REDSHIFT SOFTWARE TOOL FOR THE DESIGN AND COMPUTATION OF MISSION END-OF-LIFE DISPOSAL

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ABSTRACT

One of the deliverables of the ReDSHIFT H2020 project will be a software tool available to the scientific community and the wider public. The ReDSHIFT software is thought as a tool for spacecraft operators, space agencies and research institutions to design the end-of-life of any Earth satellite mission and to study the interaction with the space debris environment.

The tool will be able to calculate the disposal of the spacecraft, via impulsive manoeuvres and/or solar and drag sails, the spacecraft interaction with the debris environment and its re-entry.

The tool has been developed with two different user interfaces: a desktop one based on the ESA openSF integration framework and a web one to reach a wider base of users.

It is the aim of the ReDSHIFT tool to contribute in a proactive way to the mitigation of space debris problem via passive end-of-life mitigation.

1. INTRODUCTION

The impact of debris on the space activities has to be reduced by adopting a global strategy able to address the problem from different points of view, from the very beginning of the planning of a space mission. The choice of the orbit, of the spacecraft bus, of the spacecraft power system and propulsion, are all aspects that influence, and have to be optimized, having in mind not only the goal of the mission but also the minimization of the environmental impact of the spacecraft, in particular at its end-of-life. The space debris related aspects can be summarized in terms of: prevention, protection, mitigation and regulation. All these aspects are considered within the Horizon 2020 project ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies). ReDSHIFT has been funded by the European Union in the framework of the PROTEC Call of Horizon 2020 (see http://redshift-h2020.eu/).

The main goal of ReDSHIFT is to tackle the space debris issue from a global perspective using expertise from several different fields: long-term simulations of the space debris environment, astrodynamics, 3D printing, design for demise, protection and hypervelocity impact testing, legal and normative issues.

As a preliminary step, a thorough analysis of the currently adopted mitigation measures was performed to highlight their benefits and, possibly, their deficiencies in some aspects. This analysis was assisted by a number of simulations of the long-term evolution of the space debris environment showing the overall effects of these measures in a quantitative way [1]. In the following sections the most recent results of the project will be briefly described. In Sec. 2., a comprehensive study of the orbital dynamics in the whole circumterrestrial space allowed us to identify stability and instability regions with the aim of exploiting them to open preferential routes (we called them de-orbiting highways) minimizing the energetic requirements for the operators, thus improving the applicability of the disposal manoeuvres through the exploitation of the natural dynamics or the use of solar and drag sails. In Sec. 3 the generation of an initial assessment of the fragmentation and demise of a vehicle re-entering the Earth's atmosphere is described, performed by the Design for Demise (D4D) module. The last computational module presented in Sec. 4 is the one computing the Flux and Collision Probability: it performs an annual flux calculation and the collision probability calculation on the spacecraft demise trajectory. It relies on a comprehensive database of results computed as activity of the project and averaged over all the Monte Carlo runs [1]. One of the final outputs of the project is a software tool that provides to the scientific community and the wider public a powerful computational tool that summarises the theoretical and engineering findings, allowing the design of a space debris compliant mission (e.g., by suggesting the disposal trajectories and the technologies needed to achieve them, the best shielding opportunities for a given spacecraft and the possibility to produce it with additive manufacturing, etc.).

1.1. ReDSHIFT Software Toolkit Overview

Given the initial orbit of the spacecraft, the spacecraft characteristics in terms of its cross-sectional area and mass and the available Δv on-board, the feasible options for end-of-life disposal are given; namely end-of-life disposal via one or a sequence of manoeuvres, end-of-life disposal through the use of a solar or drag sail or end-of-life through a hybrid manoeuvre + solar/drag sail approach with fixed area-to-mass ratio A/m equal to 1 m^2/kg. This module is based on the study of the natural orbit evolution in the low to medium and geosynchronous regions that was performed to identify long-term stable and unstable orbits to be used as graveyard or re-entry trajectories, respectively. Details on this dynamical atlas can be found in [2][3][4]. The manoeuvre to reach such re-entry or graveyard conditions is calculated. Moreover, the re-entry can be enhanced through a sail. In this case, different strategies for sail attitude control and selected.

The available disposal solutions computed by this module are passed to the environmental protection module so that the effect of the given disposal strategy on the space debris environment is evaluated. This is done based on precomputed long-term simulations of the whole space debris environment, under different scenarios, to be used for the computation of the collision risk for the spacecraft in the disposal phase.

In the case the disposal trajectory is a re-entry one, the condition of the orbit at 120 km are used to verify the demisability of the spacecraft. This is done, by default, using some predetermined spacecraft configuration but the external user can also load a preferred configuration.

2. DISPOSAL MAPPING

This module is aimed at providing the user with the best disposal strategy from different orbital regimes (LEO to GEO). To this aim, different end-of-life disposal strategies are computed.

The main component of the module is a number of “maps” of the phase space indicating, for each orbital regime, the most convenient locations (in terms of Keplerian orbital elements) where a spacecraft should be moved at the end-of-life, to minimise its residual orbital lifetime or, conversely, to maximise its stability in that specific orbital altitude (e.g., in the case of the GEO graveyard orbits). Namely, the disposal mapping module will perform the following tasks:

- Provide the desirable manoeuvre to accelerate or improve the re-entry or graveyard injection.
- Characterise the natural re-entry time or the stability of a graveyard orbit.

In both cases, the initial epochs that can be assumed are either December 22, 2018 at 17:50:21 or June 21, 2020 at 06:43:12. The Disposal Mapping module outputs the orbital parameters of the selected disposal orbit, along with the Δv of the manoeuvre possibly required to reach that specific orbit from the last operational orbit. The Δv computation considers the possible use of area augmentation devices (when selected by the user) of fixed area-to-mass ratio. Alternatively, the optimal solar/drag sail area and its control strategy is selected by the sail module.

Moreover, the module outputs the ephemerides corresponding to all the available disposal trajectories. The information on the final disposal trajectories is shared with the D4D Assessment Tool (to identify possible re-entry risks related to the selected trajectory) and with the Environmental Protection Module (to compute the expected collisional flux on the disposed spacecraft along the selected disposal trajectory). Depending on the orbital regime, the Disposal Mapping module calculations include:

- a database search algorithm to look through the space phase maps and to identify the proper disposal regions (given the selected inputs);
- a simple schematic orbital propagation algorithm to propagate the status of the spacecraft from the selected disposal status up to the desired residual lifetime.

2.1. LEO Regime

The computation of the disposal strategy that can be adopted from a LEO is established on three possible solutions, namely,

1. a direct re-entry down to 120 km with a single impulsive manoeuvre;
2. a delayed re-entry in 10 or 25 years (according to the user’s choice);
3. a graveyard solution beyond 2000 km of altitude.

The delayed re-entry can be achieved following either what we called non-resonant or resonant paths.

In a nutshell, non-resonant paths take advantage only of the effect due to the atmospheric drag and a single impulsive manoeuvre is aimed at lowering the pericentre altitude to this end. In other words, the non-resonant solutions correspond to given combination of semi-major axis and eccentricity.

The resonant paths, on the other hand, are de-orbiting highways made by the combined effect of atmospheric drag and other natural perturbations. In the case of an area-augmenting device, the solar radiation pressure (SRP) is the main responsible of these new solutions; while for a typical spacecraft, SRP, lunisolar gravitational perturbations and J5 effect can all play a role, even if very weak. The resonant solutions correspond to specific values of semi-major axis, eccentricity and inclination, which give rise to a dynamical resonance which yields a quasi-secular eccentricity growth.

The orbital elements to be targeted are well-defined for both non-resonant and resonant paths and they have been derived on the basis of the numerical dynamical mapping [2][5]. This implies in particular that for LEO, the Gauss planetary equations, which give the components of the manoeuvre to be applied, are solved online.

Specific details on the whole procedure can be found in [6].

As an example, in Table 1 we show the Δv (m/s) computed by the software (R in the table) in case of direct and delayed re-entry (non-resonant and resonant) in less than 25 years assuming e=0.001, i=70 deg, *A/m*=0.012 m2/kg starting from the 2020 initial epoch. In the same table, they are shown also the analogous values provided in [7] and computed with the ESA DRAMA's OSCAR software [8]. In the latter case, it is assumed "bipropellant 1" for the chemical propulsion system and ECSS sample solar cycle for the solar and geomagnetic activity. We can notice a very close correspondence between ReDSHIFT and OSCAR apart for the delayed solutions computed at 800 km and 900 km of altitude. The different atmospheric drag and solar activity models are likely the responsible of this incoherence.

Table 1 As a function of the initial altitude h (km), we show the Δv (m/s) computed by different approaches to re-enter for a typical spacecraft, assuming e=0.001 at the disposal epoch. K: [7] Table 6.1; O: OSCAR DRAMA; R: ReDSHIFT; dir: direct re-entry down to 120 km; del: re-entry in less than 25 years; res: resonant solution assuming i=42 deg. S.H.: significantly higher. See text for more details.

h	K	O dir	R dir	O del	R del	R res
800	199.4	185.7	185.7	65.2	80.6	77.9
900	224.3	210.6	210.6	99.8	127.2	115.8
1000	248.6	234.0	234.0	131.2	139.6	S.H.
1100	272.3	258.7	258.7	160.4	166.1	S.H.
1200	295.4	281.9	281.9	188.1	191.7	S.H.
1300	317.9	304.5	304.5	214.4	216.0	S.H.
1400	339.9	326.6	326.6	239.8	239.6	S.H.
1500	361.5	348.1	348.1	264.2	262.2	S.H.
1600	382.5	369.2	369.2	287.8	283.9	S.H.

In Table 2, we provide an example for a spacecraft equipped with an area-augmentation device, assuming A/m=1 m^2/kg. In this case, we compare the delayed 25-year solution computed by OSCAR and the ones computed by the ReDSHIFT software. Note that OSCAR does not provide the manoeuvre needed to de-orbit with the sail. Also, in the case of the ReDSHIFT solutions we display the Δv associated with a deorbiting achieved only by means of the atmospheric drag and the one associated with the combined effect of SRP and atmospheric drag. In the latter case, the table shows the minimum resonant solution found.

Table 2 As a function of the initial altitude h (km), we show the Δv (m/s) computed by different approaches to re-enter for a spacecraft equipped with an area-augmentation device, assuming A/m=1 m^2/kg and e=0.001 at the disposal epoch. O: OSCAR DRAMA; R: ReDSHIFT; del: re-entry in less than 25 years; res: resonant solution (the value of the resonant inclination is specified in brackets).

h	O del	R del	R res
800	0	0	/
900	0	0	/
1000	0	7.4	19.6 (59 deg)
1100	N.A.	48.8	24.5 (41 deg)
1200	N.A.	71.9	24.6 (78 deg)
1300	N.A.	117.4	24.2 (78 deg)

2.2. MEO Regime

Since the MEO regime by definition covers a wide range of orbital altitudes – between 2,000-35,786 km – while the actual operational space is much more limited, we focused in two specific regions; around the Global Navigation Satellite Systems (GNSS), and the region of the Geosynchronous Transfer Orbits (GTO). We integrated several millions of fictitious satellites, for time spans of 120-200 years, using a dynamical model that consisted of Earth's gravity field up to degree and order 2, the Moon and Sun as perturbing point masses, and Solar Radiation Pressure (SRP) (assuming the 'cannonball' model) and atmospheric drag (assuming an exponential density model). The integration was duplicated for two different values of the area-to-mass ratio (A/m), and for two different epochs. Full description of the dynamical model can be found in [4], while the grid of initial conditions and the dynamical study can be found in [9] and [10] for the GNSS and GTO regimes, respectively.

The results of these dynamical studies can be used to define end-of-life, (passive) debris removal strategies, in particular to search for ΔV-optimal re-entry and/or graveyard solutions and T-optimal re-entry solutions – where T is the 'waiting' time from the end of the mission to re-entry. The user of the ReDSHIFT software toolkit should provide an initial orbit that he desires to dispose ('starting orbit'), the epoch, A/m, and maxima ΔV budget. Then, the software calculates the ΔV needed to transfer from the starting orbit to any final orbit among our set of pre-computed re-entry and/or graveyard solutions (database) on the same (a,e) plane, using a single- or two-burn manoeuvre. The output given by the software consists of i) the lifetime map that matches the starting orbit, ii) T-ΔV diagrams of re-entry solutions and/or e_{max}-ΔV diagrams of graveyard solutions, iii) initial conditions of the ΔV- and T-optimal solutions (if they exist), iv) final conditions of the optimal solutions upon reaching 120km perigee altitude, and v) time evolution of the orbital elements for all optimal solutions.

An example of the output given by the tool-kit for a Galileo-type stating orbit can be seen in Table 3 (see [10] for more examples from the GNSS dynamical study). In general, the results depend strongly on the assumed secular angles configuration and epoch. If a generous ΔV_{max}=300m/s is assumed, optimal solutions with re-entry times of ~80yr and e<0.3 can be found. Moreover, in general, these solutions, although having long 'waiting' times, actually spend less than 25 years in the LEO protected region (from the first moment of entry until they reach 120 km altitude).

Table 3: Initial conditions and required Δ*V* of all optimal solutions, when the starting orbit has a=29601.31km, e=10^{-4}, i=56°, Ω=282.83°, ω=106.50°.

Reentry Optimal Solutions					
	a(km)	e	DV(m/s)	DT(h)	T(yr)
Δ*V*-optimal	29620.33	0.12	217.3	7.69	120
T-optimal	29831.15	0.16	288.5	7.95	102.81
Graveyard Optimal Solution					
	a(km)	e	DV(m/s)	DT(h)	e_{max}
Δ*V*-optimal	29662.49	0.00	3.8	7.05	0.00027

2.3. GEO Regime

Most of the available disposal tools focus mainly on designing the optimal manoeuvre sequence for geostationary satellites. Our software tool extends the design space and is able to provide the available disposal options to any kind of geosynchronous satellite. The design process is based on an exhaustive dynamical mapping of the geosynchronous region [3]. Our results suggest that there is a natural separation in the long-term orbital dynamics among orbits with inclination less or greater than 40 degrees with respect to the equator. Namely, for orbits with inclination less than 40 degrees, the long-term evolution of the trajectories reveals a stable behaviour with low eccentricity variations. In this regime the selection of a graveyard trajectory is the only plausible disposal scenario. On the other hand, for orbits inclined more than 40 degrees, the situation reverses. Within the 120 years of propagation, most of the orbits exhibit large eccentricity variations, with a good amount of them reaching Earth's atmosphere. The lifetimes of some of the orbits is low enough to allow reasonable re-entry disposal designs.

The disposal manoeuvre design process is based on an optimal 2-burn strategy. Given the post-mission orbit of the satellite and an available Δv on board, the reachable disposal orbits are selected. Orbits that cross the GEO protected region are excluded from this search. Then, a Lambert-solver is employed to provide the Δv information for the transfers within the reachable orbital element space. The results are presented as Pareto-fronts of the two-dimensional optimization problem: Δv – Δe (eccentricity variation) in the case of graveyard design or Δv – Δt (lifetime) in the case of re-entry design [14].

An example of the output given by the software for the graveyard design of a geostationary satellite is provided below. The post-mission orbit is a=42164, e=0.001, i=0.0°, Ω=0.0 ° , ω=0.0 ° and the available fuel on board is Δv = 100 m/s. The pareto front for this case is presented in Table 4. The orbital elements of the targeted disposal orbits are given in Table 5.

Table 4: Pareto front solutions for the graveyard disposal design of an orbit of *a*=42164 km, *e*=0.001, *i*=0.0°, *Ω*=0.0°, *ω*=0.0° and available Δ*v* = 100 m/s.

#	Δv [m/s]	Δe x 10^{-3}
1	9.909	1.116
2	9.915	1.115
3	10.280	1.107
4	11.212	1.096
5	11.484	1.089
6	55.634	1.072

Table 5: Target orbits for the graveyard disposal design of an orbit of *a*=42164 km, *e*=0.001, *i*=0.0°, *Ω*=0.0°, *ω*=0.0° and available Δ*v* = 100 m/s.

#	Δa [km]	e	i [°]	Ω [°]	ω [°]
1	+250km	0.001	0.0	180	135.5
2	+250km	0.001	0.0	190	135.4
3	+250km	0.001	0.0	230	134.5
4	+250km	0.001	0.0	50	134.5
5	+250km	0.001	0.0	40	134.7
6	+250km	0. 0175	0.0	40	134.7

2.4. Solar and Drag Sails Disposals

The feasibility of disposal design using solar and drag sails is assessed by combining the possibilities of the so-called passive [11] and active [12] deorbiting strategies. They both assume an already fully deployed sail and differ in the attitude control manoeuvres. The passive control keeps the sail always perpendicular to the main disturbing acceleration, either solar radiation pressure for high altitude orbits, or drag for orbits below 800 km. The active sail control consists of decreasing the semi-major axis of the orbit by maximizing the sail acceleration when travelling towards the sun and minimizing it when travelling away from it. These control strategies were compared and assessed in [15] and the passive deorbiting strategy was showed to be more convenient in terms of deorbiting time at the same sail area deployed. Based on these findings, as a novelty of the ReDSHIFT project a new sail control strategy was proposed, named modulating control strategy, that changes the attitude of the sail, making it perpendicular or at feather to the Sun direction every six months, to keep increasing the orbit eccentricity [15].

The ReDSHIFT software tool implements these findings and gives the optimal sail design and attitude strategy for deorbiting within a user-defined deorbiting time.

First, provided the operational data on the orbit and the spacecraft, which includes mass, area of the sail and maximum time to deorbit, the passive approach is tested. This consists of fixing the attitude of the sail to be perpendicular to the sunlight direction. Deorbiting in the specified time interval may be possible depending on the area-to-mass ratio and initial orbital elements, and it is achieved by the increase of the eccentricity of the orbit. In case it is not possible to deorbit in the prescribed time using the passive approach, as the required sail area would be too large considering current sail technologies, the modulating approach is tested. This is achieved by changing the sail attitude to be perpendicular or parallel to sunlight, respectively every six months, so that the orbit eccentricity is increased monotonically until re-entry.

These tests are performed only if the construction of such a sail is feasible according to current technological boundaries [11], and if any of the two strategies are successful, the module outputs the actual re-entry time, the Keplerian elements at 120 km of altitude, details on the design of the sail and maps to aimed to characterize the sail requirements for the given operational orbit. As an example Figure 1 shows the requirements in terms of effective area-to-mass (c_RA/m) for a 25-year deorbiting time with modulating solar radiation pressure strategy. The colour bar represents the required effective area-to-mass.

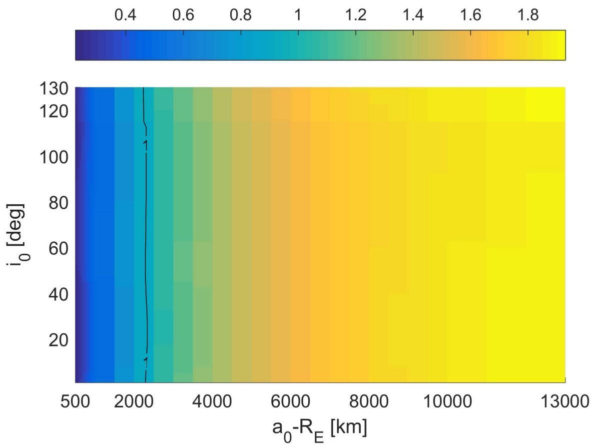

Figure 1. Requirements in terms of effective area-to-mass (*c_RA/m*) for a 25-year deorbiting time with modulating solar radiation pressure strategy. The colour bar represents the required effective area-to-mass.

3. DESIGN FOR DEMISE

The Design for Demise module is responsible for generating an initial assessment of the fragmentation and demise of a vehicle re-entering the Earth's atmosphere. It is design for use in situations where a rapid first order assessment of the demise of critical components is required. In order to operate within the constraints of a web environment it is necessarily based on a number of simplifying assumptions. The module has been designed to generate a conservative assessment of the demise of key components with execution times of the order of one second and has been validated against BRL's SAM atmospheric re-entry code.

The assessment of demise is divided into two phases. Initially, a simplified description of the entering vehicle and its orbit are supplied by one of the disposal mapping modules and used to assess whether it will be subject to direct entry. If the vehicle is predicted to enter on the current orbit, the approximate altitude, flight path angle and speed of the vehicle at a catastrophic break-up event is assessed. On the successful completion of this first phase, the demise of a catalogue of critical components, supplied by the user, is evaluated. This assessment is initiated at the break-up condition identified in the first phase.

3.1. Fragmentation assessment

The first stage of the D4D evaluation takes a simplified description of the parent vehicle and entry conditions, comprising the mass and average projected area of the spacecraft; and the semi-major axis, eccentricity and inclination of the orbit. Having confirmed that the vehicle is predicted to re-enter on its current orbit, these are used to assess the altitude, speed and flight path angle of the primary break-up event.

Both the assessment of re-entry and the prediction of the point of catastrophic fragmentation are based on the interpolation of database entries of pre-computed results. The two databases used in this first phase were built from parametric entry studies conducted using BRL's 3dof trajectory tool ATS3. In both cases, entries of vehicles of varying mass and area were simulated from an altitude of 120km above a spherical model of the earth with an r^2 gravity model and US Standard 1976 atmosphere. This model is necessarily simple, making the entry independent of starting location and thereby restricting the resulting databases to 30,000 and 160,000 entries respectively.

The criterion used to assess the catastrophic fragmentation of the parent vehicle assumes that this event is thermo-mechanical in nature. The break-up is triggered when the product of the dynamic pressure and total heat load to the vehicle is equivalent to that experienced by an equivalent spacecraft at the nominal fragmentation altitude of 78km when re-entering from a circular orbit.

The estimated values of the parent vehicle's altitude, velocity and flight path angle at the primary fragmentation event form the output of the first phase evaluation.

3.2. Demise assessment

The second stage of the D4D evaluation takes the initial condition generated by the first phase and uses it assess the demise of one or more components. The component catalogue is supplied by the user in a separate file to the entry conditions used by the first phase.

Each component is identified in terms of its primary material, mass, canonical length and aspect. All components are modelled as cylinders. This approach is a necessary compromise between the ability to represent components and the size of the resulting demise database. In addition to the description of the component the catalogue also identifies the number of each component type found on the vehicle, enabling the aggregate casualty area to be assessed. Like the fragmentation assessment, these inputs are used as keys to look up the results in a demise database of approximately 640,000 simulation results. The results retrieved are interpolated to generate an estimate of the demise altitude and / or change in landed mass and area associated with the fragment. Where objects are predicted to impact the ground the per component landed mass, projected area and casualty area are computed from the initial values.

Finally, a heuristic is generated for each component indicating whether it survives, probably survives, probably demises, demises or has an uncertain outcome. This heuristic is based on the number of relevant bounding observations found in the database and the proportion of these that display either complete demise or complete survival.

3.3. Verification

The output of the D4D module has been verified against BRL's SAM aerothermodynamic entry code. A Monte-Carlo analysis of single executions of the D4D module from randomly selected initial conditions has been conducted. The results in terms of the conditions at break-up and landed fragments predicted have then been compared with the output of SAM. A total of 4000 simulations have been executed, designed to cover the full range of input accepted by the D4D module. Although it is based on the output of the SAM code, because of the simplifying assumptions and reliance on interpolation between points in a finite database, the D4D module cannot fully replicate the performance of SAM. However, despite these limitations the output of the D4D module is seen to match that of SAM well in terms of both whether an object is deemed to fully demise, and in the event that it does not demise, the resulting casualty area.

As such the performance of the ReDSHIFT D4D module is deemed acceptable as a first order approximation of demise behavior during re-entry for use in situations where a rapid assessment of the casualty area of critical components is required.

4. FLUX AND COLLISION PROBABILITY

The flux and collision probability part of the software is a tailored space environment projection tool. It takes mission related parameters as input, e.g. mass of the spacecraft, area-to-mass ratio and the target orbit. The necessary annual background populations are stored alongside the tool and originate from long-term space debris environment simulations conducted at the beginning of the project for ReDSHIFT. A total of seven variations of the long-term simulations were performed. The baseline scenario was a case were the parameters are chosen to be conform with IADC Space Debris Mitigation Guidelines. The variations cover several important aspects for mitigation. This includes different success rates for collision avoidance and disposal manoeuvres, variations in the launch rates (e.g. introduction of large constellations) and active debris removal. The user of the ReDSHIFT software can select the background population as desired at the beginning of the analysis. For more information on the reference scenarios, please refer to [1]. The results of the long-term scenarios are present as annual files and provide a statistical distribution of the debris in the circumterrestial space averaged over all conducted Monte-Carlo runs.

The program logic is depicted in the following Nassi-Shneiderman-structogram. The software runs an outer loop over simulation time. The time step is set to one year. In every simulation step, the module first loads the applicable background population and introduces the target object into the population. The collision rate orbit trace algorithm calculates the flux for the given orbit of interest. The value represents an annual flux on a reference area of 1 square meter. The flux values are cumulated over time and saved for later calculation of the total collision probability.

As the background populations only contain objects with a minimum size of 10 cm, it is necessary to extrapolate from this 10 cm data point to smaller particle sizes. The flux as a function of diameter, semi-major axis and inclination was derived from a series of ESA-MASTER executions with the reference population of 2013. It is worth mentioning that this approach captures the qualitative distribution of debris.

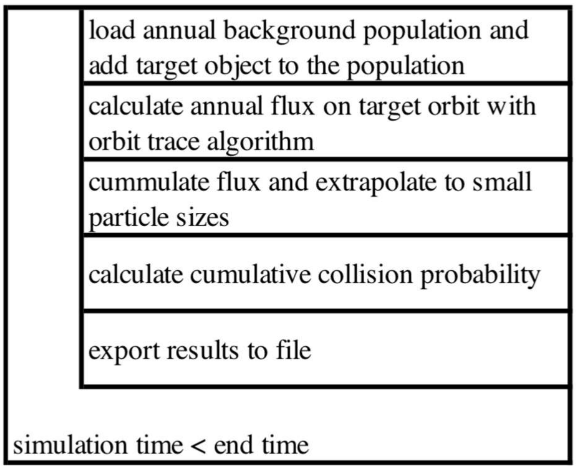

Figure 2: Structogram of the flux and collision probability module of the ReDSHIFT software

The data points acquired from the ESA-MASTER runs are used as input for a polynomial regression. The coefficients of resulting polynomial function are stored within the tool and can be evaluated for desired diameter and given semi-major axis and inclination. The qualitative flux function is scaled with the actual flux value calculated for 10 cm diameter, thus giving quantitative results for the flux for smaller particle sizes. for instance, these flux values of milli-metre size are used as input for the subsequent shielding module of the tool suite.

The forth step of the flux and collision probability module is to calculate the collision probability. The approach is to first determine the collision rate as per [7], page 61:

$$c = F \cdot A \cdot \Delta t$$

where A is the cross-sectional area of the target and Δt is the time the object is exposed to the flux F. The collision rates c_i for all the time intervals can be turned into conditional collision probabilities via a Poisson distribution function. The probability of having no impact after n years is:

$$P_{0n} = \exp\left(-\sum_{i=1}^{n} c_i\right)$$

Consequently, the probability of having at least one impact after n years is the complement of P_{0n}:

$$P_{1n} = 1 - P_{0n} = 1 - \exp\left(-\sum_{i=1}^{n} c_i\right)$$

Finally, all the values of the flux and collision probability analysis are stored in result files. They can be directly displayed for the user or used by other parts of the ReDSHIFT tool suite. In summary, the flux and collision probability module allows an evaluation of the space environmental impact on the target orbit. It can be used to compare different disposal strategies in terms of collision risk. The results can be fed back into the mission design and potentially lead to low risk disposal strategies.

5. TOOL ARCHITECTURE

The ReDSHIFT tool has been conceived as a suite, i.e. different independent and specialized software modules which will be integrated in a single framework. Both desktop and web-based interfaces are provided, to give access to two different types of users: a specialised tool for the model developers and a simplified version of the suite for public access.

The ReDSHIFT SW suite desktop Human Machine Interface (HMI) will be openSF, [16]. openSF is a generic and open source simulation framework distributed and maintained by the European Space Agency. It provides end-to-end simulation capabilities that allow assessment of the science and engineering goals with respect to the mission requirements.

Scientific modules and product exploitation tools can be plugged in the system platform with ease using a well-defined integration process. With this approach, the scientist developing modules is not constrained by the responsible of the final toolkit integration and, once defined the interfaces between the modules under his responsibility and the other modules interfaces, he can extend/modify/upgrade his implementation in total independence from the rest of the team, and at the same time preserving the capability of accessing it via a user interface.

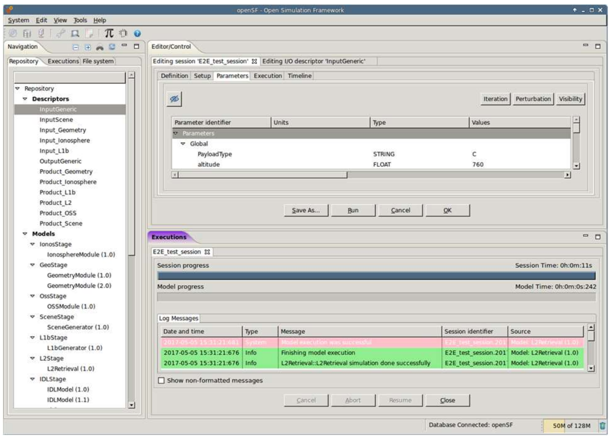

Figure 3: openSF HMI example

Another key aspect of the selected approach is that the openSF environment provides interface capability in several programming languages, letting the module developer a complete freedom in choosing the programming language for its implementation. ReDSHIFT toolkit modules have been developed in C++, Java and Fortran.

The following diagram illustrates the high-level system decomposition, with the identified interfaces among the different modules.

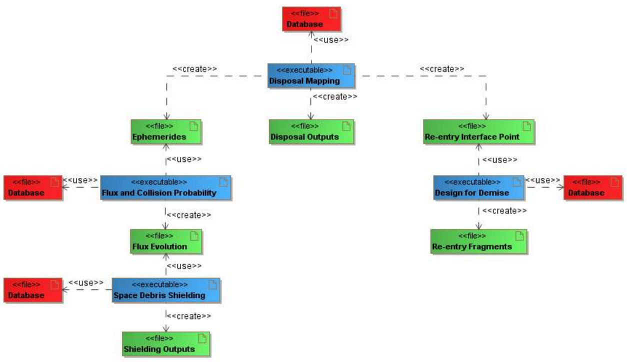

Figure 4: SW Component Diagram

The computational modules are depicted with blue boxes, the databases upon which they rely on are in red, and the file interfaces among them are in green. Other input/output interfaces defining the whole SW infrastructure have been omitted for readability.

The web interface of the tool is oriented to a wider audience and it allows to easily configure an analysis without having the burden to install the whole SW suite. The processes are invoked remotely and run into a dedicated server and the outputs can be visualised in the web interface and downloaded for further data manipulation.

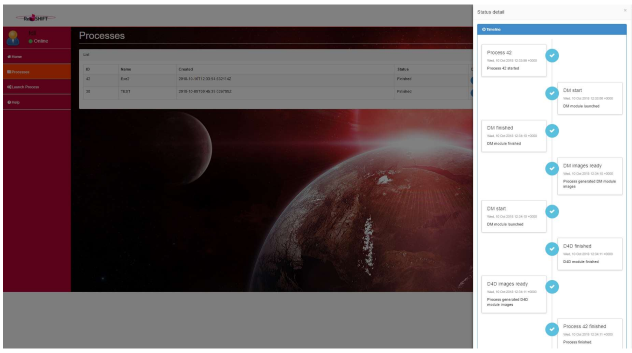

Figure 5: Web HMI example

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