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Integrating Concurrent and Model-Based System Engineering into Hands-On Space Systems Education: Lessons Learned from the Space Mission and System Design Course at Politecnico di Torino

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Abstract

Since 2012, the MSc in Aerospace Engineering at Politecnico di Torino has offered the Space Mission and Systems Design (Progetto di Missioni e Sistemi Spaziali) course, aimed at presenting the complexity, critical aspects, and opportunities of space missions while providing the tools for their design. In this context, the course has progressively evolved toward the adoption of Concurrent and Model-Based Engineering (CE-MBSE) practices to better reflect professional methodologies in space systems development. Starting from the academic year 2023–2024, a Concurrent Model-Based approach was introduced to strengthen students' understanding and support their final small-satellite mission project. The STAR (Systems and Technologies for Aerospace Research) group contributed by developing the software infrastructure to enable concurrent design, while the teaching staff acted as the Study Authority, guiding and supervising the sessions. Students assumed technical roles typical of a concurrent engineering environment, based on their interests, competencies, and prior experience, thus simulating a realistic design facility workflow. This initiative marked the beginning of a multi-year educational evolution. The 2024 edition saw 140 students divided into 10 multi-disciplinary teams simulating ESA-style Concurrent Design Facility, developing small-satellite constellation mission for wildfire monitoring. A dedicated software infrastructure, including shared calculation sheets, a central data repository, and tools such as STK and SolidWorks, enabled collaborative mission and system design. Student feedback highlighted the effectiveness of the collaborative setup while showing the need for more integrated data management, leading to the formal adoption and integration of a data-driven system engineering approach. Building upon these results, the 2025 edition transitioned toward a data-driven workflow using Valispace for parametric budgeting, requirements management, and real-time collaboration, complemented by Capella (but as a nice-to-have addition for the students, hence non-mandatory for this edition) for the formal implementation of digital Model-Based System Engineering. These two environments were interfaced through Python APIs to ensure digital continuity and consistent synchronization of architectures, requirements, operative scenarios and budgets. Finally, the upcoming 2026 course aims at consolidating this evolution within a fully integrated Concurrent Data-Driven Model-Based framework, unifying CE, DDSE and MBSE paradigms, to teach students how to implement the different system engineering approaches to a representative case study, and supporting their learning experience to bridge the gap between Academia and the Space Industry. Results highlight how this incremental transition fosters interdisciplinary collaboration, data consistency, and system-level reasoning, opening the way for a scalable Concurrent Model-Based Learning paradigm applicable to other STEM design courses.

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Acronyms/Abbreviations

CE	*Concurrent Engineering*
CDF	*Concurrent Design Facility*
MBSE	*Model-Based System Engineering*
PLB	*Project-Based Learning*
SMSD	*Space Mission and System Design*
STAR	*Systems and Technologies for Aerospace Research*
STEM	*Science, Technology, Engineering, Mathematics*

1. Introduction

The increasing complexity of modern space missions requires engineers capable of reasoning at mission and system level, integrating multidisciplinary constraints, and operating within collaborative digital environments. While traditional engineering education provides solid technical disciplinary foundations, it often lacks exposure to realistic mission and system-level decision-making processes typical of early-phase mission design.

Concurrent Engineering (CE), widely adopted in Phase 0/A space mission development [1], enables multidisciplinary teams to iterate rapidly using shared models, usually parametric, and collaborative decision-making. However, contemporary industrial practices increasingly rely on digital continuity, data-driven processes, shifting toward Model-Based System Engineering (MBSE). The integration of these two paradigms poses new educational challenges.

This paper presents the progressive evolution of the *Space Mission & Systems Design* (SMSD) course at Politecnico di Torino toward a fully integrated Concurrent Model-Based educational framework. Starting from the explicit Concurrent workflow adoption in 2024 [2], the course transitioned toward a data-driven workflow supported by Valispace and complementary MBSE practices and is currently evolving toward a fully unified CE-MBSE paradigm for the 2026 cohort.

The objective of this work is not only to describe a course redesign, but to analyse the incremental integration of industrial system engineering approaches within a large-scale academic environment, identifying benefits, limitations and key enabling factors.

2. Project-based Learning with CE-MBSE

2.1. Concurrent Engineering & Model-Based System Engineering Overview

System Engineering (SE) is defined by the International Council of System Engineering (INCOSE) as an interdisciplinary approach that supports the realization of complex systems across their entire lifecycle, from concept to disposal [3]. In the space sector, SE practices are traditionally structured according to the V-model, formalized in ECSS standards such as ECSS-M-ST-10C [4]. While a robust and well established, this approach can be time-consuming for space systems, as strong subsystem interdependencies often cause cascades changes propagating across the entire architecture, leading to costly iteration.

To mitigate these limitations, Concurrent Engineering (CE) has progressively been adopted in space mission design [1]. CE promotes the simultaneous involvement of multidisciplinary experts during early conceptual phases, enabling parallel analysis including mission architecture definition, system and subsystem preliminary design, costs and risks assessment. This approach supports faster convergence and early identification of inconsistencies, when design flexibility is still high and the cost of change remains relatively low.

However, CE itself introduces technical and organizational challenges. Managing heterogeneous data, maintaining consistency across discipline-specific tools, and ensuring coherent decision-making in dynamic environments can limit its effectiveness[5]. In the absence of a unified system representation, information is often fragmented across spreadsheets, documents and analysis tools, reducing traceability and increasing the risk of inconsistencies. Moreover, effective concurrent collaboration requires strong coordination mechanisms and cultural alignment among stakeholders and involved actors.

Model-Based Systems Engineering (MBSE) addresses many of these limitations by formalizing system knowledge within structured models. According to INCOSE, MBSE is the "*formalized application of modelling to support system requirements, design, analysis, verification and validation*" [3]. Models act as a single authoritative source of truth, representing mission context, functional and physical architectures, interfaces and behaviours across lifecycle phases. By enhancing traceability, interface management ad dependency control, MBSE supports the structured handling of complexity typical of space missions.

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When embedded within a concurrent workflow, MBSE provides structure and consistency to a highly dynamic design environment. The integration of CE and MBSE combines multidisciplinary iteration with formalized system representation, improving traceability, transparency and decision-making robustness during the product lifecycle, from early mission phases.

2.2. Project-Based Learning within a CE–MBSE Framework

Project-Based Learning (PBL) provides a natural educational environment for implementing CE-MBSE principles. In PBL settings[6], students are required to address open-ended problems, integrate multidisciplinary knowledge, and produce tangible design outcomes under realistic constraints. Embedding CE within PBL introduces structured collaboration and role-based responsibility, simulating industrial concurrent design facilities. The addition of MBSE further strengthens this framework by requiring students to formalize assumptions, explicitly model system architectures, and maintain traceability between stakeholder needs, requirements, and technical solutions.

Within such an integrated CE–MBSE educational approach, students are not only exposed to technical analysis, but also to system-level reasoning, negotiation of trade-offs, and management of interdependencies across disciplines. The combination of rapid concurrent iteration and structured model-based representation fosters deeper understanding of architectural coherence, design rationale, and lifecycle thinking. This makes CE–MBSE particularly suited for space systems education, where complexity, multidisciplinary coupling, and early-phase decision-making play a central role.

3. Evolution of the SMSD Master's Course towards an Integrated CE-MBSE

3.1. SMSD 2024: Introduction of the Concurrent Model-Based Approach

The academic year 2023-2024 marked a major transition for the Space Mission & System Design (SMSD) course at Politecnico di Torino. A structured Concurrent Engineering methodology, adapted from ESA's CDF process, was embedded into this project-based course, resulting in what was defined as a Concurrent Model-Based educational approach [2]. With more than 140 students enrolled divided into 10 multidisciplinary teams, the course introduced four 3-hour concurrent sessions distributed over one month. The sessions were structured according to a simplified CDF-inspired workflow (Kick-off, Mission Design, System Design, Baseline Consolidation). Additionally, roles were explicitly defined - Project Manager, System Engineer, Requirements Engineer, subsystem engineers, etc. - and students were required to conduct real-time iterative design activities supported by: (i) Discipline-specific calculation sheets (Excel-based), (ii) a Central Repository (Excel-based) for shared budgets, (iii) STK for mission analysis, (iv) SolidWorks for structural configuration, (v) Risk and cost modelling sheets.

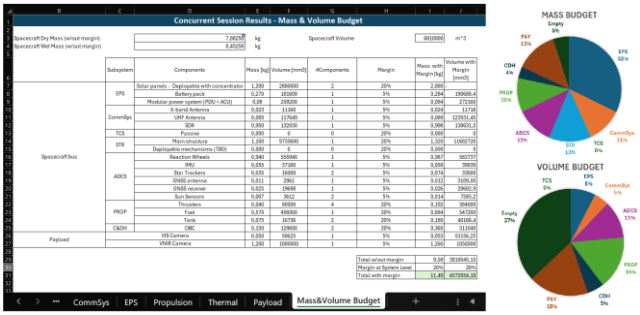

Figure 1. Central Repository - Mass & Volume Budget

The experience demonstrated that CE significantly improved multidisciplinary alignment, through milestone-driven progress checks. It implemented realistic simulation of industrial workflows, while guiding students through a learning experience improving system-level awareness and collaboration.

Feedback analysis (118 responses) confirmed that students perceived the sessions as useful for their mission design process. However, several structural limitations emerged: (i) *Limited iteration time* - 3-hour sessions perceived as too short, (ii) *Late start of concurrent sessions*, compressing workload toward the end, (iii) *Central Repository limitations*, due to manual synchronization and lack of integration with discipline tools (46% medium-to-low usefulness rating), (iv) *Noise and logistics issues* due to multiple teams working in parallel.

The 2024 edition therefore represented the explicit adoption of Concurrent Engineering, where the focus was on process structuring and real-time multidisciplinary interaction.

3.2. SMSD 2025: Transition toward a Data-Driven Workflow

Building upon the 2024 experience, the 2024–2025 edition introduced a significant shift: the progressive replacement of the Excel-based

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Central Repository with *Valispace,* a collaborative engineering data management platform. Additionally, two teams implemented Capella models throughout the concurrent sessions, as first trial.

The objective of this transition was mainly to improve traceability and configuration control, as well as to reduce fragmentation between requirements, budgets, and subsystem data.

In parallel with the adoption of Valispace, a pilot experimentation with Model-Based Systems Engineering was conducted by two volunteer teams using *Capella*, an open-source MBSE tool. The objective of this trial was to assess whether a structured MBSE tool could enhance architectural clarity and traceability within the concurrent workflow in an educational environment.

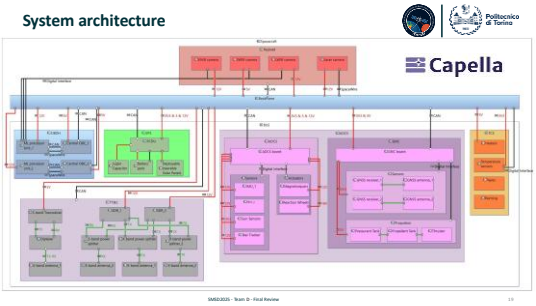

Figure 2 System Architecture in Capella by Tempest Team

The introduction of Valispace and the pilot use of Capella provided important insights into the integration of digital tools within a large-scale concurrent educational environment.

Valispace was positively evaluated for improving requirement centralization, traceability, and configuration control. Students appreciated the existence of a shared data environment aligned with industrial practices. However, adoption was uneven: several teams used the platform only passively, continued relying on Excel for subsystem sizing, and reported insufficient hands-on training. These results highlighted that tool introduction must be accompanied by structured onboarding and clearer workflow integration.

The Capella trial, conducted by two volunteer teams, showed that early functional and logical modelling improved architectural clarity and interface definition. Teams using MBSE demonstrated stronger system-level reasoning during concurrent sessions. At the same time, the additional modelling effort was perceived as extra workload, and integration with parametric sizing tools remained limited.

Overall, the 2025 experience confirmed that digital continuity and model-based reasoning can enhance concurrent design learning, but only if fully embedded in the methodology.

3.3. SMSD 2026

For the 2026 edition, starting in March 2026, the course evolves towards a fully integrated digital concurrent environment combining Valispace and Capella within the same workflow. In this configuration, Capella provides the architectural backbone, supporting the modelling of Stakeholder needs analysis and operational context, high-level functional tree, logical architecture and subsystem decomposition, as well as the explicit interface modelling. Valispace, on the other hand, supports engineering data and requirement management, with Requirement formalization and traceability, budgets (mass, power, data, ΔV), verification planning and configuration control, component-level parameter tracking.

The objective is to eliminate fragmentation between architecture and numerical sizing by aligning the functional/logical model with the parametric repository. Functional elements defined in Capella are mapped to subsystem entries in Valispace, ensuring coherence between mission objectives, system architecture, and quantitative budgets.

Within the concurrent sessions, iteration now operates on two synchronized layers: (1) Architectural layer (Capella) – to structure decisions and manage complexity; (2) Parametric layer (Valispace) – to quantify and verify design feasibility. This approach enables students to experience digital continuity similar to contemporary industrial practice: architectural reasoning guides sizing decisions, while quantitative constraints inform architectural trade-offs.

4. Conclusions

The experience gathered over three academic years demonstrates that integrating Concurrent Engineering and Model-Based System Engineering within a project-based course significantly enhances the educational return aligned with industrial practices in space systems education.

The 2024 edition established a structured educational concurrent workflow, strengthening multidisciplinary interaction and milestone-driven design. In 2025, the introduction of Valispace improved requirement traceability and data centralization, while the Capella pilot confirmed the educational value of formal functional and architectural modelling. These

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steps revealed that digital tools are effective only when fully embedded in the methodology.

The 2026 redesign consolidates a unified educational CE-MBSE framework, combining architectural modelling and parametric data management, as well as requirements management, within the same concurrent process. This approach promotes digital continuity, structured decision-making, and closer alignment with industrial practices, to bridge the gap between Academia and Industry.

A key enabler of this evolution has been the systematic collection and analysis of student feedback after each edition. Continuous assessment of strengths, weaknesses, and organizational aspects has guided iterative refinements of tools, session structure, and learning materials. This feedback-driven approach ensures ongoing improvement of the educational framework and supports its long-term sustainability and scalability.

Future work will focus on refining tool integration, strengthening onboarding strategies, and assessing the long-term impact of this integrated CE–MBSE approach on students' systems engineering competencies.

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