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Research initiative sustainable space logistics: an overview on the work performed at EPFL from 2019 to 2021 in space logistics modelling and optimisation

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Abstract
The research initiative on sustainable space logistics was initiated in May 2019, to be an intellectual hub for the current logistics revolution in space. The paper will present the main outcomes of the initiative from the top-down approach on space logistics modelling. Section 2 will present the work performed to model space logistics scenarios using an in-house software called TCAT and its impact on sustainability. Section 3 will introduce a new project on Connecting Space Logistics & Architecture through a pattern language for robust mission design. The paper will conclude on the lessons learned and the perspectives around space logistics modelling and optimisation.

Acronyms and Abbreviations

ACT	Assessment and Comparison Tool
ADR	Active Debris Removal
CDF	Concurrent Design Facility
ConOps	Concept of Operations
ESA	European Space Agency
eSpace	EPFL Space Center
FLPP	Future Launcher Preparatory Program
GSL	Green Space Logistics
ISRU	In-Situ Resource Utilization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LOR	Lunar Orbital Rendezvous
NRHO	Near-Rectilinear Halo Orbit
RAAN	Right Ascension of the Ascending Node
RISSL	Research Initiative on Sustainable Space Logistics
SSR	Space Sustainability Rating
STV	Space Transportation Vehicle
TCAT	Technology Combination Analytical Tool

1. Introduction

The new logistics paradigm in space includes shoebox-sized “nanosatellites”, a reusable rocketry renaissance, and satellite constellations that map the Earth in one day, or provide internet everywhere. Similarly, the agencies' attention on the Moon and in-situ resources utilization (ISRU) emphasizes new logistics approaches. Finally, space logistics amplifies some key issues, like space debris – and brings new opportunities, such as on-orbit servicing and active debris removal (ADR). This is a profound, long-term shift, and thus has deep implications for sustainability.

The research initiative on sustainable space logistics (RISSL) contributes to the development of space research, technologies, and education, with the specific objectives:

- To initiate and support research initiatives that have the potential to drive innovation and contribute to Swiss thought leadership in Sustainable Space Logistics;
- To connect EPFL and other Swiss laboratories with a background in space technology, via space logistics technology scouting;
- To identify commercial applications and opportunities from the developed research and support technology transfer;
- To develop talents and inspire new vocations.

In order to structure this objective, the initiative has been articulated around three priorities:

- Produce tangible research outcomes
- Engage the community
- Make SSL sustainable

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eSpace has been active in space sustainability for several years, and even more since 2019 with the launch of the RISSL pilot phase which organized many research projects and activities around the topic. The RISSL flow of research was since the beginning split into three levels of details with projects at macro-, meso-, and micro-scale (see Figure 1).

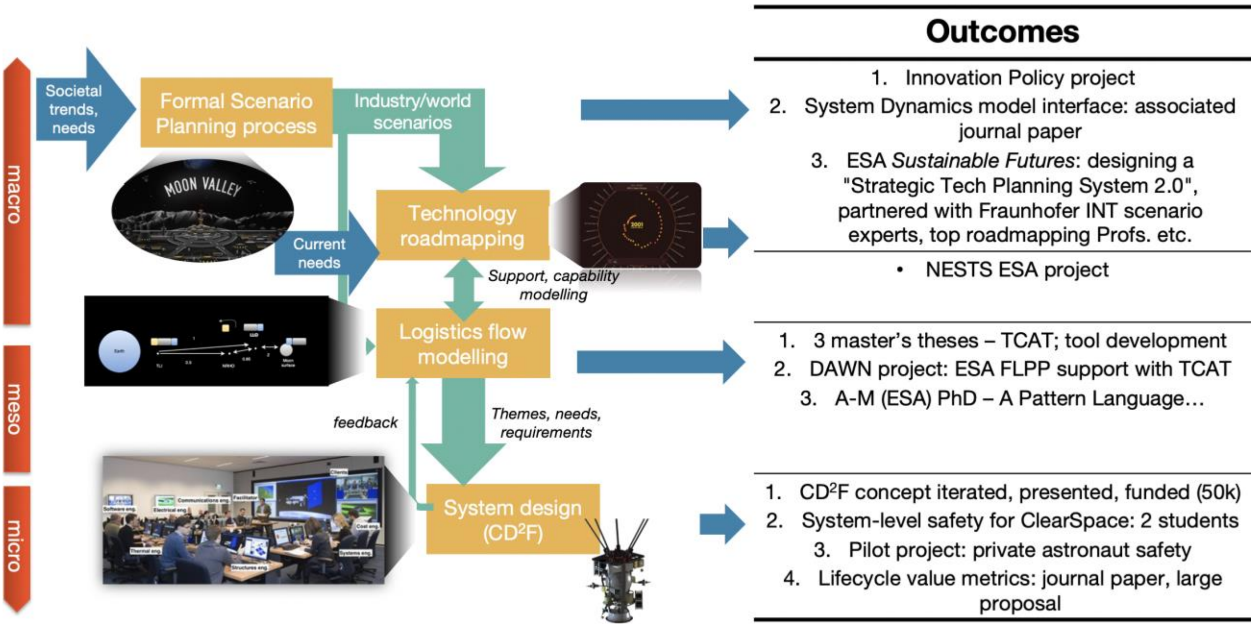

Figure 1 Flow of research conducted by eSpace on Sustainable Space Logistics from 2019 to 2021 with the three scales on the left [1].

At macro-scale, the interest is to plan for the long-term space transportation strategy at the European Space Agency by understanding the market evolution with commercial and institutional needs, and future opportunities and trends arising from the NewSpace approach. These can be analysed to define the needed technologies & technology readiness levels in road-mapping, leading to e.g. investment priorities. The *Sustainable Futures* project, to design and deploy ESA's Strategic Tech Planning System 2.0, and the collaboration with Prof. Dominique Foray for the NewSpace Innovatisation project were the two main outcomes at this level. [4][5][6].

Looking at the micro-scale means using methods to design actual products and equipment that will be part of missions in the market identified at macro-scale. In the case of RISSL, it translated into participating to the design of a spacecraft to carry active debris removal missions. For instance, a System-level Safety study for ClearSpace has been conducted with two student projects in 2020 and 2021 [7][8].
The set up and use of a concurrent design and data facility (CD^{2}F) was also investigated [9]. eSpace later focused on the setup of a concurrent design facility (CDF). This research culminated in April 2022 with eSpace participation to the ESA concurrent engineering challenge (CEC 2022). An intensive, week-long design process from mission requirements to mission concept and first subsystems' budgets. This challenge allowed the center to validate its CDF infrastructure, list many lessons learnt and gain a lot of knowledge on concurrent engineering [10]. This design method will be applied to other projects in the future and serve as a platform to provide eSpace expertise on space sustainability in missions' design for EPFL and external stakeholders.

At meso-level, eSpace was involved in a consortium to research preliminary elements of NESTS (New European Space Transportation Solutions). During this project, an evaluation methodology to assess different space transportation services was developed [15]. The study contributed to European technology planning and service selection by working on real-world criteria for road-mapping.
The Technology Combination Analysis Tool (TCAT) and the pattern language research are also situated at meso-level. They link high level scenarios with low level requirements by modelling the logistics flow and generating mission architectures.

The three key words in *sustainable space logistics* each bring elements and add constraints to the global definition of the SSL research initiative. The core questions of logistics in space are similar to those on Earth: with supply chains becoming more and more complex, how does one manufacture, transport, store, deliver and remove materials, goods, structures, or humans to, in, and from space?

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In recent years, there has been a shift in the way space logistics is imagined, and soon, in how it will be implemented (Figure 2). For the early exploration missions like the Apollo program, the paradigm was to “carry-along” all necessary resources for the trip. With the construction of the international space station (ISS), many “re-supply” cargo vessels or capsules can be launched from Earth. In the future, complex missions will require a combination of “carry-along” and “re-supply” strategies and may take advantage of ISRU, with goods travelling from and to several celestial bodies and orbits, called nodes [2].

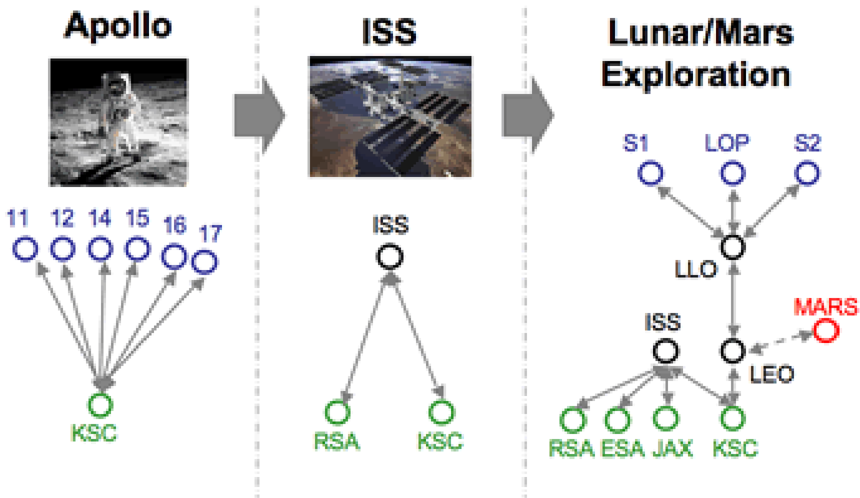

Figure 2 Space logistics paradigm evolution from “carry-along” (left), to “re-supply”, to more complex, mixed strategies with more nodes. Borrowed from MIT Space Logistics project.

Space adds constraints for logistics: unlike on Earth, distances are not measured in kilometres but rather in Δv required to perform a necessary change in orbit or a trajectory. Vehicles also have to survive the harsh environment of space with special radiations and thermal conditions in particular. Not to mention humans who need a lot of equipment and consumables to survive, increase the requirements for reliability, and generate waste.

Ensuring a sustainable access to space for all starts with limiting the impacts on the Earth’s environment of manufacturing, testing and launching space assets (see section 4). But sustainability in space has become a pressing issue too. For now, mainly in Low Earth Orbit (LEO) and soon also in the whole cis-lunar environment: With the increasing number of satellites and the cumulated risks that space debris are creating, it may become dangerous to place space assets on some valuable orbits. It is thus key to develop this new ecosystem with a long-term and sustainable vision.
Another project carried at EPFL, which is relevant to this aspect of SSL, is briefly mentioned here: eSpace is responsible for the operations of the Space Sustainability Rating (SSR) [11][12]. The SSR is a notation system that allows satellites operators to understand the impacts of their mission(s) on the space environment and highlight areas of possible improvements. It will be applied starting in 2022 and certifications will be delivered by 2023. The mindset of the rating is to incentivize better design choices and on-orbit operational behaviours to prevent more debris generation and keep the space environment accessible for future missions.

This paper will detail two of the projects performed under the RISSL: the DAWN project, funded by ESA, with the development of TCAT (section 2), and a PhD thesis on “Connecting Space Logistics & Architecture: A Pattern Language for Robust Mission Design” (section 3). At their level, they both try to answer the core questions of the RISSL, by looking for the optimal mission architecture. While pattern language can be used to generate mission concepts based on high level objectives, and identify the optimal one, TCAT can provide first estimates on the design of a type of servicer, used for the mission.

2. Technology Combination Analytical Tool

2.1 Context

Running simulations of future space transportation scenarios can help identify gaps in the European space transportation capabilities. By scouting, missing types of vehicles or space technologies can be identified several years in advance to allow for development and testing before they are brought to the market. This process of anticipating the

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needs and de-risking technologies by demonstrating new capabilities in an early development phase is done at ESA to attract investors, lower prices, and accelerate innovation. It is only possible if the correct missing assets are identified early by modelling tools such as TCAT.

Beginning in 2012, the Technology Combination Analysis Tool was first developed on Matlab and later translated into python, to run simulations of space logistics scenarios and rapidly size spacecrafts. In 2019, during project Sunrise, a collaboration between OneWeb, eSpace, and the center's spin-off ClearSpace, the tool was extended to support a study to understand if a commercial ADR service could be created, and which architecture it should be designed on. The high volume of spacecrafts launched in constellations and their required low recurring cost can result in a significant number of them becoming space debris. And debris on the operational orbits of constellations are really to be avoided. With an ADR mission, the interest for constellation operators is double: the failed satellite is deorbited, and space is created for a new satellite to fill the gap in the constellation network.

Project DAWN was built on the results of project Sunrise, and saw TCAT being developed in the frame of several master thesis and a contract with ESA Future Launcher Preparatory Programme (FLPP) since 2020 (ESA Contract No. 4000132531/20/FR/JLV). The latest objective was to add a new use case that could output the best deployment strategies for constellations. Because project Sunrise was tackling ADR missions for constellations' satellites, many concepts in the code could be reused for the definition of the orbit and the simulation of the servicers needed for the deployment.

2.2 Scope

TCAT has two objectives:

1. Offer quick assessments of feasibility of space missions (both in systems design and operations)
2. Enable trade-offs of architectures, technologies, etc. by providing rough estimates of cost and performance

Its scope was originally to simulate the logistics of low Earth orbit (LEO) missions, with refuelling of space stations for instance. An extension project allowed for simulation of missions traveling beyond low orbits, up to the Moon and its surface. Now, TCAT is capable of modelling two other space transportation use cases: active debris removal (ADR) missions, and constellation deployments (see Figure 3 and Figure 4).

With a provided list of targeted objects, the tool can compute the required fleet of servicers, and the series of manoeuvres they will have to follow to perform the required mission (the plan). Finally, the tool outputs relevant key performance indicators (KPIs) to filter the most appropriate architecture and servicers' design. The same concepts have been reused for all scenarios to extend the capabilities of the tool.

For instance, the KPI "Total launched mass" [kg] is given by equation **(1)**.

$$\text{Total launched mass} = \sum_{i=1}^{N}(m_{dry_i} + m_{prop_i} + m_{disp_i} + \sum_{j=1}^{K} m_{pay_{i,j}}) \quad \textbf{(1)}$$

with N the total number of missions, m_{dry_i} the dry mass of the servicers delivered at mission i, m_{prop_i}, the propellant mass of servicers delivered at mission i, m_{disp_i}, the mass of dispenser used at mission i, K the number of deployment orbits, $m_{pay_{i,j}}$ the payload mass delivered at mission i to orbit j [17]. Other KPIs include the payload mass launched to orbit, the filling ratio of the launcher(s) in terms of mass and volume, estimates of the prices of the launch(es) and of the mission for the customers, and an estimate of the campaign risk [17].

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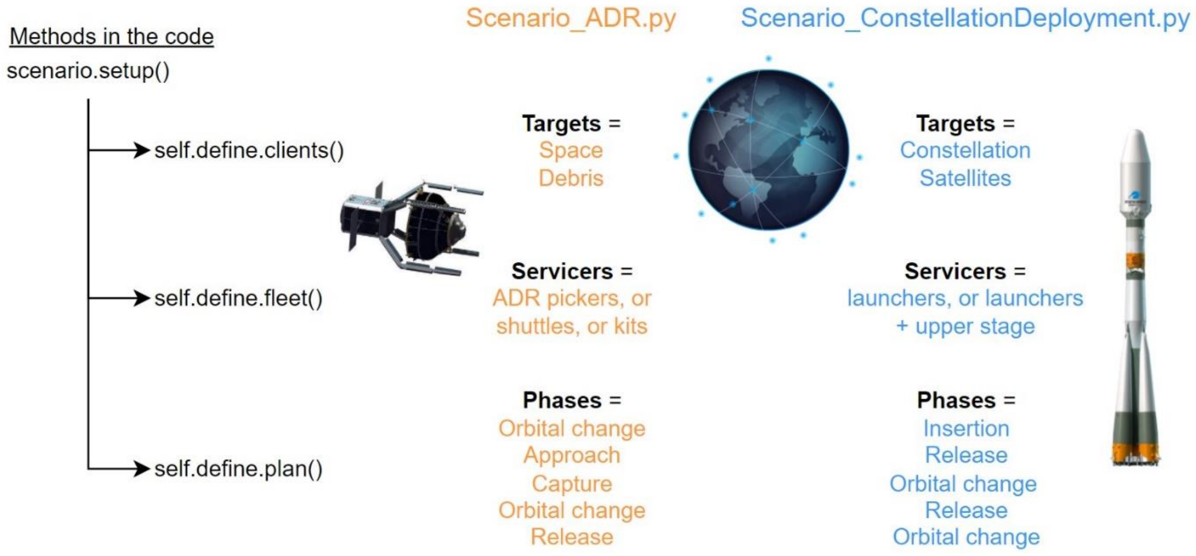

Figure 3 Sketch summarizing the setup() method in the code and the necessary elements for the simulation, for the ADR and constellation deployment scenarios. Three methods are called to define the clients, the fleet, and the plan (see section 2.3). The phases listed here in the plans are just examples [3].

2.3 Design flow

In the user's point of view, using TCAT is decomposed in three main tasks:

1. Specify the inputs
2. Execute the simulations
3. Analyse the results

Figure 4 described the flow of information from the user defined inputs to the computed outputs. The setup of the simulation starts with the target(s) class (the clients), which consist of objects that can be transported by servicers: one or more space debris in the case of the ADR scenario, the satellites to be deployed in the constellation deployment scenario. In LEO, the targets can be space stations to re-supply and for Moon operations, they are cargos to deliver. Those are defined by the user. Then, the fleet, a dictionary of servicers (satellites or launch vehicles), is defined to complete the required mission(s). Finally, the plan, the chronological list of manoeuvres and actions the servicers will perform to solve the scenario, is created.

Then comes the execution of the methods to design the fleet: Each servicer is made of a set of modules describing its subsystems. Some modules simply hold parameters' values (called static modules) but others have an impact on other elements of the code (dynamic modules). Precisely, the dynamic modules can be assigned to one or more phases of the global plan. For instance, a capture module is assigned to the capture and release phases of a plan. A propulsion module is assigned to any change in orbit (orbital change, orbit maintenance, etc.).

TCAT will converge on a solution for the fleet by running the assigned plan several times, only modifying the initial propellant mass of the servicer(s). The outputs of the tool describe the plan, with the phases and their corresponding manoeuvres in a chronological order, the fleet, with the detail of the modules that make up the servicers, and some KPIs for architecture selection.
By modifying some input values to generate several solutions, one can compare the output KPIs, and apply logical filters to select the best solutions found. Filters such as selecting the cheapest option or the less risky one, can be applied depending on the users' needs.

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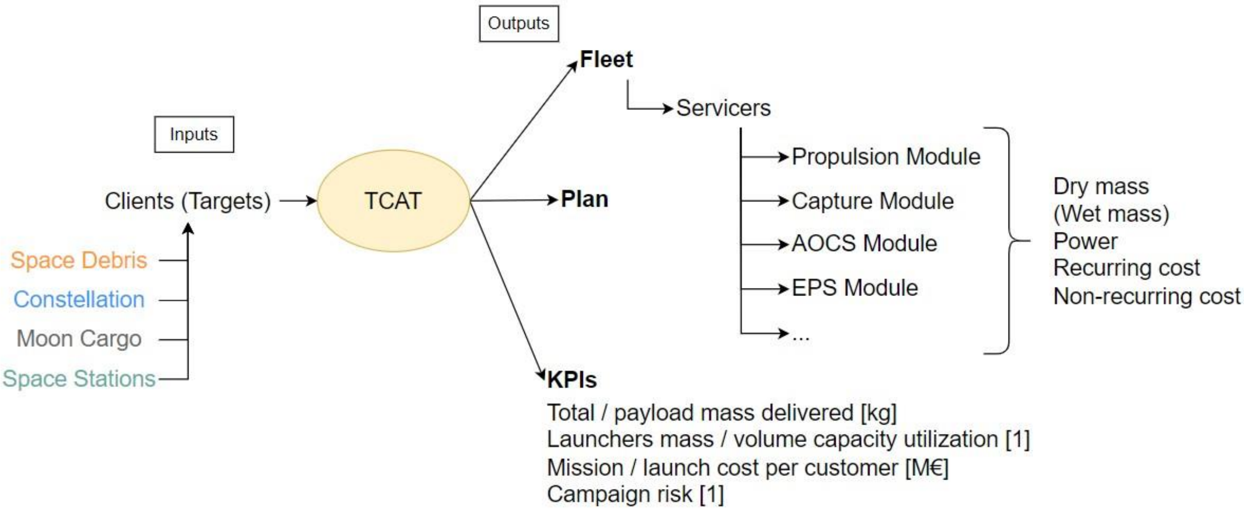

Figure 4 Description of the inputs and outputs of the tool [3].

2.4 First results and possible improvements

TCAT's capabilities have been proven for several simulated scenarios like a lunar mission, or the deployment of a constellation in LEO. Those missions are still relatively simple and it is foreseen that more modelling freedom could be added in the future development of the tool.

Actual data of past or coming missions are used to validate the models. For instance, the tool's simulation of a Moon operation was validated by comparing its output masses with actual values from Apollo 11 (see Table 1). Comparative values for KPIs like price and risk are hard to find from real missions, and similarly for the exact plan of manoeuvres. So for now, it is checked that the values are reasonable, and the phases are coherent in terms of chronology, duration and Δv.

Table 1 TCAT Moon scenario validation with Apollo 11 values [14].

	Dry mass [kg]		Propellant mass [kg]		Wet mass [kg]		Wet mass
Vehicles	Apollo 11	TCAT	Apollo 11	TCAT	Apollo 11	TCAT	difference [%]
Service + Command module	10396	10571	18410	17956	28806	28527	-0,98
Lunar module (Descent Stage)	2291	2836	8248	8294	10539	11130	+5,31
Lunar module (Ascent stage)	2179	1981	2376	3028	4555	5009	+9,07

For missions to the Moon, different concepts of operations can be traded-off, for instance using a direct trajectory to low lunar orbit (LLO, below 2000km), or going through the Near-Rectilinear Halo Orbit (NRHO, based on lunar Gateway's highly elliptical orbit: 3000kmx70'0000km [18]) as a node, or including a reusable transfer module from NRHO to LLO and back. Using the latter option would reduce the initial mass of the servicer transporting the cargo, at the expense of operation complexity [14].

The work is still ongoing to get coherent results for ADR missions, with three possible architectures: a single ADR picker removing one debris, an ADR shuttle targeting several debris, or a mothership carrying several ADR kits, each deorbiting a debris.

For deployment scenarios, several constellations already on orbit and some fictional ones are used for validation. They make sure the tool can handle a wide range of cases with different orbit types, number of satellites, satellites' mass, or selected launch vehicles. For now, orbital changes in this scenario are made following a two steps logic for the Right Ascension of the Ascending Node (RAAN) drift (Figure 5, Figure 6). The RAAN spread, the sum of changes in RAAN values between each satellite deployment, is computed for all possible deployment sequence. The ideal order for the deployment is chosen first to minimize the total RAAN spread and second to start with satellites at lower altitudes. The former criterion means that satellites which follow each other in terms of RAAN spacing in the precession direction

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will be deployed one after the other, while the latter one is useful when several launches are required to deploy all the satellites of the constellation. For each manoeuvre, the required Δv and corresponding propellant mass is computed. In the inputs, a disposal orbit is specified for the launcher or its upper stage. After deploying all the satellites, the tool also accounts for this last manoeuvre to find the total amount of propellant needed for the mission.

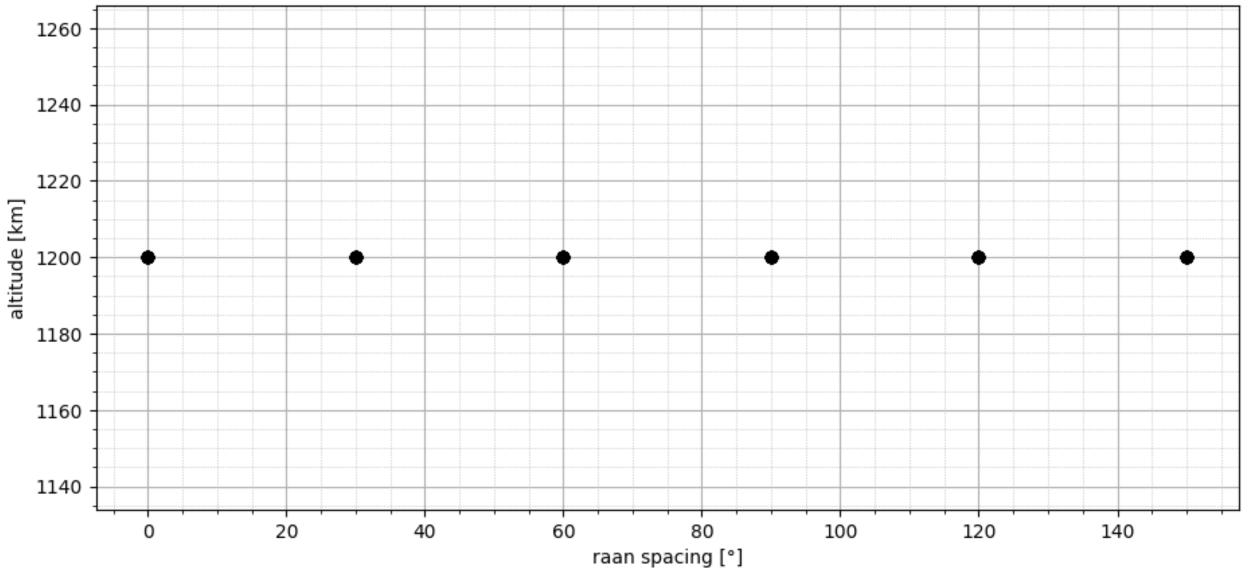

Figure 5 In this example, a fictional constellation with 6 planes and 10 satellites per plane is defined. All the satellites in a plane are deployed before the launcher manoeuvres to the next one with a RAAN drift, from 0° to 30° to 60° to 90° to 120° and to 150°.

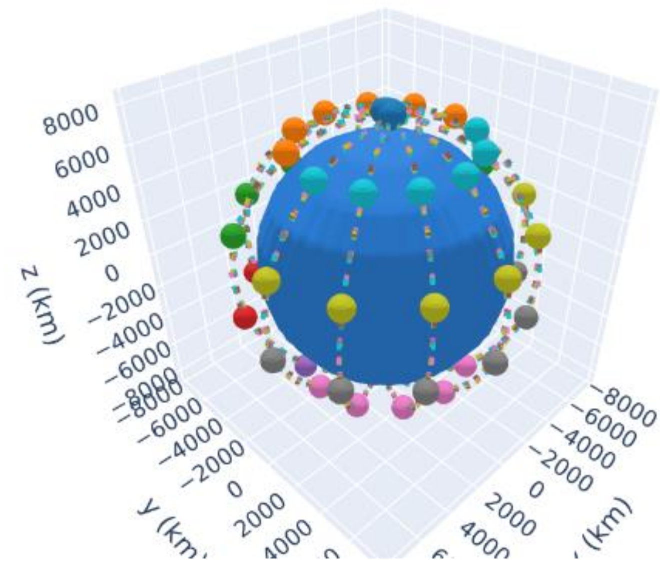

Figure 6 3D disposition of the satellites after deployment, same example constellation as on Figure 5.

Thanks to the KPIs estimates, a first sets of recommendations for space transportation vehicles could already be identified. It has been noticed that the main limitation of current launchers is not volume, but mass. Indeed, our model show that launchers full in terms of payload mass over performance still have a lot of volume available. This information could be used by launch service providers to change the shape of their fairings to maximize mass performance while keeping enough volume under the fairing to answer to market demands. Designing and operating space transportation vehicles that are used to the maximum of their performance is a way to reduce the environmental impacts as it means less vehicles are needed, and less space debris generated per payload transported.

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On the architecture of launch vehicles, those without upper stages have very limited manoeuvring capabilities due to short life in orbit or lack of restarting capability. Adding an upper stage, a kick stage, or an in-orbit transportation servicer, can enable further flexibility.

In future developments, the current limitations of the tool will be addressed. Namely the models, the output selection, and the scope of the simulation.
The models used for orbital mechanics calculations and subsystems' sizing should be improved. The RAAN drift model or the de-orbiting strategy can be complexified and a model to compute the true anomaly change manoeuvres shall be added. Additional building blocks of the servicers' architecture could be created to model launcher's upper stages, or more servicers' modules for instance.
For now, TCAT does not embed an optimization process. Only simple logical filters allow a user to select the architecture that best fulfils its mission's objectives. Adding a loop that automatically applies variations to the input parameters, to find designs that optimise the KPIs would allow to find solutions to the mission's objectives which are guaranteed to yield the best results based on the user defined inputs.
Finally, the scope of the tool could be increased, allowing more modelling freedom, and interconnecting different types of services to perform more complex missions. One could add in-situ resource utilization capabilities, in-orbit tankers, etc., to bring TCAT closer to being a comprehensive space logistics tool, able to run simulations in any context. Also, the scenarios of in-orbit servicers could be coupled with the one of launch vehicles to run one simulation for the entire mission. The outputs would be several plans, each one applied to one vehicle by opposition to having one simulation for the launch vehicle and another, decoupled one, for the servicer.

As explained later in section 5.2, TCAT will soon be linked with other software tools by exchanging data in a compatible format.

3. Connecting Space Logistics & Architecture

3.1 Context

The objective of this thesis is to develop a digital design support tool for complex space missions. As seen previously, space missions rely on increasingly more flows of material and nodes at which to meet. There are considerations for new in-orbit servicing technologies and plans for highly ambitious missions, such as large instruments, or sending humans deeper and longer into space than ever before. The design of the Apollo missions revealed a major difficulty is finding the "right" design ideas, which may depend on multiple disciplines, such as trajectory, architecture, or resource (re)manufacturing methods. In the Apollo missions, the "right" idea was to include the separation of the vehicles into a Lunar orbiter (Command and Service Module) and a Lunar lander (Lunar Module), see Figure 7.

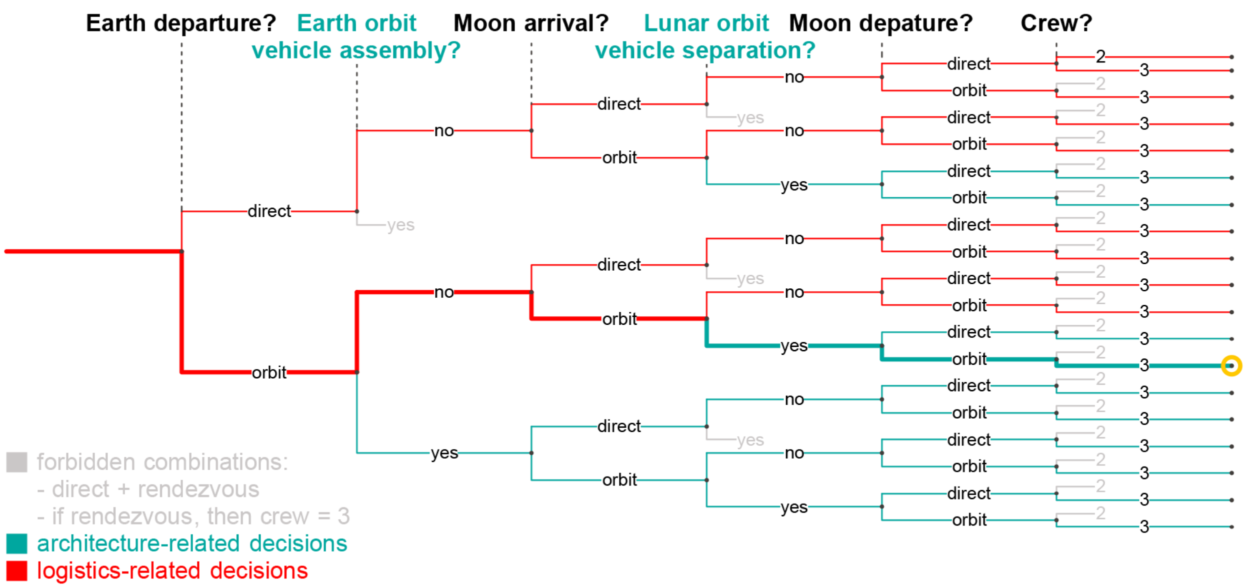

Figure 7 Decision tree for the design of the Apollo missions. This diagram is adapted from *System Architecture: Strategy and Product Development for Complex Systems* by Crawley, E., Cameron, B, and Selva, D. (2015) [19].

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3.2 Scope

This project proposed to solve this problem by using the architectural design concepts developed by Christopher Alexander in 1969. His strategy to generate the best fit for housing families based on their budget and needs includes the selection of patterns, or parts of a plan. Once the families had answered a form to define their needs, a technician would assemble patterns following an assembly algorithm, to create the most comfortable house that fell within the family's budget, as each pattern is attributed an inherent cost [16]. This technique meant a faster and more affordable architecting process, and could be applied to space mission design, supporting pre-phase A studies, such as during concurrent engineering session for example.

One of the main intended outcomes of this tool is the ability to visualise and compare many different generated mission concepts using predefined patterns. The implies that 1) the most efficient concept can be identified for a set of objectives, and 2) high value infrastructure concepts that could be effective for multiple sets of mission objectives can be identified. This is enabled by being able to compute both estimates for key figures of merit and infrastrucure design requirements using the patterns appearing in a mission's profile.

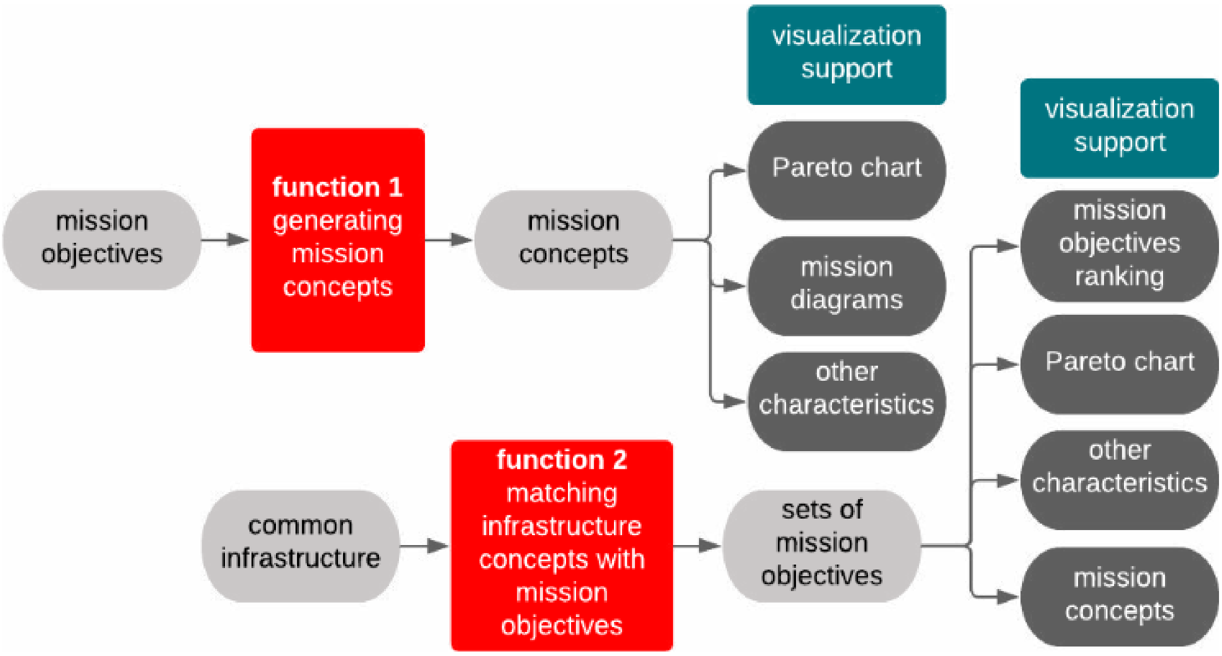

Figure 8 Connecting mission objectives to mission concepts and infrastructure design.

This tool is also intended to facilitate identifying more sustainable space mission concepts, as using patterns typically used for space mission design enables to identify and visualise not only quantitative, but also qualitative information, such as if debris are produced in orbit. It could, in the future, be considered for integration with the Space Sustainability Rating (SSR, section 1) or other tools (see section 5.2). To maximise the added value to European space, this tool will be developed and implemented with the support of ESA (ESA Contract No. 4000136422/21/NL/GLC) and ArianeGroup.

4. Lessons Learnt

Software tools at the meso-scale level in the design of space missions (see Figure 1) are useful to generate missions' concepts based on objectives and provide first, high-level estimates of cost, mass, power, or risk, associated with the architecture. These values, with other qualitative outputs, allow users to "see" and better understand the impacts of their missions on the space environment, mainly related to the question of space debris.

Understanding and visualizing the information are the first steps required to reduce the impacts. Once several concepts have been generated, mission architects can evaluate them and perform trade-offs between different options by

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considering all the KPIs computed by the tools. For example, experts might choose a mission with a slightly higher mass to LEO, if it can avoid producing debris in Earth's orbit.

At the end of the SSL initiative's contractual duration, two "lessons learnt" sessions were conducted, one internally and one with the research council supervising it. They identified a possible area of improvement to be recruitment. Indeed, the initiative has suffered from difficulties to recruit postdoctoral researchers, maybe due to the novelty of the thematic. But overall the conclusion stated that the RISSL has been a success: The research council acknowledged the correct assumptions when starting the initiative, and the efforts to bring sustainability at the heart of space transportation. Especially since the deployment of large constellations is ongoing, with more satellites to come, and as the space market is growing. The initiative was able to create research momentum even though the topic was broad.

EPFL will continue developing its expertise around SSL by improving on past projects and signing new ones, connecting its capabilities, and collaborating with an extended network of stakeholders. For the latter, not only research labs but also industries, students' associations, professors, and end-users of the space infrastructure shall be included. The next section gives a summary of the development perspectives with new projects related to sustainable space.

5. Perspectives

5.1 Green Space Logistics

A new aspect that is taking more and more importance in the life cycle of any products is its environmental impact. For the space domain, the UNCOPUOS guideline D1.3 declares that "States and international intergovernmental organizations should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets and that maximize the use of renewable resources and the reusability or repurposing of space assets to enhance the long-term sustainability of those activities" [13].
In 2021, ESA FLPP defined a new project with eSpace around the development of a tool to assess the environmental impacts of different space transportation vehicles (STVs). The green space logistics (GSL) project started in March 2022 with eSpace being the prime contractor of a consortium grouping all necessary knowledge: the Paul Scherrer Institute for their expertise in life cycle assessment (LCA), Ateleris GmbH for the software development, and ESA FLPP supported by the Cleanspace office acting as the customers.

The main objective is to allow ESA engineers to model and compare several STV configurations to help trade-off design options by including the environmental impacts in the decision-making process. FLPP is particularly interested in understanding the differences in impacts between propellant types of launch vehicles, and the impacts of the supply chain on the ground from procurement and manufacturing, up to the launch complex. The impacts coming from space debris should also be accounted for as they become a major concern for the sustainable access to space.

After a first design phase, requirements from the customers and the LCA methodology were gathered to lay the groundwork for the development. The assessment and comparison tool (ACT) is now being developed following an iterative and incremental method. In the scope of this project, the tool will output environmental impacts for three STV scenarios: expendables and reusable launch vehicles, and active debris removal satellites. Each scenario will be provided with a default configuration to facilitate the creation of new ones by the users.
After providing the required inputs to define new configurations, the user will generate an environmental report with LCA results represented using bar charts and Sankey diagrams. The tool will also provide the means to compare several configurations for the users to have a clear visibility on the differences in environmental impacts from one design to the other.

5.2 Space Logistics Tool Compatibility

The tool developed in the frame of the green space logistics project, ACT (section 5.1), and TCAT (section 2) will be made compatible. This means that a user shall be able to import some values used or computed by a tool into the other. It is foreseen that the masses of the subsystems and some KPIs from TCAT will be imported to prefill a template of an STV configuration defined in ACT. This way the user can add specific information required for the simplified LCA like materials and ground logistics, to compute the environmental impacts of the architecture proposed by TCAT to solve a given scenario (see Figure 9).

It may also be interesting to prepare the tools for a feedback loop, from ACT to TCAT. After computing several configurations and finding a compromise on the environmental impacts of the architecture, ACT could apply those

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constraints to the modelling of the fleet in TCAT with new masses and more precise cost estimates also based on the materials used and the costs of ground logistics and operations.

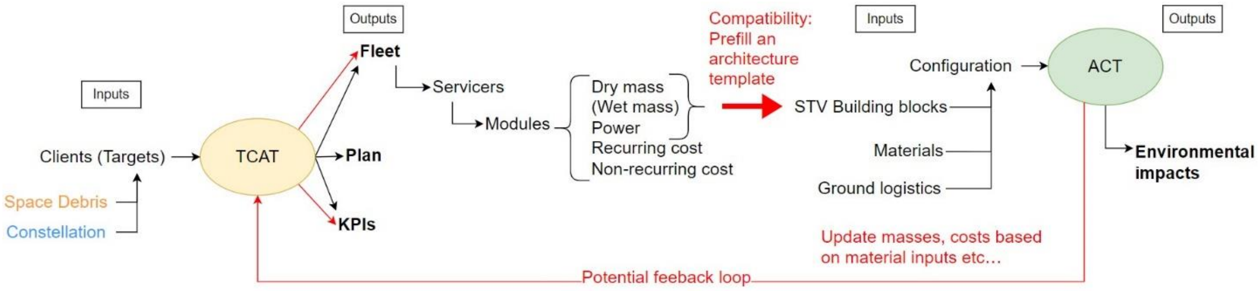

Figure 9 Highlight of the potential links (red arrows) foreseen to implement compatibility between TCAT and ACT.

The pattern language design support tool could also be linked to TCAT and ACT. Using it as a pre-processor to find feasible mission concepts based on stated mission's objectives. It would feed both tools with an STV servicer template that is used to run the logistics scenario and assess all environmental impacts. This way, eSpace could provide a tool that helps systems engineers during the feasibility study and first design phases of a space mission.

For longer-term developments, the question to be answered at EPFL, in collaboration with ESA FLPP, is how to make the best use out of those tools. They could be used during concurrent engineering sessions at EPFL that would focus on early phase design, especially for space mission design. There are also discussions ongoing to connect them with other software developed across Europe to achieve a comprehensive space logistics modelling tool which could include architecture design, trajectory optimization, environmental assessment, and multi-criteria optimization of the STV design.

6. Conclusion

Overall, thanks to the achieved outcomes, the RISSL was noted to be a success. From 2019 to 2021, the pilot phase of the research initiative on sustainable space logistics conducted at EPFL generated tangible results with the development of modelling software, the publication of several scientific papers and the success of consortia projects [1].

In addition to the technical outcomes presented in this paper, the initiative led to the creation of a large community of industry, researchers, and decision makers through the organisation of different events and exhibitions for different target audiences. In the last two and a half years, with this activity, eSpace has managed to put EPFL and Switzerland at the forefront of the sustainable space logistics topic.

After the pilot phase, the RISSL has entered its securing phase in 2022 with four main strategic directions detailed below, and it is foreseen the initiative will reach a growing phase after 2025.
The focus right now is on the operational launch of the space sustainability rating with the first ratings to be issued starting in 2022 (in-space sustainability direction).

eSpace will also continue providing support to research labs at EPFL and in Switzerland on projects around space and in particular space sustainability. Currently five projects are on-going in partnership with EPFL labs, and ClearSpace. Other projects in partnership with the International Risk Governance Center (IRGC) and the Chair of Economics & Management of Innovation at EPFL, are secured (research & innovation support, and SSL technologies directions).

Finally, the last strategic direction (space logistics optimisation) is about the two projects highlighted in this paper, at the RISSL meso-scale. The goal is to mature them to the point when they can be used by a broader space community including analysts in agencies, companies, and research laboratories. They may be used synergistically with other tool to create a comprehensive space logistics modelling software.

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