The Debris Mitigation Facility

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ABSTRACT

ESA has been developing their space debris modelling, assessment and mitigation support tool suite for over 30 years, starting with the core tool MASTER (Meteoroid And Space debris Terrestrial Environment Reference), which presents the space debris environment model. For assessment of the impact on satellite missions and the development of mitigation strategies the DRAMA (Debris Risk Assessment and Mitigation Analysis) tool suite has been created and maintained.

In the next evolutionary step, the functionalities of MASTER and DRAMA are made available in the Debris Mitigation Facility (DMF). DMF has a mission-centric approach of creating the inputs for the analysis. Users can define multiple mission phases and satellite configurations, instead of re-defining the orbits individually for each analysis. The analysis modules are then executed for each phase and satellite, producing results in the respective phases of the mission and satellite configuration.

To achieve this paradigm shifting mission-centric approach the architecture of DMF has been designed to be more flexible than previous iterations of the tool suite. The backend has been implemented using Python, using the available python wrappers from DRAMA as a starting point. The concept of workflows has been added. A workflow can create inputs and handle outputs for multiple analysis modules. Their results can depend on each other. This means, that conversions that previously needed an extra step to use a helper tool are now built-in, allowing seamless executions of the analyses. Furthermore, within this iteration of DMF, analysis modules can be combined in workflows to create outputs for the compliance verification for space debris mitigation guidelines, standards and space laws. DMF supports the ISO 24113 standard, the French Space Operations Act (FSOA), and the US Governments Orbital Debris Mitigation Standard Practices (ODMSP). These contain requirements for operators to ensure a limitation of the orbital lifetime after end of mission ("25-year rule"), limit the collision probability below defined thresholds, and to reduce the on-ground casualty risk from a re-entering satellite below a given threshold.

DMF also supports the connection to model-based engineering databases, such as the open COMET (Concurrent Model-based Engineering Tool) standard.

1 INTRODUCTION

In an effort to better understand the near-Earth environment, including meteoroids and space debris, ESA created the Meteoroid And Space debris Terrestrial Environment Reference (MASTER) in the beginning of the 1990s, with the first beta version available from 1995 [1]. MASTER refers to a statistical population, that discriminates the debris sources (launch and mission related objects, explosion and collision fragments, solid rocket motor slag etc.) into bins (altitude, inclination, eccentricity, object size and mass, ...) and derives the debris flux (in 1/(m²a)) and spatial density (in 1/km³). but also provides the flux browser to process and visualize the flux and spatial density for different orbital regimes. The latest version is MASTER-8, released in 2019.

Based on the insight that the MASTER population can give on the space debris environment a companion software suite has been developed called DRAMA (Debris Risk Assessment and Mitigation Analysis). Its purpose is to support satellite and mission designers to assess the effectiveness of debris mitigation strategies, calculate the statistical risk posed by debris on the spacecraft and caused by the re-entry on ground. For this purpose, the following analysis modules are available as part of DRAMA [3]:

- ARES (**A**ssessment of **R**isk **E**vent **S**tatistics),
- MIDAS (**M**ASTER-based **I**mpact Flux and **D**amage **As**sessment),
- OSCAR (**O**rbital **S**pace**c**raft **A**ctive **R**emoval),
- CROC (**Cr**oss Section **o**f **C**omplex Bodies) and
- SARA (Re-entry **S**urvival **a**nd **R**isk **A**nalysis).

In addition, the helper tool CSTATE is part of the suite to convert between different representations of the state vector.

ARES assesses collision event statistics between operational spacecraft and the trackable object population. It can calculate the mean conjunction avoidance manoeuvres and the associated fuel consumption.

MIDAS on other hand performs damage analysis on defined surfaces in space. The MASTER population is used to derive the flux on the surfaces and estimate the number of impacts, probability of collision. By using ballistic limit equations (BLE) associated with those surfaces the number and probability of penetration can

also be assessed.

To iterate disposal strategies OSCAR is able to estimate the remaining orbital lifetime of space objects and also derive the delta-V needed to reach a target orbit. OSCAR supports various means of disposal, including chemical and electrical propulsion systems, electrodynamic tethers and drag augmentation systems.

To support the modelling efforts CROC has been added as part of DRAMA 2. It allows to model a satellite using 3D primitives. It can then compute the cross-sectional area of the structure from various aspect angles.

The SARA analysis module can compute the re-entry trajectory of a space object through Earth's atmosphere to the ground. Based on the fragments that survive and their trajectories, it calculates the risk for the on-ground human population [4].

DRAMA 1.0 has been developed from the early 2000s, with the second version DRAMA 2.0 being released in 2014 with upgrades to all analysis modules except SARA and updated MASTER interface and a new graphical user interface [2,3]. Its latest iteration (DRAMA 3.1) became available in April 2022. The DRAMA 3 iterations added a more complex re-entry analysis and minor updates to the other analysis modules and user interface [5].

With DMF MASTER and DRAMA are combined in one framework. Focus of the Debris Mitigation Facility is to simplify the input definition from the tool-centric approach of DRAMA and MASTER to a mission-centric approach. Users of DRAMA must define their mission and satellite for every analysis module separately. However, in many cases the different analysis modules need to use the same input in a slightly different way. DMF lets users define multiple satellites and mission phases.

2   MISSION DEFINITION

Satellites can be related to mission phases. All options that have been there in DRAMA and MASTER are also available in DMF but partly fused and re-arranged to support the new input paradigm. As a result, duplicated fields as known in DRAMA (e.g., the orbit definition) are no longer required. Figure 1 shows a mission phase definition. The start and end of the phase as well as the type of the mission phase and the related satellites are shown. The selectable types of mission phases are:

- Launch,
- Mission,
- Disposal,
- Drifting, and
- Other.

They are used as part of the compliance verification workflows, discussed in Sec. 3.2.

The tabs on the top of the main window allows users to define the orbit, spacecraft attitude and additional settings, like the collision avoidance strategy, disposal options and on ground risk options. In the sidebar, on the left, multiple mission phases and satellites can be defined and selected for editing.
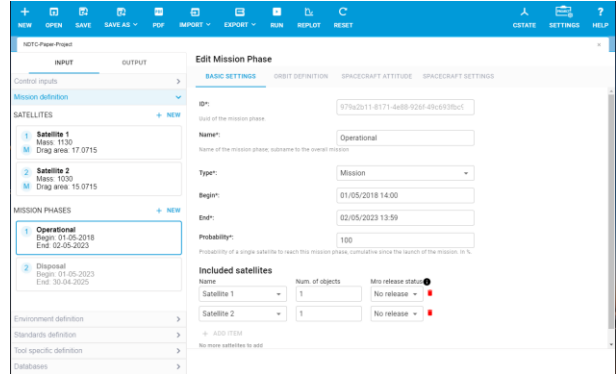

Figure 1 Frontend of DMF showing the Mission definition, with begin, end and included satellites.

When selecting a satellite, as shown in Figure 2, the user can define its parameters, like mass and its cross-sectional area. In the additional tabs on top the 3D model, the propulsion system and the disposal systems can be defined. The 3D model is now harmonized (between SARA and CROC). The user can define a satellite using primitive shapes. The "primitives" can be a

- Sphere,
- Sphere-cap
- Box,
- Cone,
- Cylinder, or
- Ring.

As in previous DRAMA versions, multiple of the primitives can relate to each other. A primitive can also contain one or more primitives. This is important for re-entry computations.
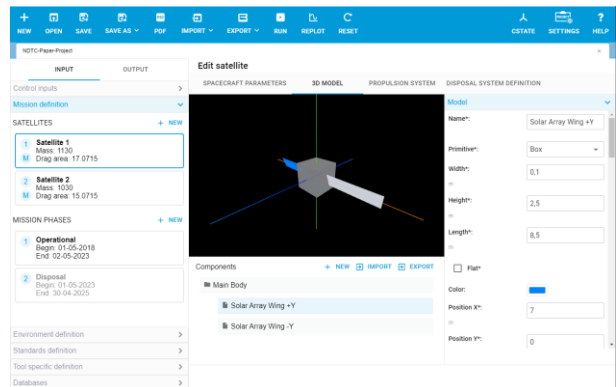

Figure 2 Frontend of DMF showing a satellite 3D model.

3   WORKFLOWS

The concept of workflows has been created to simplify the use of the analysis modules using convenient automation by means of helper tools. A workflow configures and executes analysis modules. The outputs of one analysis module can then be used as input for the next analysis module.

3.1   Analysis module workflows

Selecting one or more analysis modules in the *Control Inputs* sidebar enables the respective workflows, when running the project. When multiple workflows are selected, like ARES and MIDAS, as shown in Figure 3 their workflows are executed sequentially.
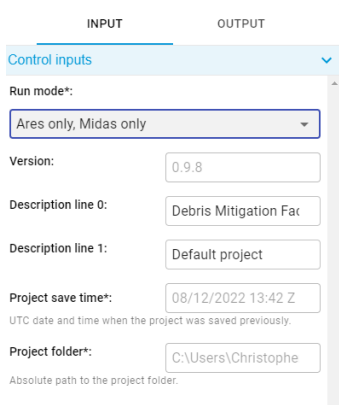

Figure 3 Control inputs sidebar allows to define which workflows to execute.

As the user can define multiple mission phases with different orbit and satellites as inputs the, the respective workflows must convert certain inputs to the format the underlying analysis module expects. Thus, every workflow uses CSTATE and CROC as helper tools. CSTATE automatically converts any orbit input into singly averaged Keplerian elements in the cases of ARES, MIDAS, MASTER, and OSCAR or osculating elements for SARA.

While many of the inputs for the analysis modules are covered in the *Mission definition* sidebar, some are distributed in further categories, like *Environment definition*, *Standards definition*, and *Tool specific definition*, shown in Figure 4.

The *Tool specific definitions* hold inputs that are tied to the special configuration of a given analysis module, like the run modes of ARES and SARA or plots options of MASTER and OSCAR.
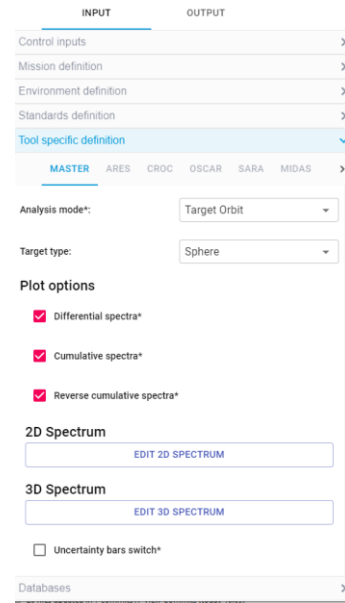

Figure 4 Sidebar showing tool specific definitions with tabs for MASTER, ARES, CROC, SOCAR, SARA and MIDAS.

The *Environment definition* includes:

- space debris population (sources and size threshold),
- collision parameters to define the catastrophic collision flux,
- the detectability of the space debris, using simplified assumptions for radars and telescopes,
- the re-entry environment (atmospheric model, density scaling factor etc.)
- space object catalogue uncertainties, and
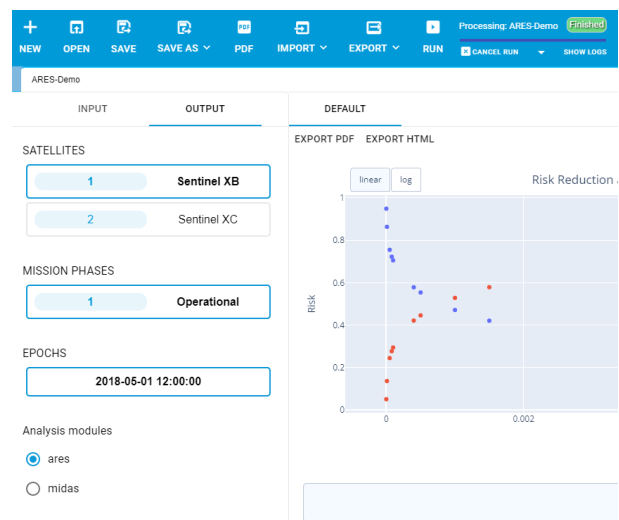- the world population definition to evaluate the casualty risk of re-entries.

Figure 5 Multiple results shown per satellite and mission

phase and analysis module.

Once the analysis modules have finished, the results will be displayed. When multiple satellites and mission phases are configured, and multiple analysis modules have been selected for execution, the output is structured respectively, as shown in Figure 5. The user can view the output per analysis module, mission phase and satellite by clicking on the available fields.

The plots that are generated are comparable to the outputs of DRAMA and MASTER but as part of DMF a new plotting engine is used, which makes the plots interactive. The user can hover over data points, zoom in and out, as shown in Figure 6 for an ARES 2D plot. Individual plots can be exported as PNG. Each plot has a data section below, where the underlying data can be inspected. Figure 7 shows a 3D plot generated by MASTER. The object flux is shown over the impact right ascension and the declination. Also, in the 3D plot the user can inspect different areas of the displayed surface by hovering on it. By clicking and dragging the graph can be rotated about every axis. As in the previous MASTER version also heat maps can be created, as shown in Figure 8.
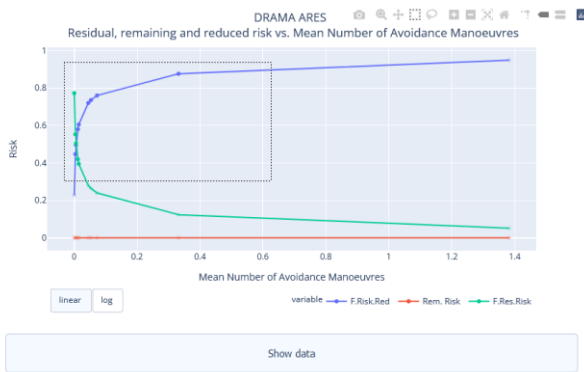

Figure 6 ARES output of residual, remaining and reduced risk vs mean number of avoidance manoeuvres.
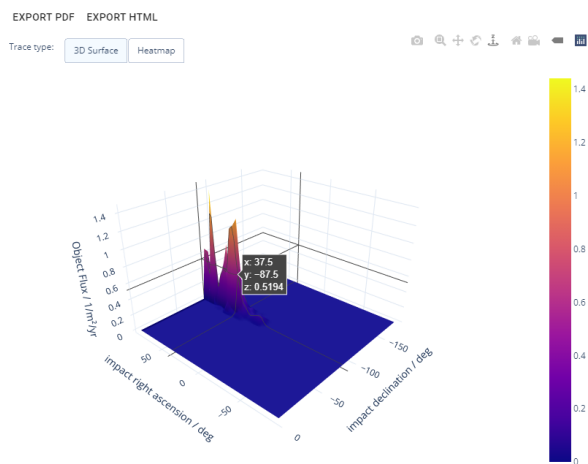

Figure 7 A 3D surface plot based on flux data of MASTER, over the right ascension and declination.
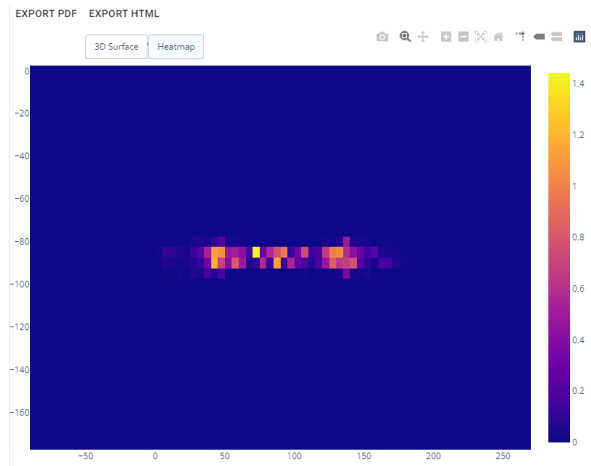

Figure 8 A heatmap based on flux data of MASTER, over the impact angles right ascension and declination.

3.2 Compliance verification workflows

To check compliance against requirements of space debris mitigation guidelines and standards special workflows are available that use the mission phase and satellite definitions. The workflows then configure the analysis modules and retrieve outputs to compile a compliance report. DMF supports the following standards and guidelines:

- ESSB-HB-002 / ISO 24113:2019 requirements [6]:
  - 6.1 Avoiding the intentional release of space debris into Earth orbit during normal operations,
  - 6.2 Avoiding break-ups in Earth orbit,
  - 6.3.1 Provisions for successful disposal,
  - Disposal orbit (6.3.2/6.3.3 Disposal to minimize interference with the GEO/LEO protected region,
  - 6.3.4.1 Re-entry casualty risk acceptance,
- U.S. Government Orbital Debris Standard Practices (ODMSP) requirements [7]:
  - Objective 1: Control of Debris released during normal operations,
  - Objective 3: Selection of safe flight profile and operational configuration,
  - Objective 4: Post mission disposal of space structures
  - Objective 5: Clarification and additional standard practices for certain classes of space operations,
- French Space Operations Act (FSOA) requirements [8]:
  - Article 20 on launch and re-entry risks and Article 23/46 for the ground track,
  - Article 44 for casualty risk and Article

46 for the ground track,
- o Article 21.1: Avoiding release of launcher elements into orbit,
- o Article 21.2: Ensure re-entry safety of launch MROs,
- o Article 21.5: Protected region clearance – LEO,
- o Article 21.6: Protected region clearance – GEO,
- o Article 40.1: Avoiding release of MRO,
- o Article 40.4: Protected region clearance – LEO,
- o Article 40.5: Protected region clearance – GEO,
- o Article 40.6: Energy Resources,
- o Article 22 for launchers; Article 40 for orbital systems

The individual options for verification can be selected in the sidebar (see Figure 9), enabling, and disabling requirements to be verified. In addition, some standards use thresholds, like the individual or cumulative lifetime of MROs in protected regions by the ODMSP, that can be defined by the user.
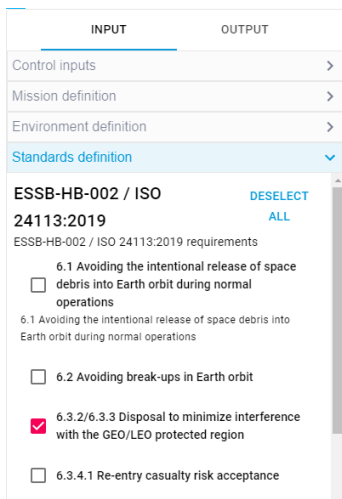

Figure 9 Standards definition sidebar.

An example workflow as implemented in DMF is shown in Figure 10. The ODMSP MRO workflow, that addresses "control of debris released during normal operations", first checks whether the MRO has a largest edge length of > 5 mm. If so, the MRO is regarded in the following analysis. For all MROs > 5 mm the drag area of the MRO is computed using CROC followed by a disposal orbit analysis using OSCAR. The protected region analysis is executed thereafter. Every MRO has an individual maximum orbital lifetime in a protected region (LEO / GEO) of 25 years. The sum of the orbital lifetimes of multiple MROs shall not exceed 100 years. These values can be overridden by the user in special use cases, e.g., to investigate changes in guidelines and/or investigate the impact of changes to guidelines on special missions.
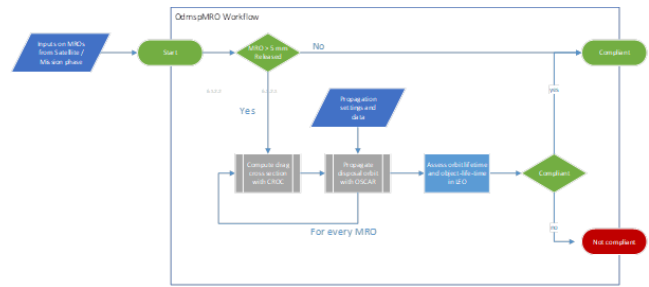

Figure 10 Overview of the ODMSP MRO Workflow

An example space debris mitigation guidelines compliance report is shown in Figure 11. DMF executed:

- 6.3.1 Provisions for successful disposal,
- Disposal orbit (6.3.2/6.3.3 Disposal to minimize interference with the GEO/LEO protected region, and
- 6.3.4.1 Re-entry casualty risk acceptance.

The report shows a non-compliant and shows graphs (not all shown in the Figure) with details of the outcome.
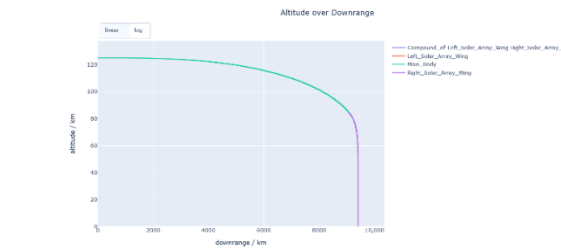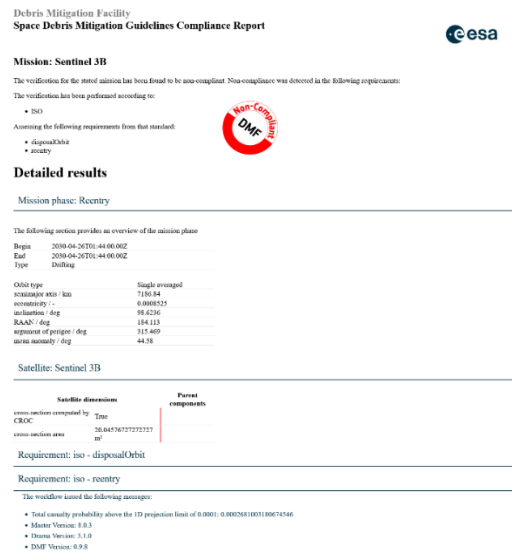

Figure 11 Exemplary space debris mitigation report showing a summary of the outcomes.

The report gives an overview of the compliance and the

mission parameters. The report is extended with plots and tables for visual inspection of the compliance criteria. The report can be exported as PDF or HTML.

4 INTERFACES

The project structure on disc remained the same, as shown in Figure 12. A DMF project can be anywhere in user-writeable space. The project is not confined to a workspace. The JSON file format has been chosen to replace the clear text ASCII or XML input and output files used by MASTER and DRAMA analysis modules.
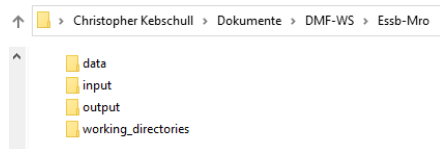

Figure 12 DMF project folder structure.

As a result, a single JSON input file contains all inputs, including databases (material, objects, solar & geomagnetic activity, propulsion systems, and ballistic limit equations) for ease of exchange. It is stored in the *input* folder. Also, results are contained in a single output file. The file is stored in the *output* folder. The input and output folder also contain a *previous* subfolder, where inputs and outputs are stored respectively, in a time-tagged way to keep track of changes between iterations of the inputs. E.g., a user iterates and runs different configurations, which are all stored in the *previous* folder. These configurations can be re-opened as a project. The user interface is also able to open multiple configurations at the same time. The user can switch between them using tabs, as demonstrated in Figure 13.
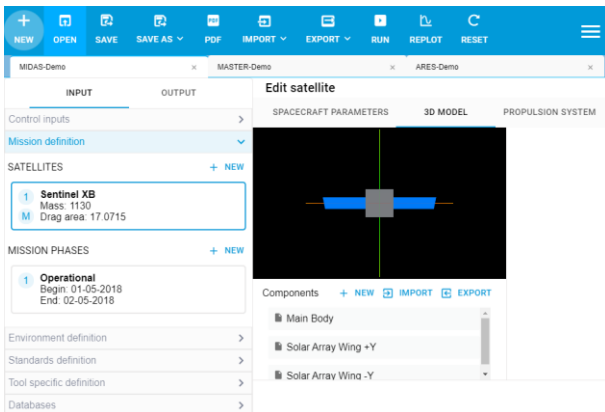

Figure 13 DMF user interface showing multiple projects opened in tabs above the sidebar and editing area.

The ability to interact with external data sources has been extended. Most notably connections have been prepared with COMET and ESA's DISCOS database [9].

The user can now import from and export to a COMET server. COMET is enabling a model-based system engineering approach for concurrent design. It is based on CDP4, which in turn follows ECSS-E-TM-10-25. It defines the underlying data model and exchange protocol [10]. The import from the server allows to retrieve the data model and map it to relevant fields of the mission phase and satellite. Not all fields may be compatible, which means that the user needs to fill the missing fields and relations.

The user can also import from DRAMA 3.1 and MASTER-8 projects, which fill respective fields for a single mission phase and satellite.

The DMF GUI offers a convenient way to automatically update the solar & geomagnetic activity data as well as the material list. A dialog appears when loading a project that updates are available. After clicking OK, the data is downloaded automatically and stored in the database, which is valid for all analysis modules that need it.

5 ARCHITECTURE

The software was designed to be extended easily. A frontend and backend have been developed. The frontend builds on ReactJs [11] and ElectronJs [12] web technologies. It connects to the backend via REST endpoints. The backend is written Python and uses Flask [13] as a webserver to enable the communication between the frontend and the backend. The technology stack allows cross-platform software development and makes DMF available on Windows, Linux and macOS.

The backend uses Python wrappers for all analysis modules shipped with DRAMA 3. as a foundation. These wrappers have been extended to use JSON inputs, including the validation of the input model using schema files. A new Python wrapper for MASTER has been developed. The wrappers execute the respective analysis nodule and parse the output data. The workflows discussed in Sec. 3 create JSON configurations that are directly usable by the wrappers. The behaviour of these workflows can easily be adapted. Also, workflows can execute multiple independent analyses in parallel, e.g., for multiple mission phases and satellites.

A DMF JSON schema defines valid sections and input fields, with examples and descriptions. As inputs from MASTER and DRAMA are fused into this schema, a structure has been created (see Figure 14) which is also reflected in the sidebar of the user interface.

```json
{
    "toolSpecificDefinitions": {…
    },
    "missionDefinition": {…
    },
    "populationDefinition": {…
    },
    "standardsDefinition": {…
    },
    "databases": {…
    },
    "controlInputs": {…
    },
    "dates": {…
    },
    "name": "Essb-Mro-1",
    "id": "fac5c2f9-2fe2-42e9-81c7-b07fa8ec51d1",
    "editedItem": "979a2b11-8171-4e88-926f-49c693fbc997"
}
```

Figure 14 Example DMF input file structure.

The JSON schema defines which values can be passed to the backend. These values can then be accessed in the workflows.

The output is defined in a similar way. The JSON schema defines how the results are structured. There are two different output modes available: one for analysis module runs and one for compliance verification runs. The structure again is similar to how the user interface structures it (see Figure 15). The output JSON contains the parsed output files of the analysis module but also logs of the executable and the *markups*. The markups object contains formatted code (HTML), which are summary texts and plots, displayed in the user interface.

```json
{
    "controlOutputs": {
        "runStatus": "Finished",
        "progress": 100,
        "logs": […
        ]
    },
    "singleModuleOutputs": {
        "satellites": [
            {
                "name": "Sentinel XB",
                "id": "979a2b22-8171-5e88-926f-49c693fbc997",
                "missionPhases": [
                    {
                        "name": "Operational",
                        "id": "979a2b11-8171-4e88-926f-49c693fbc997",
                        "epochs": [
                            {
                                "epoch": "2018-05-01T12:00:00.00Z",
                                "analysisModules": [
                                    {
                                        "process_id": [
                                            "07ec4d28-6331-46e1-b9bb-e3fe2947f14d"
                                        ],
                                        "results": {…
                                        },
                                        "markups": […
                                        ],
                                        "logs": […
                                        ],
                                        "analysisModule": "ares"
                                    },
                                    {…
                                    }
                                ]
                            }
                        ]
                    }
                ]
            },
            {…
            }
        ]
    }
}
```

Figure 15 Example DMF output file structure.

6 CONCLUSION

The Debris Mitigation Facility combines the analysis capabilities of DRAMA and MASTER while using a mission-centric input paradigm. The flexible design allows to link analysis modules and enables compliance verification tasks as well as reduces complexity by automatically performing state vector conversions and cross-sectional area computations. A new user interface allows a more interactive handling of the outputs and is also able to manage multiple projects at the same time. The software is currently in the final stages of development.

Extensions of DMF are on the way, which add more functionality and make further use of the connection to ESA's DISCOS database. The analysis modules are updated to simulate the attitude of space objects and use this input in the analyses of ARES and MIDAS.

Furthermore, the capability to analyse and simulate the trackability of space debris and spacecraft by Space Situational Awareness (SSA) systems is being prepared, which prepares ARES to assess risk events not only based on the established catalogue of the 18th SPCS but also other (commercial) SSA providers. This iteration enables satellite and mission designers to take into account the trackability of their spacecraft.

7 ACKNOWLEDGEMENT

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