. Ballistic limit equations

Ballistic Limit Equations (BLE) are semi-empirical equations, developed from HVI tests and analysis and used for numerical modelling of the MMOD risk assessment. They are used to evaluate the **critical diameter** d_c of a configuration as function of its design and the characteristic of the particle impactor.

BLE for a specific configuration is a function f of the form:

$$d_c = f\left(V, \theta, t_w, \rho_w, \rho_p, \sigma, k\right)$$

$$Conditions\ \{A, B, C \dots\}$$

With usual parameters:

- V = projectile velocity
- ρ_t = target density
- t_t = target thickness
- θ = impact angle from target normal
- ρ_p = projectile density
- σ = Yield stress or Brinell hardness of the target
- k a damage parameter allowing to select failure mode other than penetration
- $Conditions\ \{A, B, C \dots\}$ a set of conditions that have to be verified for the equation to be valid.

Critical diameterd_c: if the incoming particle is smaller than d_c , the surface successfully stops the particle. If the incoming particle is bigger than d_c the surfaces fails at stopping the particle.
This critical diameter linked with an environment model and geometry can be used for computing the penetrating flux.

Main difficulty of risk assessment is to use the correct equation to describe:

- The geometry encounters by the penetrating particle.
- The type of failure of the sensitive element.

4 parametric equations are implemented in Systema-Debris:

- One wall standard equation,
- Two walls standard equation,
- Schäfer Ryan Lambert (SRL) equation,
- Crater sized standard equation.

1. 1 One wall standard equation

For the single-wall configuration, user can customize the coefficient in order to obtain the desire BLE as shown equation (1) provided in [4].

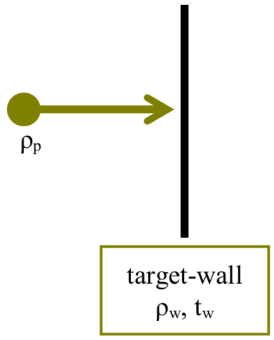


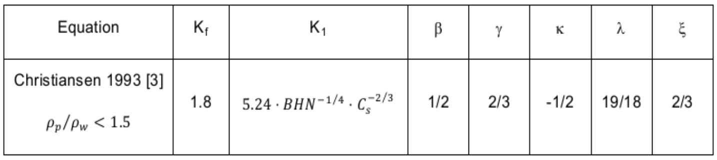
Figure II.18: Single wall configuration

$$d_c = \left[\frac{t_w}{K_f \cdot K_1 \cdot v^{\gamma} \cdot (\cos\theta)^{\xi} \cdot \rho_p^{\beta} \cdot \rho_t^{\kappa}}\right]^{1/\lambda} \qquad (1)$$

Where

- **BHN** = Brinell hardness of the target
- **Ct** = speed of sound in the target (km/s)
- **dc** = critical projectile diameter on threshold of given damage mode (cm)
- $\mathbf{K_f}$ = damage parameter, either 1.8, 2.2, or 3.0 for perforation, detached spall or incipient attached spall
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\mathbf{t_w}$ = rear wall thickness (cm)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); θ = 0° impacts normal to target
- $\boldsymbol{v}$ = projectile velocity (km/s)

It is possible to use the predefined Christiansen equation (Table II-1) or to modify the parameters of the equation directly into the Systema-Debris interface.



Equation	K_f	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1.8	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Table II-1: Christiensen direct impact equation

1. 2 Two walls standard equation

For the double-wall configuration, user can also customize the coefficient in order to obtain the desire BLE as shown equation (2) provided in [4].

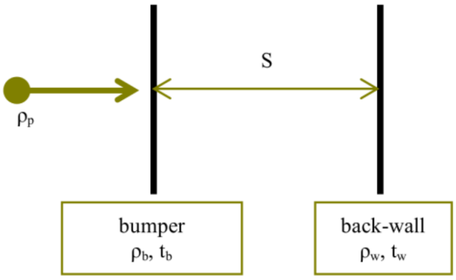


Figure II.19: Double-wall configuration

$$d_c = \left[\frac{t_w + k_2 \,.\, t_b^{\mu} \,.\, \rho_b^{\nu_2}}{k_1 \,.\, \rho_p^{\beta} \,.\, v^{\gamma} \,.\, (\cos\theta)^{\xi} \,.\, \rho_t^{\kappa} \,.\, S^{\delta} \,.\, \rho_b^{\nu_1}}\right]^{1/\lambda} \qquad (2)$$

Where

- **dc** = critical projectile diameter at shield failure threshold (cm)
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\mathbf{t_w}$ = rear wall thickness (cm)
- $\mathbf{t_b}$ = bumper wall thickness (cm)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); note impact at $\boldsymbol{\theta}$ =0 deg is normal to the target.
- $\boldsymbol{v}$ = projectile velocity (km/s)
- **S** = spacing (cm)

It is possible to use the predefined Wipple Shield equation (Table II-2) or to modify the parameters of the equation directly into the Systema-Debris interface.

Equation		K_1	K_2	β	δ	γ	κ	λ	μ	ν_1	ν_2	ξ
Christiansen 1993 [3]	V<3 km/s	$0.6 \cdot (\sigma_{y,ksi}/40)^{-1/2}$	$(\sigma_{y,ksi}/40)^{-1/2}$	1/2	0	2/3	0	19/18	1	0	0	5/3
	V>7 km/s	$\left[3.918(\sigma_{y,ksi}/70)^{1/3}\right]^{-3/2}$	0	1/2	-1/2	1	0	3/2	0	1/6	0	1

Table II-2: Wipple Shield indirect impact equation

The Wipple Shield equations assume that the bumper thickness is adequate to fragment the projectile at high velocities. For undersized bumpers, the computing process is presented below.

1. 3 Undersized bumper modelling with Systema-Debris

The conditions of validity of the Christiansen equation are:

- The material of the first wall have the **desirable qualities of a bumper**.
- The **standoff between the first wall and the rear wall** (S) **must be high enough** in regard of the critical diameter to allow the expansion of the debris cloud, typically a factor 15 [1].
- The **bumper must be thick enough to fragment the particle** and verifies "the bumper condition". If this condition is not validated, the Cour-Palais/Christiansen equation is used to modelling an undersized bumper.

a. Undersized thickness bumper

Christiansen equations assume that the bumper thickness is adequate to fragment the projectile at high velocities, i.e., the bumper thickness must verify:

$$\mathrm{t_b}^{\mathrm{sized}} = \frac{\mathrm{c_b\, d_c\, \rho_p}}{\rho_\mathrm{b}} \qquad (3)$$

Where

- $\mathbf{t_b}^{\mathbf{sized}}$ = bumper thickness sized (cm)
- $\mathbf{c_b}$ = coefficient 0.25 when S/d < 30, and $\mathrm{c_b}$ = 0.2 when S/d ≥ 30
- $\mathbf{d_c}$ = projectile diameter (cm)
- $\boldsymbol{\rho}_\mathbf{p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho}_\mathbf{t}$ = target density (g/cm3)

for Vn = 7 km/s. If:

- $\mathrm{t} \geq \mathrm{t_b}^{\mathrm{sized}}$: the Christiansen equations can be applied. However the bumper is oversized and extra bumper mass will not improve shielding performance.
- $\mathrm{t} = \mathrm{t_b}^{\mathrm{sized}}$: the bumper is optimized. The protection is optimal.
- $\mathrm{t} \leq \mathrm{t_b}^{\mathrm{sized}}$: the bumper is undersized, which means that the equations overestimate the performance of the shield. Indeed, the bumper is too thin to allow a complete breakup of the projectile. Depending on how undersized is the bumper; the particle upon impact will be partially fragmented to unfragmented. The Christiansen equations have been modified to model undersized bumper.

The computation process implemented on Systema-Debris to compute the critical diameter to undersized bumper is described in [3]. Here after some elements.

A factor F2* was introduced in the Christiansen equation to take into account thinner shields effects:

- If the shield thickness approaches zero, the back-up wall acts as a single wall.
- If the shield thickness is sized, the equation converges into the double-wall equation

This leads to a general formulation of F2*:

$$F_2^{\,*} = \begin{cases} 1 \; if \; \frac{t_b}{d_p} \geq \left(\frac{t_b}{d_p}\right)_{crit} \\ r_{s/D} - 10\,\frac{t_b}{d_p}\left(r_{s/D} - 1\right) + 25\left(\frac{t_b}{d_p}\right)^2 \left(r_{s/D} - 1\right) \; if \; \frac{t_b}{d_p} < \left(\frac{t_b}{d_p}\right)_{crit} \end{cases} \qquad (4)$$

With $\mathrm{r_{s/D}}$ the ratio between the requirement wall thickness to stop the particle if no bumper is present and the requirement thickness when the bumper is properly sized $\frac{\mathrm{t_b}}{\mathrm{d_p}} = \left(\frac{\mathrm{t_b}}{\mathrm{d_p}}\right)_{\mathrm{crit}}$ at a velocity of 7 km/s.

$$r_{s/D} = \frac{t_w,\ \text{required at } (t_b = 0)}{t_w,\ \text{required at } \left(\frac{t_b}{d_p} = \left(\frac{t_b}{d_p}\right)_{crit}\right)} \qquad (5)$$

Finally solution is corrected (for V > 7 km/s):

$$d_{c\ Modify\ eq} = d_{c\ 2\ wall} * {F_2}^{*\ -2/3} \qquad (6)$$

Figure II.20 illustrates the critical diameter as a function of impact particle velocity for different values of the bumper thickness t_b.

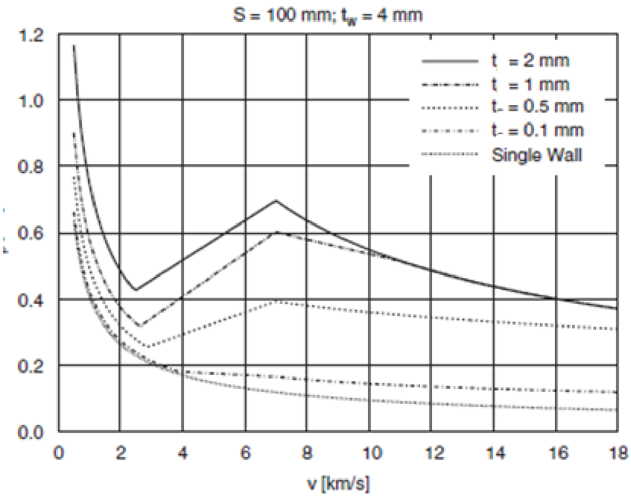
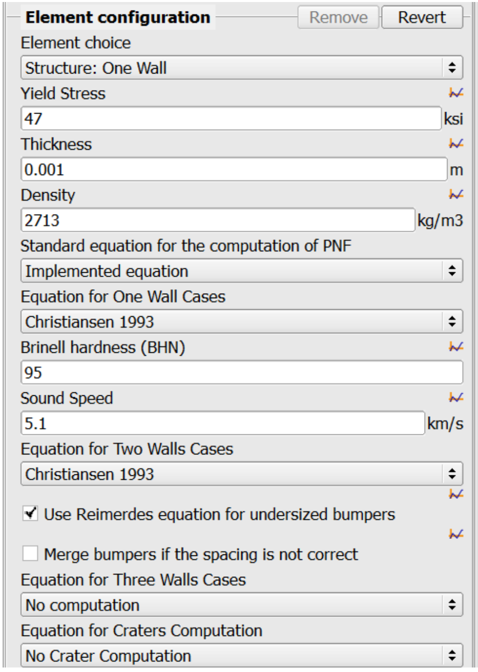


Figure II.20: **Critical particle diameter as a function of impact velocity and various shield thicknesses—modified equations [4].**

Using the “use Reimerdes equation for undersized bumpers" option in the Christiansen equation allows the user to model undersized bumper on Debris (Figure II.21).



Element configuration

Element choice: Structure: One Wall

Yield Stress: 47 ksi

Thickness: 0.001 m

Density: 2713 kg/m3

Standard equation for the computation of PNF: Implemented equation

Equation for One Wall Cases: Christiansen 1993

Brinell hardness (BHN): 95

Sound Speed: 5.1 km/s

Equation for Two Walls Cases: Christiansen 1993

☑ Use Reimerdes equation for undersized bumpers

☐ Merge bumpers if the spacing is not correct

Equation for Three Walls Cases: No computation

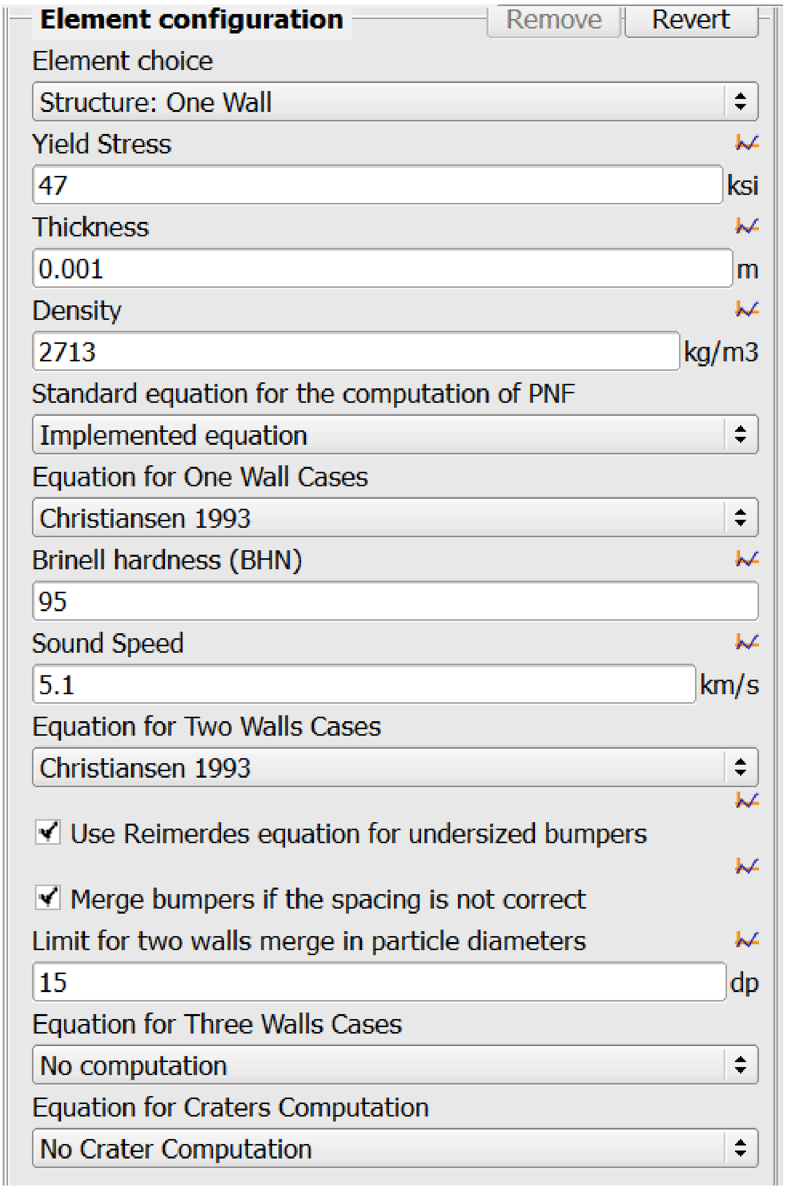
Equation for Craters Computation: No Crater Computation

Figure II.21: Reimerdes equation for undersized bumpers option.

b. Undersized thickness bumper

Christiansen equations is valid when the standoff between the first wall and the rear wall (S) must be high enough in regard of the critical diameter to allow the expansion of the debris cloud.

An option on Systema-Debris (Figure II.22) allow merging two shapes thickness is the standoff is not correct, by default S/d < 15. The user can change the ratio.



Element configuration

Element choice: Structure: One Wall
Yield Stress: 47 ksi
Thickness: 0.001 m
Density: 2713 kg/m3
Standard equation for the computation of PNF: Implemented equation
Equation for One Wall Cases: Christiansen 1993
Brinell hardness (BHN): 95
Sound Speed: 5.1 km/s
Equation for Two Walls Cases: Christiansen 1993
☑ Use Reimerdes equation for undersized bumpers
☑ Merge bumpers if the spacing is not correct
Limit for two walls merge in particle diameters: 15 dp
Equation for Three Walls Cases: No computation
Equation for Craters Computation: No Crater Computation

Figure II.22: Merge bumper if spacing is not correct

1. 4 SRL equation

The SRL equation is a ballistic limit equation developed for the case of a double wall configuration or a sandwich panel with honeycomb core placed in front of a back wall (cf Figure II.23).

The objective of this BLE is to consider explicitly the three plate thicknesses, materials and spacing and also the presence of MLI. Thus it can be used at a component level in order to predict the probability of no failure of equipment such as fuel and heat pipes, pressure vessels, electronic boxes, harness, and batteries placed behind the satellite structure wall. This equation is described in [6].

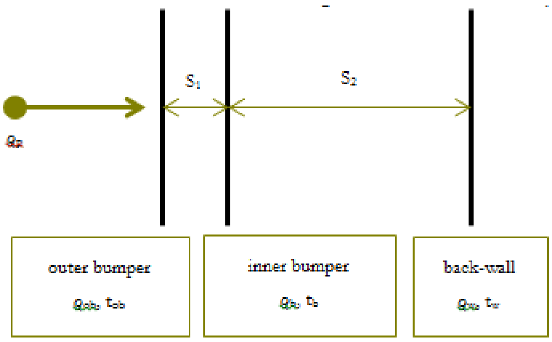


Figure II.23: SRL configuration

The critical projectile diameter in the ballistic velocity regime ($V_n \leq v_{t1,n}$) is given by:

$$d_{p,crit} = \left[\frac{\frac{(t_w^\alpha + t_b)}{K_{3S}} \left(\frac{\sigma_{y,ksi}}{40} \right)^{1/2} + t_{ob} + K_{MLI} \cdot t_{eq,MLI}}{0.6 \cdot (\cos\theta)^\delta \cdot \rho_p^{1/2} \cdot v^{2/3}} \right]^{\frac{18}{19}}$$

and in the hypervelocity regime ($V_n \geq v_{t2,n}$) is:

$$d_{p,crit} = \frac{1.155 \left(S_1^{1/3} (t_b + K_{tw} \cdot t_w)^{2/3} + K_{S2} \cdot S_2^\beta \cdot t_w^\gamma \cdot (\cos\theta)^{-\varepsilon} \right) \left(\frac{\sigma_{y,ksi}}{70} \right)^{1/3}}{K_{3D}^{2/3} \cdot \rho_p^{1/3} \cdot \rho_{ob}^{1/9} \cdot v^{2/3} \cdot (\cos\theta)^\delta}$$

In the shatter velocity regime a linear extrapolation is made between the critical diameter limits of these two regimes:

$$d_{p,crit} = d_{p,crit}(v_{t1}) + \frac{d_{p,crit}(v_{t2}) - d_{p,crit}(v_{t1})}{v_{t2} - v_{t1}} (v - v_{t1})$$

For further information on the use of this BLE, in particular the application to equipment, refer to [6].

1. 5 Crater sized equation

The parametric form of the Crater Size Equation for the penetration depth P is implemented into Systema-Debris:

$$\mathrm{P} = k_1 \, . \, d_p^{\lambda} \, . \, \rho_p^{\beta} v^{\gamma} \, . \, (\cos\theta)^{\xi} \, . \, \rho_t^{\kappa} \qquad (7)$$

Where

- **dp** = projectile diameter (cm)
- $\boldsymbol{\rho_p}$ = projectile density (g/cm3)
- $\boldsymbol{\rho_t}$ = target density (g/cm3)
- $\boldsymbol{\theta}$ = impact angle from target normal (deg); note impact at q=0 deg is normal to the target.
- ***v*** = projectile velocity (km/s)

The diameter D of the crater is given by:

$$\mathrm{D} = k_c \, . \, P \qquad (8)$$

with Kc varying from 1 to 10 depending on the nature of the target. The factor 2 normally seen in this equation has to be included in the k1 parameter.

It is possible to use the predefined Christiansen equation (Table II-3) or to modify the parameters of the equation directly into the Systema-Debris interface.

Equation	K_c	K_1	β	γ	κ	λ	ξ
Christiansen 1993 [3] $\rho_p/\rho_w < 1.5$	1	$5.24 \cdot BHN^{-1/4} \cdot C_s^{-2/3}$	1/2	2/3	-1/2	19/18	2/3

Table II-3: Crater equation parameter

For further information on the use of this equation refer to [4].

1. 6 Python equations

Python functions can be defined in the python file in the processing box. The file will contains functions with precise arguments that will be called by Systema Debris to compute the critical diameter of a configuration.

a. Failure computation

For failure computation the python function takes 8 arguments in the following order:

1. Velocity of the incoming particle (km/s).
2. Density of the incoming particle (g/cm3).
3. Cosine of the impact angle relative to the rear wall (-).
4. Number of wall encountered, one if the equipment is in direct view of space and up to 3 walls (no computation can be performed with a 4 wall configuration).
5. An array of thicknesses of each of the walls, the first element always being the thickness of the rear wall (cm) for example [0.1, 0.05] for an equipment wall thickness of 0.1cm and a bumper of 0.05cm.
6. An array of densities of each walls (g/cm3)
7. An array of the yields of each walls (ksi), some value may be Python None if they are not defined in the model (for example if a shape is defined as a double wall only the rear wall yield is specified).
8. An array of spacings between each walls, the first value being the spacing between the rear wall and the first bumper.

The function returns the critical diameter of the configuration in cm.

Here is an example of a Python script giving Christiansen OW equation results for a one wall and 100cm for the rest:

```
import math

def myEquation(v, rho_p, cos_alpha, nWalls, t_walls, rho_walls, target_yields, spacings):
    # Compute the OW critical diameter
    if nWalls == 1:
        criticalDiam = math.pow(t_walls[0]*math.pow(target_yields[0],
0.25)*math.pow(rho_walls[0]/rho_p, 0.5)/(1.8*5.24*math.pow(v*cos_alpha/5.1, 2./3.)),
18./19.)
    else:
        criticalDiam = 100
    return criticalDiam
```

b. Crater computation

Crater equations have the same parameters as the failure computation except an added parameter in the beginning being the particle diameter in cm. The function returns the crater diameter.

Here is an example of a the function computing the Christiansen crater diameter for a OW case:

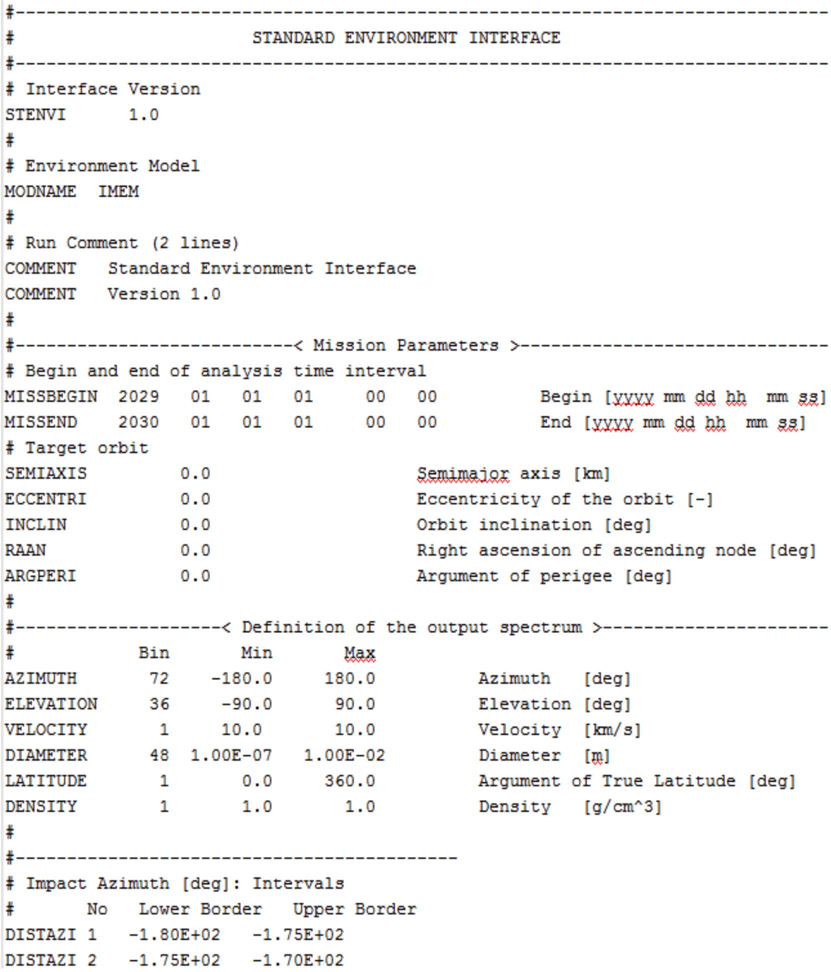
```
import math

def testCrater1(dParticle, v, rho_p, cos_alpha, nWalls, t_walls, rho_walls,
target_yields, spacings):
    # Compute the OW ccrater diameter
    if nWalls == 1:
        craterDiam = 2.*5.24*math.pow(dParticle, 19./18.)*math.pow(target_yields[0], -
0.25)*math.pow(rho_walls[0]/rho_p, -0.5)*math.pow(v*cos_alpha/5.1, 2./3.)
    else:
        craterDiam = 0
    return craterDiam
```

4. Generation of a realistic debris/micrometeoroid environment

Various type of environment can be used, ranging from detailed to simplified isotropic environment on 4π steradian. The STENVI format, recommended standard by the IADC, is used to feed the computation module. Environment models used are for example MASTER which is the ESA standard, ORDEM and MEME which are the NASA standards. Models generate fluxes of particles around the concerned orbit. Those fluxes give information about the particles velocity, density and size.
The STENVI is a standardized interface between MMOD environment models and damage prediction tools. It is the output format of MASTER. To use other environments, the user needs to build a STENVI file or convert the outputs of other environment tools like MEM.

STENVI file contains the flux contribution for each bin as a function of:
- impact azimuth,
- impact elevation,
- impact velocity,
- particle diameter,
- argument of true latitude,
- particle density.



```
#-------------------------------------------------------------------------------
#                       STANDARD ENVIRONMENT INTERFACE
#-------------------------------------------------------------------------------
# Interface Version
STENVI      1.0
#
# Environment Model
MODNAME   IMEM
#
# Run Comment (2 lines)
COMMENT   Standard Environment Interface
COMMENT   Version 1.0
#
#---------------------------< Mission Parameters >------------------------------
# Begin and end of analysis time interval
MISSBEGIN  2029   01   01   01     00   00          Begin [yyyy mm dd hh  mm ss]
MISSEND    2030   01   01   01     00   00          End [yyyy mm dd hh  mm ss]
# Target orbit
SEMIAXIS         0.0                      Semimajor axis [km]
ECCENTRI         0.0                      Eccentricity of the orbit [-]
INCLIN           0.0                      Orbit inclination [deg]
RAAN             0.0                      Right ascension of ascending node [deg]
ARGPERI          0.0                      Argument of perigee [deg]
#
#--------------------< Definition of the output spectrum >----------------------
#            Bin       Min       Max
AZIMUTH       72    -180.0     180.0          Azimuth   [deg]
ELEVATION     36     -90.0      90.0          Elevation [deg]
VELOCITY       1      10.0      10.0          Velocity  [km/s]
DIAMETER      48  1.00E-07  1.00E-02          Diameter  [m]
LATITUDE       1       0.0     360.0          Argument of True Latitude [deg]
DENSITY        1       1.0       1.0          Density   [g/cm^3]
#
#--------------------------------------------
# Impact Azimuth [deg]: Intervals
#       No   Lower Border   Upper Border
DISTAZI 1   -1.80E+02   -1.75E+02
DISTAZI 2   -1.75E+02   -1.70E+02
```

Figure II.24: Standard environment interface

For further information on the STENVI format see [[5]].

Table II-4 present the optimum bin definition parameters and Figure II**.25** present the geometrical bin definition.

	Bin	Max	Min
Azimuth	36	-180	180
Elevation	18	-90	90
Velocity	40	0.5	70.5
Diameter	60	0.001	10
Latitude	1	0	360
Density	5	0	5

Table II-4: STENVI bin definition

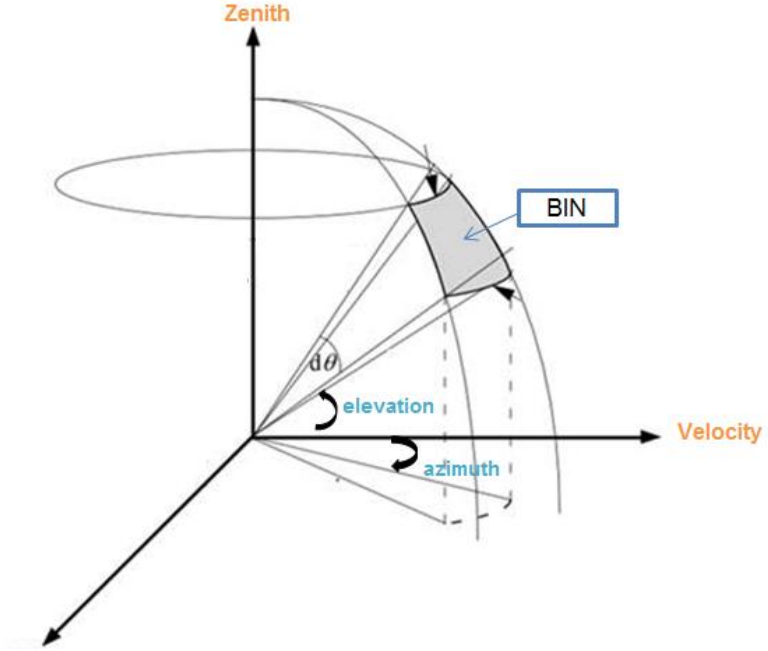


Figure II.25: Bin definition

5. Penetration flux

Penetrating flux is the cumulative penetration flux that the sensitive element withstands during the mission, averaged over the surface.

$$\boldsymbol{N} = \sum_{i=1}^{n} \boldsymbol{N}_i = \sum_{i=1}^{n} (\boldsymbol{FAt})_i \qquad (9)$$

With:

- $\boldsymbol{N}$ = the average number of penetration of the equipment,
- **F** = the penetration flux on the mesh i (penetration/year/m2),
- **A** = the surface of the mesh i (m2) and
- **t** = the mission time.

Once the user has created his model, mesh and environmental input files, the processing needs to be set up to launch the incident and penetration flux computation.

To launch the Debris computation, the user needs to:

1 – Double click or drag and drop the Debris module.

2 – Edit or activate option of Debris module.

3 – Add the environments files by right click to activate the file.

4 – Provide a python function library file if using custom Python equations in the model.

5 – Configure the Debris and common tab (Figure II.28).

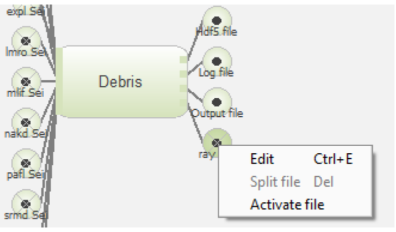


Figure II.26: Activation of input/output files

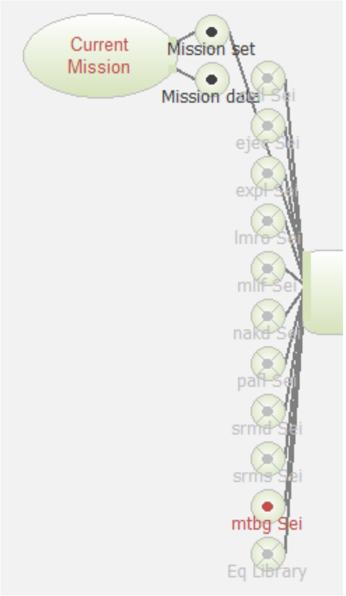
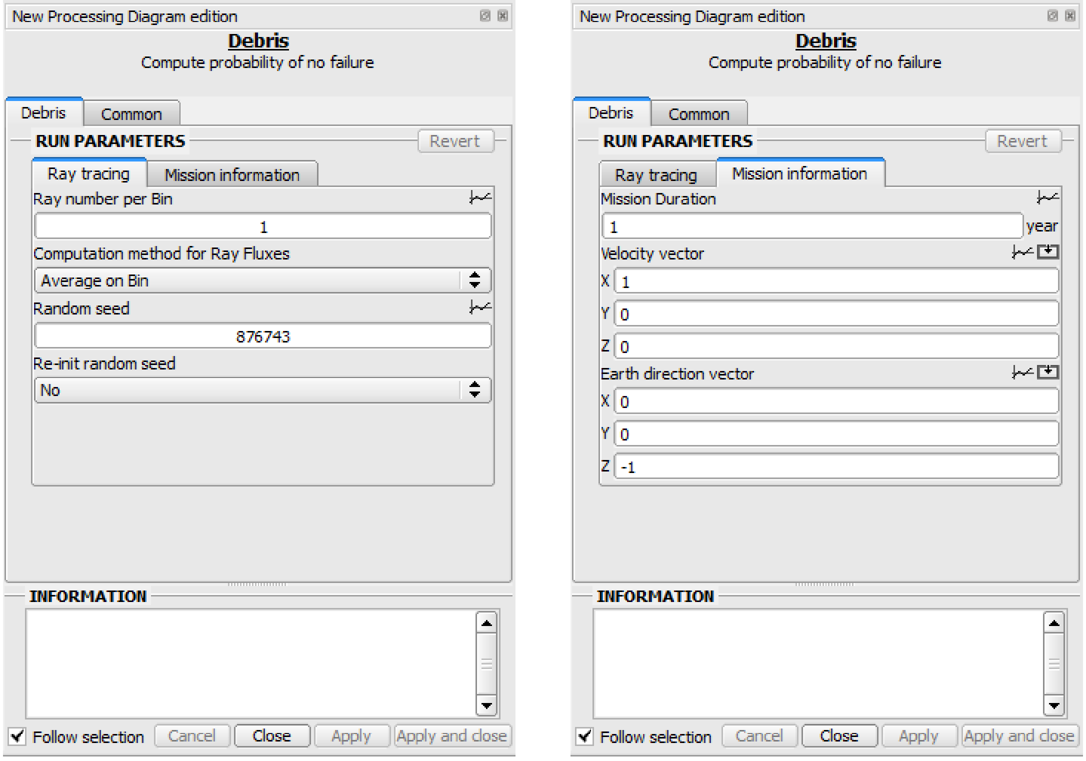


Figure II.27: Input files definition



Ray number per Bin: 1
Computation method for Ray Fluxes: Average on Bin
Random seed: 876743
Re-init random seed: No

Mission Duration: 1 year
Velocity vector: X 1, Y 0, Z 0
Earth direction vector: X 0, Y 0, Z -1

Figure II.28: Run parameters of Systema-Debris

Ray tracing

It allows selecting options concerning the “ray tracing” computation.

The random seed corresponds to the seed used in the algorithm which defines the position of the rays on an element.

If the seed is reinitialized, the random numbers sequence is the same for each element of the model. It allows keeping the same results when moving the objects in the tree structure of the model.

Mission information

It allows defining the pointing of the satellite in the model reference frame and the duration of the mission.

Debris can now be launch.

6. Probability of Failure

From the penetration flux, the probability of failure (if the failure is the penetration) can be computed using a Poison law.

$$P = 1 - e^{-N} \qquad (10)$$

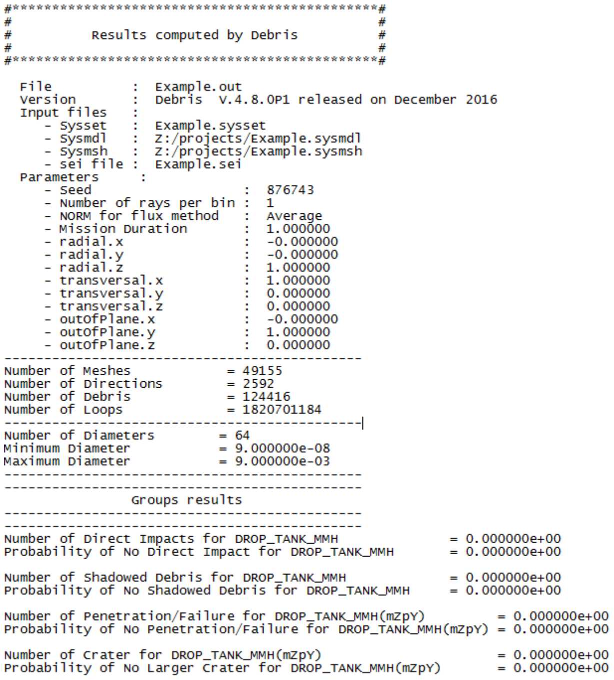
with $\boldsymbol{P} \in [\boldsymbol{0}, \boldsymbol{1}]$ the probability of failure of the equipment due to a micrometeroid impact.

Systema-Debris has two output types to support analysis: a text file (.out) and the possibility to visualize a color risk contour on the 3D geometry (.H5).

The text file contains the following information:

- **Area [m²]:** Area of the selected mesh.
- **Number of Craters [1/m²/yr]:** Number of Craters with a crater surface larger than the user specified surface.
- **Number of Direct Impacts [1/m²/yr]:** Number of particles impacting directly the mesh.
- **Number of Penetrations [1/m²/yr]:** Number of particles with a diameter larger than the associated critical diameter.
- **Number of Shadowed Impacts [1/m²/yr]:** Number of particles encountering one or more elements during backwards ray tracing.
- **Relative crater area:** Area of Craters with a penetrating depth larger than the user specified depth relative to the area of the selected mesh.

Figure II.29 shows an example of the output file of Systema-Debris.



```
#**********************************************#
#                                              #
#          Results computed by Debris          #
#                                              #
#**********************************************#

  File          :  Example.out
  Version       :  Debris  V.4.8.0P1 released on December 2016
  Input files   :
     - Sysset   :  Example.sysset
     - Sysmdl   :  Z:/projects/Example.sysmdl
     - Sysmsh   :  Z:/projects/Example.sysmsh
     - sei file :  Example.sei
  Parameters      :
     - Seed                     :  876743
     - Number of rays per bin :  1
     - NORM for flux method     :  Average
     - Mission Duration         :  1.000000
     - radial.x                 :  -0.000000
     - radial.y                 :  -0.000000
     - radial.z                 :  1.000000
     - transversal.x            :  1.000000
     - transversal.y            :  0.000000
     - transversal.z            :  0.000000
     - outofPlane.x             :  -0.000000
     - outofPlane.y             :  1.000000
     - outofPlane.z             :  0.000000
---------------------------------------------
Number of Meshes              = 49155
Number of Directions          = 2592
Number of Debris              = 124416
Number of Loops               = 1820701184
---------------------------------------------|
Number of Diameters          = 64
Minimum Diameter             = 9.000000e-08
Maximum Diameter             = 9.000000e-03
---------------------------------------------
---------------------------------------------
                Groups results
---------------------------------------------
---------------------------------------------
Number of Direct Impacts for DROP_TANK_MMH              = 0.000000e+00
Probability of No Direct Impact for DROP_TANK_MMH       = 0.000000e+00

Number of Shadowed Debris for DROP_TANK_MMH             = 0.000000e+00
Probability of No Shadowed Debris for DROP_TANK_MMH     = 0.000000e+00

Number of Penetration/Failure for DROP_TANK_MMH(mZpY)         = 0.000000e+00
Probability of No Penetration/Failure for DROP_TANK_MMH(mZpY) = 0.000000e+00

Number of Crater for DROP_TANK_MMH(mZpY)                      = 0.000000e+00
Probability of No Larger Crater for DROP_TANK_MMH(mZpY)       = 0.000000e+00
```

Figure II.29: Results output example computed by Debris

Systema-Debris generates an output containing the same outputs as the text file for each mesh. This information can then be displayed on the meshing to produce images like these shown in Figure II.30. Note that the colours in this example are set to show high risk as red and low risk as blue with other colours for intermediate risk values. The colour-risk scale can be modified.

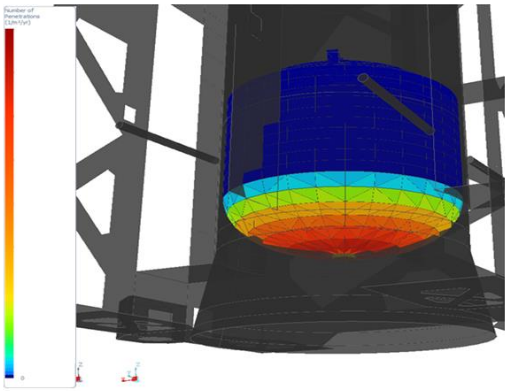


Figure II.30: Debris colour risk images

Systema-Debris can also display information on each ray like the ray type (Figure II.31), the velocity or the number of impacts (Figure II.32).

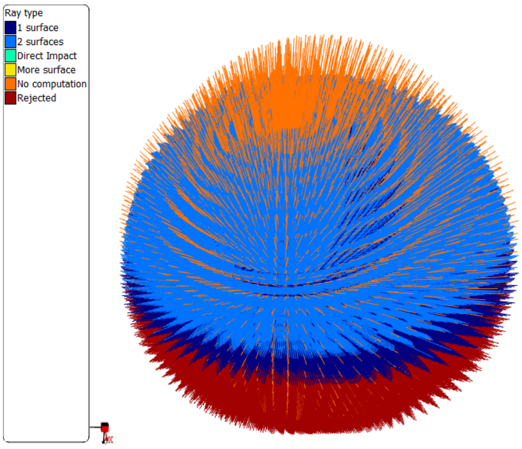


Figure II.31: Systema-Debris ray type display

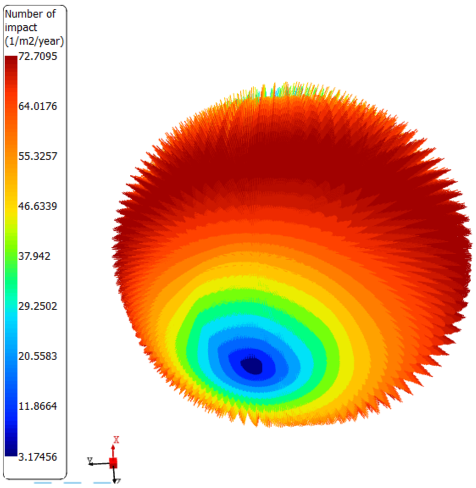


Figure II.32: Systema-Debris ray number of impact display

7. Generalities

The following tables present the inputs and outputs of Systema-Debris:

Module	File extension	
Debris	**.sei**	Environment files description.

Table II-5: INPUT File extension

Module	File extension	
Debris	**.h5**	Used to display the impact information. These file cannot be deactivated.
	.out	File containing the probabilities for the specified groups. This file can be opened with standard text editor. This file cannot be deactivated.
	.log	General information file gathering messages written during the computation. If the computation does not go to an end, an error message or a warning may be found in this file. This file cannot be deactivated.
	Optional: **.ray.h5**	Ray-tracing results

Table II-6: OUTPUT File extension

8. References

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[6] Frank Schäfer, Robin Putzar, Shannon Ryan, Michel Lambert (2009). Improving the significance of MMOD risk analysis by application oft he SRL ballistic limit equation. Fraunhofer Institute for High-Speed Dynamics.