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Abstract. Ambitions for sustained human presence beyond Earth are accelerating, while environmental accountability and long development timelines expose limits of document-centric systems engineering approach. Crewed mission architectures integrate propulsion, communications, life support, and habitats under tight safety, performance, and sustainability constraints; decisions propagate across technologies and phases, and their impacts unfold over space and time under uncertainty. Model-Based Systems Engineering (MBSE) can manage architectural complexity, but it rarely embeds life cycle sustainability reasoning with sufficient fidelity or timeliness. This paper introduces the concept of a framework that unifies MBSE and Scenario-Based Life Cycle Assessment (SB-LCA) to perform continuous, traceable, time- and location-aware sustainability evaluation as systems' designs evolve. The framework consists of two layers: (i) a process-based LCA that quantifies the environmental impact of technologies to drive architecture trades; (ii) a transportation layer that selects payload-feasible launcher classes and partitions their footprint into static (manufacture, propellants, end-of-life) and variable (trajectory-resolved operations) contributions. Within this second layer, mission analysis couples emissions and atmospheric-response models to generate a geo-referenced inventory. Hetero-functional graphs capture interdependencies and enable reuse of SB-LCA modules across phases. The proposed approach is envisioned to identify dominant drivers, quantify sensitivities to payload growth, vehicle choice, and trajectory design, and iteratively guide lower-impact configurations – providing measurable environmental targets for responsible human space exploration.

Introduction

Designing crewed space exploration systems represents a complex system-of-systems problem: various subsystems – propulsion, communications, life support, etc. – must function coherently under harsh environments, long development timelines, and stringent safety and performance constraints [1]. Traditional, document-centric Systems Engineering (SE) has struggled to provide timely, traceable decision support across these tightly coupled design spaces. Model-Based Systems Engineering (MBSE) advances the state of practice by shifting to model-centric artifacts that improve consistency, collaboration, and lifecycle traceability [2]. Yet, even MBSE workflows rarely embed environmental sustainability with sufficient fidelity to influence early trades, despite the growing imperative to account for life-cycle impacts of space infrastructures. Life Cycle Assessment (LCA) and its broader sustainability formulations have recently been proposed to inform mission design, but adoption remains fragmented and often decoupled from architecture

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models and design iteration [3]. Moreover, launcher footprint and the chemical emissions produced throughout a space mission have emerged as potentially dominant contributors to climate and atmospheric impacts, reinforcing the need to co-design payload architectures with transportation choices. Recent studies quantify large climate impacts tied to rocket exhaust and compare environmental burdens across launcher architectures [4][5], while analyses of rapidly expanding space infrastructures highlight prospective greenhouse-gas footprints at constellation scale [6]. These insights motivate sustainability assessments that are (i) scenario-aware, (ii) time- and location-resolved, and (iii) natively integrated within systems models and mission analyses. Scenario-Based LCA (SB-LCA) offers a principle-based language to represent uncertainty in future technologies, operations, and policies, enabling structured comparison of plausible pathways [7]. However, practical integration of SB-LCA into MBSE remains limited by representational gaps (how to bind LCA elements to system architecture and behavior), data gaps (how to reuse and update inventories as designs evolve), and analytical gaps (how to propagate mission analysis, emissions, and atmospheric responses into life-cycle metrics). Closing these gaps is especially important in early phases of crewed missions, where small architectural changes – mass growth, interface choices, duty cycles – can cascade into different launcher classes, trajectories, and, ultimately, different environmental profiles.

This paper addresses these gaps by introducing an MBSE ARCADIA/Capella-based Modeling & Simulation (M&S) framework [8], enriched with SB-LCA, for human exploration architectures, demonstrated on a notional Lunar Habitat mission. The framework embeds LCA constructs directly into system and mission models, enabling continuous, traceable sustainability evaluation alongside performance and safety considerations. It enforces a two-layer architecture: (i) a process-based LCA layer quantifies sustainability metrics for habitat technologies to drive architecture trades; and (ii) a transportation layer that, after preliminary habitat sizing, supports the user in selecting feasible launcher classes from payload-driven macro-categories and partitions their footprint into static (manufacturing, propellants, end-of-life) and variable (trajectory-resolved operations) contributions. The variable contribution is quantified by coupling mission analysis with emissions and atmospheric-response models to produce a geo-referenced inventory along the prescribed trajectory, which is then integrated with habitat delivery impacts for a mission-level footprint [4][5]. In doing so, it turns MBSE from a passive container of sustainability results into an active co-simulation environment where environmental objectives can be traced to architecture choices, requirements, and operational concepts [2][3].

Proposed methodology

First layer. The first layer of the proposed methodology presents as main baseline a ARCADIA/Capella-based workflow [9], with the model acting as the authoritative source for requirements, behavior, interfaces, and physical architecture. Specific Capella add-ons for creating parametric extensions (PVMT) and Python bridges (Python4Capella) [10] enable the automatic extraction of model data, the execution of external analyses and simulations, and the write-back of results, thereby maintaining configuration coherence and traceability throughout iterative trade studies and early V&V. This integration pattern has been demonstrated in previous Capella applications to quantitative assessment and dynamic simulation, establishing a reliable path for analysis-in-the-loop [8]. An example of the framework structure is presented in Fig. 1.

Within this baseline, the lifecycle and the Concept of Operations (ConOps) with associated Operating Modes are modeled as co-equal artifacts and tightly linked to the evolving architecture. Mission phases and mode logic structure the full sequence of activities from early development and verification through commissioning to nominal operations, providing the temporal scaffold required for scenario-aware assessments and allowing performance and behavior to be evaluated consistently from the earliest stages [8].

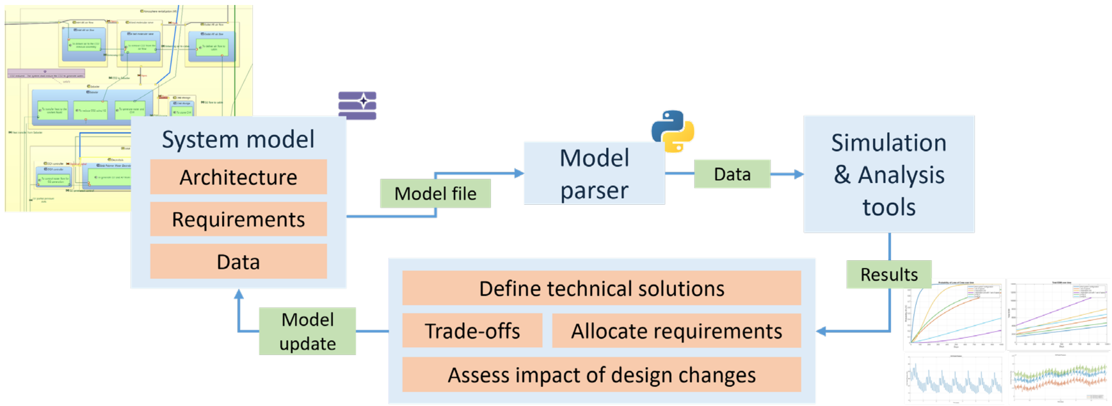

Fig. 1: First layer and M&S framework structure.

Scenario-Based Life Cycle Assessment (SB-LCA) is embedded in this environment to transform the modeled lifecycle and ConOps into quantified sustainability evidence. For a selected configuration and scenario, the Capella bridge composes the pre-operational and operational activity set from the lifecycle and ConOps, projects each activity to its planned execution year, aggregates inventories, and computes characterized impacts that are written back to the model as figures of merit alongside mass, power, reliability, and other metrics. In this way, environmental performance becomes a peer objective in model-driven trades rather than an external report, consistent with the two-layer methodology in which process-based LCA supports technology decisions at habitat level while transportation impacts are assessed separately and merged to produce a mission-level footprint. A practical bottleneck lies in building the life-cycle inventory for every component and every modeled activity. To avoid out-of-model information spread, LCA metadata are authored directly in Capella – leveraging PVMT and domain extensions – so that materials, energy, logistics, facility usage, consumables, and end-of-life assumptions are attached to components and to lifecycle/ConOps activities within the same authoritative model. This approach reuses the proven data plumbing employed for quantitative analyses and enables consistent queries by configuration, phase, or scenario; Ecodesign4Capella add-on [10] supports this in-model inventory capture and governance.

Second layer. The second layer of the framework enables the selection of a launch vehicle using outputs from the first layer – payload mass, volume, and sustainability-feasible habitat configurations – and evaluates the chosen vehicle's environmental performance on a life-cycle basis. Vehicles are drawn from a predefined pool grouped by lift capacity; once a candidate is identified, its impacts are quantified across production and operations and decomposed into: (i) a static contribution covering manufacturing of hardware and propellants and end-of-life treatment, sourced from referenced impact databases and industrial inventories [5][6][11][12]; and (ii) a variable contribution covering mission operations along the trajectory, including atmospheric responses to pollutant and greenhouse-gas emissions generated during flight [4][13][14]. The aggregation of static and variable parts yields a comprehensive, LCA-based environmental profile that supports comparative assessment and sustainability-driven trade-offs within mission design. Inputs comprise payload descriptors and a candidate set characterized by class (medium, heavy, super-heavy), stage configuration, propulsion type, propellant mass, and fairing dimensions. A selection algorithm matches requirements to a class and vehicle, within a scenario-based LCA structure that separates modeling, scenario definition, and impact evaluation for transparency and reuse [3][5][6].

Each launcher is parameterized in the MBSE environment so that mass breakdowns, propellant demand, and geometry propagate automatically to downstream assessments. This modularity enables rapid substitution of vehicles or mission scenarios with immediate updates to impacts. For the static life-cycle portion, cradle-to-gate and launch-to-grave costs of rocket hardware and propellants are quantified and split into manufacturing/upstream propellant production and end-of-life processes; reported evidence indicates manufacturing/upstream dominates the overall footprint of launch systems [5]. Hardware inventories for structures, engines, tanks, avionics, and subsystems are taken from industry LCA studies and validated databases [15], while propellant chains (oxidizer and fuel synthesis, cryogenic processing, storage) use literature emission factors [16]. Static LCA modules are implemented as reusable elements linked to the parametric launcher model so that changes in mass, materials, or configuration are reflected automatically, preserving traceability between design parameters and impact indicators.

The variable contribution is derived from mission operations by coupling a mission-analysis tool with an emissions module that produces a time-resolved, geo-referenced exhaust profile for the selected launcher, as shown in Fig. 2. Mission analysis generates the trajectory from thrust requirements, propellant mass flow, and aerodynamic characterization. The emissions module thermodynamically characterizes the engine via a simplified propulsion model and, from propellant mass, temperature, and pressure profiles, estimates time-resolved chemical outputs using combustion-kinetic formulations. Tracked species include CO_2, H_2O, NO_x, CO, and soot (black carbon). Species-specific, altitude-dependent impact coefficients from atmospheric chemistry and radiative-transfer models capture the differing climate and ozone effects across atmospheric layers [16], with high-altitude releases receiving enhanced forcing factors to reflect disproportionate radiative and chemical effects relative to surface emissions [4]. Geospatial and temporal multipliers convert emitted masses into standardized impact units (e.g., CO_2-equivalents, ozone-depletion equivalents). Resulting inventories feed impact-assessment functions (global-warming potential, ozone effects, etc.) to yield the variable share of the launcher footprint [13][14].

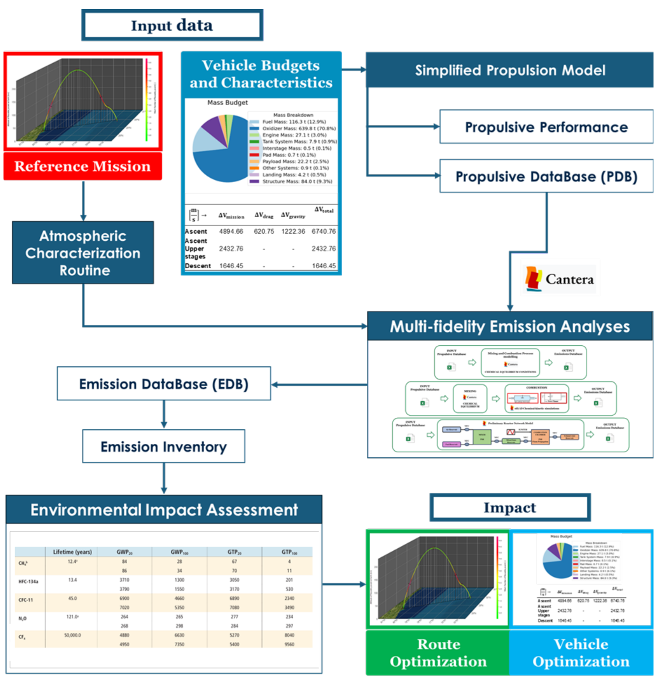

Fig. 2: Second layer dynamic contribution.

Static and dynamic contributions are then aggregated to provide the total environmental footprint of the selected transport vehicle, per mission or per kilogram of delivered habitat, expressed in standardized metrics that can be directly compared with habitat subsystem impacts from the first layer. Embedded within an MBSE/SB-LCA backbone, the process is inherently iterative: alternative vehicles, profiles (timing, trajectory), and reuse assumptions can be introduced as new scenarios, each producing updated, scenario-consistent impacts for quantitative trade-off analyses. SB-LCA principles allow systematic exploration of launch cadence, reusability rate, and technological evolution on environmental outcomes [3][5][6], while the MBSE backbone ensures consistent, traceable data flows across design iterations, inventories, and analyses [11][12][15][16].

By applying SB-LCA principles, the approach allows decision-makers to systematically evaluate how variations in key assumptions – such as launch cadence, reusability rate, or technological evolution – affect environmental outcomes, while the MBSE backbone ensures that data flows remain consistent, traceable, and fully integrated across design iterations.

In this configuration, calculated environmental impacts – time-located and scenario-consistent – serve as decision-quality figures of merit for technology selection and scheduling, while end-to-end traceability is preserved across requirements, architectural choices, lifecycle/ConOps definitions, and quantitative analyses executed from the model.

Conclusions

The presented integrated framework embeds Scenario-Based Life Cycle Assessment within an ARCADIA/Capella Modeling & Simulation workflow for crewed space systems. Lifecycle and Concept of Operations are modeled as first-class artifacts, while life-cycle inventories are authored in-model via PVMT and Ecodesign4Capella, making environmental assessment continuous, traceable, and time-located.

A two-layer formulation couples Scenario-Based Life Cycle Assessment for technology trades with a transportation layer that partitions launcher impacts into static (manufacturing, propellants, end-of-life) and variable (trajectory-resolved operations) components, ensuring delivery and pre-operational flights are captured in the mission footprint. Impact metrics are written back to the authoritative model alongside performance and safety figures of merit. The proposed approach, co-locating Scenario-Based Life Cycle Assessment with lifecycle and operating-mode models can thus expose dominant drivers early, quantify sensitivities to payload evolution, subsystem choices, launcher macro-class, and trajectory design, and support iterative convergence toward lower-impact architectures.

Current limitations center on inventory completeness, database representativeness, and uncertainty propagation across coupled analyses. Future work will emphasize uncertainty and sensitivity quantification, standardized data schemas and connectors, validation against test/flight evidence, and extensions to logistics, reuse/refurbishment, and in-situ resource utilization. With these enhancements, the framework provides a decision-grade backbone for setting – and demonstrating progress toward – measurable environmental targets in complex crewed mission design.

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