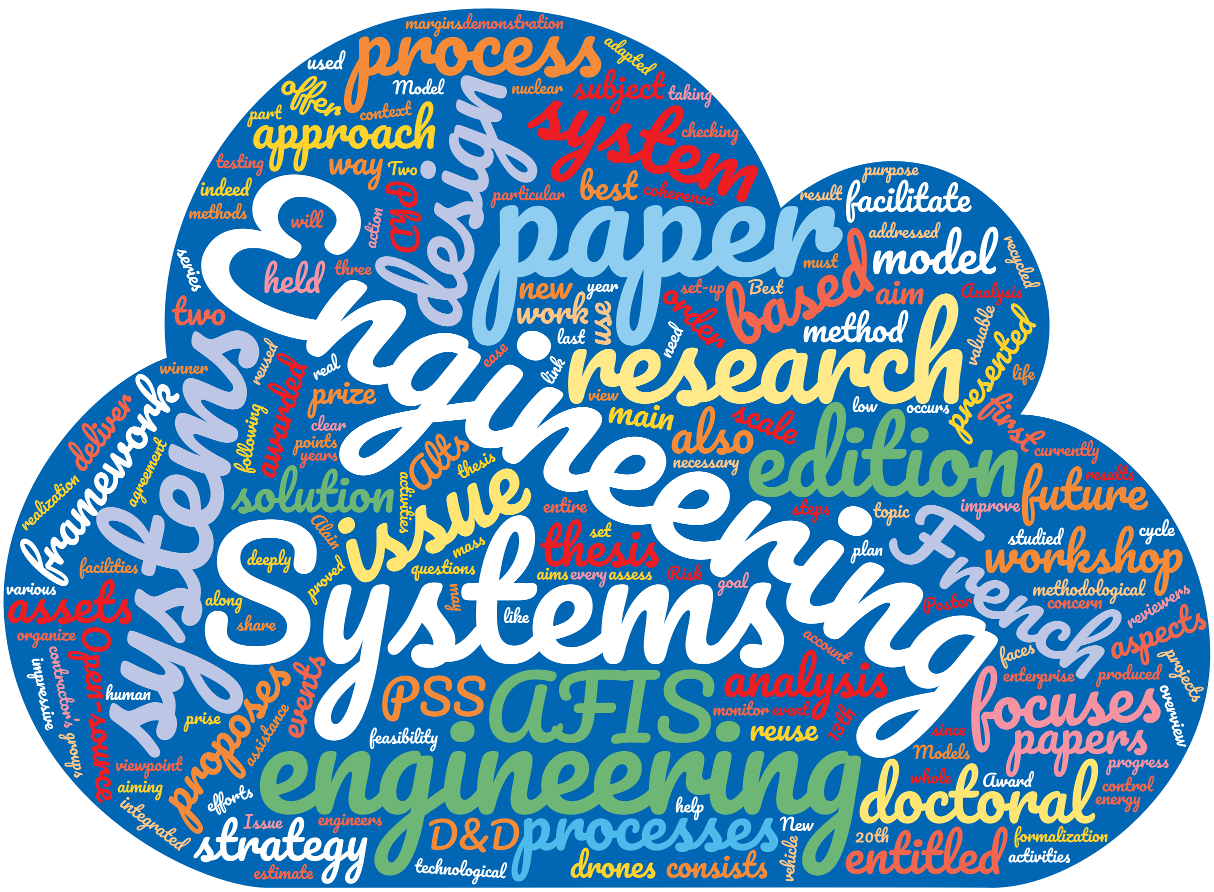
INSIGHT

This Issue's Feature:

New Challenges and Advances in Systems Engineering at French Universities



DECEMBER 2025
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INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

INSIGHT

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

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INCOSE

Inside this issue

About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 27,000 members and CAB associates and more than 200 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

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OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published six times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, digital engineering, artificial intelligence, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** tracks advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

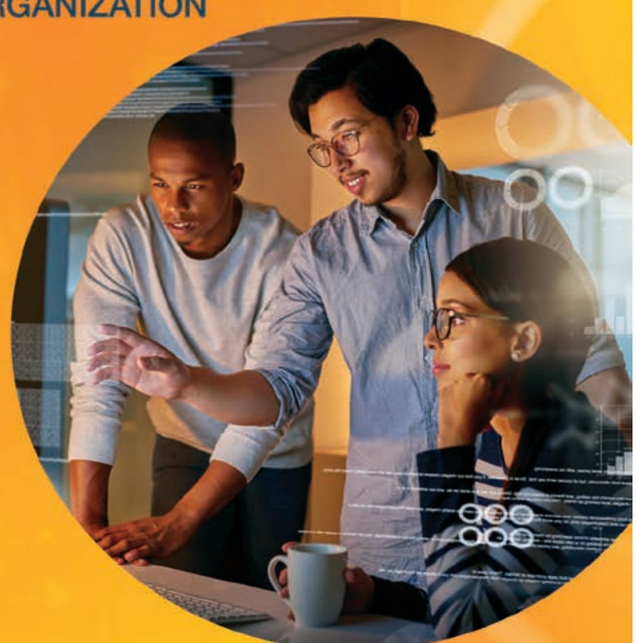
We are pleased to publish the December 2025 issue of *INSIGHT* published in cooperation with John Wiley & Sons as a magazine for systems engineering practitioners. The *INSIGHT* mission is to provide informative articles for advancing the state of the practice of systems engineering. The intent is to accelerate the dissemination of knowledge to close the gap between the state of practice and the state of the art as captured in *Systems Engineering*, the Journal of INCOSE, also published by Wiley.

The focus of this December issue of *INSIGHT* is the French Chapter of INCOSE, Association Française d'Ingénierie Système (AFIS) Doctoral Symposium: New Challenges and Advances in Systems Engineering at French Universities. We thank theme editors Jean-Marie Gauthier and Hervé Panetto. This is our ninth issue devoted to doctoral research in France. The previous issues were July 2008 (Volume 11, Issue 3), December 2011 (Volume 14, Issue 4), December 2013 (Volume 16, Issue 4), December 2015 (Volume 18, Issue 4), December 2017 (Volume 20, Issue 4), December 2019 (Volume 22, Issue 4), December 2021 (Volume 24, Issue 4), and December 2023 (Volume 26, Issue 4).

Articles were selected after peer reviews from a larger set of doctoral presentations at the French Systems Engineering Academia-Industry event in January 2025. The selected authors address the following topics:

1. Theme editorial: New Challenges and Advances in Systems Engineering at French Universities
2. Integrating Human-Conversational GenAI in MBSE: Towards Human–AI Interdependency
3. Towards a Federation Method to Enable Organizations to Interoperate on Complex Systems Engineering Projects
4. Engineering Decisions in MBSE: Insights for a Decision Capture Framework Development
5. Digital Twin Architecture Design for an Aircraft Seat Mechatronic Testbench
6. Integration of Architecture and Maintenance Points of View in an MBSE Context
7. Proposal of a Model- and Pattern-Based Method for the Engineering of a Digital Twin System
8. Digital Thread-Based Federated Interoperability for Complex Systems Engineering
9. A Requirement Conceptual Model to Support Requirements Writing and Early Verification
10. The Regeneration Ecosystems as a Holistic Approach to Overcoming the Barriers of the Circular Economy
11. Towards a CuSEF (CubeSat Systems Engineering Framework).

We thank our 2025 theme editors and authors, Chuck Eng for layout and design, the INCOSE publications office, and the staff at Wiley. We hope you have found *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. ■



INSIGHT Special Feature

New Challenges and Advances in Systems Engineering at French Universities

Jean-Marie Gauthier, jean-marie.gauthier@incose.net; and **Hervé Panetto,** herve.panetto@incose.net

INTRODUCTION

This special issue of *INSIGHT* is dedicated to the tenth edition of the French Systems Engineering Academia-Industry meetings, organized by AFIS (Association Française d'Ingénierie Système), the French chapter of INCOSE. Supported by several French universities, this series of meetings has become a regular event, usually held every two years. The tenth edition took place in January 2025.

These meetings, which are composed of workshops and plenary lectures, provides the opportunity for both academics and industrials practitioners to:

- discuss systems engineering practices, education, and competence development in professional contexts
- foster and promote research in systems engineering.

The articles gathered in this special issue are related to research presented during the doctoral seminar, offering an overview of ongoing systems engineering research in France. For this edition of *INSIGHT*, doctoral students and their supervisors were invited to submit extended versions of their presentations, with a particular emphasis on the research dimensions of systems engineering. Ten papers have been selected for publication, showcasing a diverse range of research efforts aimed at advancing systems engineering methods and practices.

Integrating Human-Conversational GenAI in MBSE: Towards Human–AI Interdependency? — *Émilie Perreau, Romain Pinquié, and Cédric Masclet (Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP)*

This research explores how conversational generative AI (CGenAI) can be meaningfully integrated into model-based systems engineering (MBSE) practices, emphasizing the human–AI interdependency that arises within socio-technical systems. The authors propose a human-centered approach to modeling human–CGenAI interaction (H-CGenAI.I) and formalize interactive patterns between engineers and generative systems. Building on a scenario-driven methodology, the work introduces a framework combining heuristic evaluation and practitioner feedback to assess these interactions. By shifting the focus from a purely techno-centric perspective toward a co-adaptive human–AI partnership, the study contributes to bridging engineering modeling practices with human-centered design principles and paves the way for more reliable, traceable, and collaborative systems engineering processes.

Towards a Federation Method to Enable Organizations to Interoperate on Complex Systems Engineering Projects — *Benjamin Robinet, Vincent Chapurlat, and Maxence Lafon (IMT Mines Alès, AXONE)*

This paper addresses the persistent challenge of interoperability in large, multi-organizational systems engineering projects, where stakeholders use diverse tools, processes, and terminologies. The authors propose a federated approach built around three core concepts: the *project organization*, the *engineering framework*, and the *collaboration space*. The engineering framework formalizes organizational practices, habits, and languages through four complementary views—functional, organic, operational, and informational—while a natural language conceptualization enables the comparison of these elements across organizations. The collaboration space then serves as a dynamic environment for negotiating and maintaining compromises to optimize interoperability without imposing uniformity. This federative method promotes a pragmatic, evolving alignment between heterogeneous engineering ecosystems, supporting more effective collaboration and knowledge sharing in complex projects.

Engineering Decisions in MBSE: Insights for a Decision Capture Framework Development — *Nidhal Selmi, Jean-Michel Bruel, Sébastien Mosser, Matthieu Crespo, and Alain Kerbrat (Université Toulouse Jean Jaurès, IRIT, McMaster University, Airbus)*

This paper investigates how decision-making can be more effectively integrated into MBSE to improve traceability and knowledge reuse. The authors propose a lightweight framework that embeds decision information directly into MBSE models by representing alternatives as "model slices," thus linking decisions to requirements, behaviors, and architectures. Using an aircraft design example, the study highlights how this approach reduces capture effort while preserving contextual knowledge and rationale. By structuring interdependencies between decisions, the method enhances understanding of design trade-offs and supports organizational learning, contributing to more efficient and knowledge-driven systems engineering practices.

Digital Twin Architecture Design for an Aircraft Seat Mechatronic Testbench — *Imane Bouhali, Jacques Martinez, Vincent Idasiak, Faida Mhenni, Jean-Yves Choley, Luca Palladino, and Frédéric Kratz (Safran Seats, ISAE-Supméca, INSA CVL, PRISME Laboratory)*

This study presents a MBSE approach for designing a digital twin architecture dedicated to testing mechatronic aircraft seats. Developed with Safran Seats, the framework integrates virtual and physical testbenches to enable earlier verification and validation through real-time simulation. The proposed modular testbench connects physical actuators and sensors with virtual multiphysics models, ensuring continuous synchronization via a dSpace controller. Structured according to the CESAM architecture grid, the digital twin encompasses operational, functional, and physical views, enhanced by the model identity card (MIC) concept to improve model traceability and reuse. By introducing a parallel V-model that combines design and virtual testing phases, the methodology allows engineers to detect integration issues earlier, optimize design iterations, and strengthen digital continuity throughout the system lifecycle.

Integration of Architecture and Maintenance Points of View in an MBSE Context *— Kim Loubat, Gwennole Boutet, Jean-Michel Bruel, Christophe Ducamp, Sophie Ebersold, Nathalie Hernandez, and Nicolas Sarda (Université Toulouse Jean Jaurès, IRIT, Airbus Defence and Space)*

This paper addresses the integration of maintenance considerations into early design stages using MBSE and ontology-based methods. Since a large portion of system costs is determined before the preliminary design review (PDR), the authors advocate for the early inclusion of maintainability and integrated product support (IPS) requirements alongside architectural design. They propose an ontology-driven framework combining MBSE and multi-disciplinary analysis and optimization (MDAO) to align architectural and maintenance data, enabling more collaborative and cost-efficient design. Using the MBike case study, the approach demonstrates how maintenance requirements, often expressed in natural language, can be formalized and integrated into design models and N^2 matrices. This method supports co-optimization of architecture and maintenance constraints, reducing life-cycle costs, and fostering a shared understanding among engineering stakeholders.

Proposal of a Model- and Pattern-Based Method for the Engineering of a Digital Twin System — *Rindra Mbolamananamalala, Souad Rabah Chaniour, and Vincent Chapurlat (IMT Mines Alès, SyCoIA)*

This paper proposes a method combining model-based systems and software engineering (MBSSE) and pattern-based systems engineering (PBSE) to support the engineering and maintenance of digital twin systems (DTS). By aligning with recent ISO standards and leveraging the digital twin capabilities periodic table, the method structures DTS development around models, data, and reusable design patterns to reduce complexity, cost, and development time. It introduces a repository of expertise, knowledge, and practices (REKP) that formalizes patterns across conceptual, architectural, and technological domains, promoting reuse and consistency. Demonstrated on a food production workshop case study, the approach guides the iterative design, verification, and validation of a DTS that optimizes scheduling through simulation and AI. The work highlights how pattern reuse within a model-driven framework enhances interoperability, maintainability, and efficiency in digital twin engineering.

Digital Thread-Based Federated Interoperability for Complex Systems Engineering — *Clarissa Gregory, Souad Rabah, and Vincent Chapurlat (IMT Mines Alès, SyCoIA)*

This paper presents a federated interoperability approach to enable digital continuity and collaboration within digital thread (DTH) environments for complex systems engineering. As heterogeneous data and models proliferate across tools and lifecycle stages, ensuring consistency and traceability becomes a key challenge. The proposed method addresses interoperability at model, data, and process levels by combining two complementary strategies: model transformation, which translates between meta-models to preserve structure, and model encapsulation, which safeguards confidentiality while allowing interaction through defined interfaces. This hybrid approach supports MBSSE processes, facilitating the reuse and integration of digital artifacts without altering stakeholders' tools or methods. By promoting on-the-fly collaboration and maintaining semantic coherence across distributed models, the study contributes to advancing digital thread implementation and enhancing interoperability, traceability, and trust in engineering data ecosystems.

A Requirement Conceptual Model to Support Requirements Writing and Early Verification — *Cyril Bacquet, Pascale Marangé, Éric Bonjour, and Alain Kerbrat (Université de Lorraine, CRAN, Airbus)*

This paper introduces a conceptual model of system requirements and a set of structured writing patterns to enhance early verification and validation (V&V) in MBSE. Addressing the limitations of natural language requirements, the proposed requirement conceptual model links requirement semantics to system functions, interactions, and observable properties, enabling formalization and traceability from textual to model-based representations. The authors define syntactic patterns for functional, performance, and interface requirements, improving consistency and interpretability across teams. Illustrated through a coffee machine case study, this approach forms the foundation of an executable model-based requirements engineering (eMBRE) framework, fostering higher-quality requirements, earlier defect detection, and a smoother transition toward model-based verification practices.

The Regeneration Ecosystems as a Holistic Approach to Overcoming the Barriers of the Circular Economy — *Martin Sautereau, Pascale Marangé, Helmi Ben Rejeb, Peggy Zwolinski, and Eric Levrat (Université de Lorraine, Grenoble INP-UGA)*

This paper proposes the concept of regeneration ecosystems as a systemic and adaptive framework to overcome the limitations of traditional closed-loop supply chains (CLSCs) in implementing the circular economy (CE). After identifying eight major barriers—including design rigidity, technological gaps, and lack of adaptability—the authors argue that CLSCs, while effective in managing reverse logistics, fail to address the broader social and environmental dimensions of circularity. Regeneration ecosystems extend CLSCs by integrating physical and digital networks that connect autonomous yet interoperable components within a system-of-systems architecture. This holistic model supports product revalorization across multiple life cycles, balancing economic, environmental, and social factors through multi-criteria decision-making. By enabling dynamic reconfiguration and continuous adaptation to regulatory, technological, or market changes, regeneration ecosystems provide a more resilient and evolutive pathway toward sustainable industrial circularity.

Towards a CuSEF (CubeSat Systems Engineering Framework) — *Mamadou Lamine Ndao, Claude Baron, and Ines Ben Hamida (University of Toulouse, Expleo Group)*

This paper introduces CuSEF, a lightweight systems engineering framework tailored to the constraints of CubeSat projects within the NewSpace context. Acknowledging the high failure rate of small satellite missions due to limited resources and the lack of structured processes, the authors propose an approach that balances methodological rigor with practical agility. Built upon the ISO/IEC 29110 standard for very small entities and complemented by key elements from the ECSS space engineering standards, CuSEF defines a simplified process model encompassing requirements, architecture, integration, and validation. The framework leverages MBSE tools such as Capella and Cameo for coherence and traceability, while integrating artificial intelligence to automate tasks like requirement drafting and test generation. By combining digital continuity, automation, and accessible engineering discipline, CuSEF aims to increase the reliability and efficiency of CubeSat developments without compromising the flexibility required by small and agile teams. ■

We are grateful to the authors for their impressive contribution and to the reviewers for their valuable assistance to the scientific relevance of this issue of *INSIGHT*.

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ABOUT THE EDITORS

Dr. Jean-Marie Gauthier is a senior research engineer in MBSE at IRT Saint Exupéry, Toulouse. His work focuses on developing and deploying MBSE methods and tools for the specification, design, verification, and validation of complex cyber-physical systems. Bridging theory and practice, he works to enhance digital continuity, user experience, and the integration of emerging technologies, such as generative AI and human–machine collaboration, into engineering workflows. He received his PhD in 2015 from the FEMTO-ST Institute, where he developed methods for integrating continuous and discrete simulation domains in SysML-based modeling and test generation. Since then, his research has spanned several industrial and European collaborative projects, including *EasyMOD* (enhancing user interaction with system models), *HECATE* (clean aviation program on digital twins for aircraft electrical power systems), *AIDEAS* (applying generative AI to engineering activities), and *ODE4HERA* (clean aviation program for digital continuity using SysML v2). Before joining IRT Saint Exupéry, he worked as an R&D engineer and consultant, contributing to major aerospace and automotive programs for Airbus, Renault, and ESA. His expertise includes model interoperability (SysML, FMI, Modelica), systems co-simulation, automatic test generation, and decision-support methods for system architects. Over his career, he has authored numerous scientific publications and received several distinctions, including the NASA MBSE SysML Challenge Award (2020). He also contributes to education and community initiatives, having lectured on systems modeling and co-simulation at ISAE-Supaero and serving as an active member of AFIS, the French chapter of INCOSE. His current research interests include model usability and human factors in MBSE, simulation and verification automation, and AI-augmented engineering environments, aiming to make systems modeling more accessible, intelligent, and collaborative. Dr. Gauthier holds the INCOSE associate systems engineering professional (ASEP) certification.

Dr. Hervé Panetto is a professor of enterprise information systems at University of Lorraine. He teaches information systems modelling and development at TELECOM Nancy and conducts research at CRAN (Research Centre for Automatic Control), Joint Research Unit with CNRS where he is managing a research project on the use of neuro-symbolic AI for formalising models related to the interoperability of cyber-physical-social systems. He is a member of the Academia Europaea and a fellow of the AAIA (Asia-Pacific Artificial Intelligence Association). He received his PhD in production engineering in 1991. He has strong experience in information systems modeling, semantics modeling and discovery, and database development. His research field is based on information systems modeling for enterprise applications and processes interoperability, He is working on the cyber-physical systems smart interoperability with neuro-symbolic techniques and cognitive digital twins. He is expert at AFNOR (French National standardisation body), CEN TC310 and ISO TC184/SC4 and SC5. He participated in many European projects including IMS FP5-IST Smart-fm project (awarded by IMS) and the FP6 INTEROP NoE (interoperability research for networked enterprises applications and software). He is serving as expert-evaluator for the European Commission, FNR, AERES, and ANR in the domain of ICT. He was visiting professor in 2013-2015 in the frame of a science without borders PVE project with PUC Parana, Brazil and visiting professor in 2016 at the UTFPR, Curitiba, Brazil. He is editor or guest editor of books and special issues of international journals. He is author or co-author of more than 200 papers in the field of automation engineering, enterprise modelling and enterprise systems integration and interoperability. From 2020 to 2023, he was chairman of the IFAC French National Member Organization (NMO). After being chair of the IFAC Technical Committee 5.3 "Enterprise Integration and Networking" from 2008 to 2014 and chair of the IFAC Coordinating Committee 5 on "Manufacturing and Logistics Systems" from 2014 to 2020, he is now vice-chair of the IFAC Technical Committee 9.3 "Control for Smart Cities". He received the IFAC France Award 2013, the INCOSE 2015 outstanding service award and the IFAC 2017 outstanding service award. He is a supporter of ELLIS, and member of DAIRO, TAILOR, and CLAIRE networks.

Integrating Human-Conversational GenAI in MBSE: Towards Human-AI Interdependency?

Émilie Perreau, emilie.perreau@grenoble-inp.fr; **Romain Pinquié,** romain.pinquie@grenoble-inp.fr; and **Cédric Masclet,** ceride.masclet@univ-grenoble-alpes.fr

■ **ABSTRACT**
Conversational generative artificial intelligence (CGenAI) offers new opportunities to support systems engineering practices but raises numerous challenges regarding human-AI teaming design. This ongoing project is exploring the design of human-CGenAI interaction (H-CGenAI.I) within socio-technical systems and proposes a modelling approach grounded in model-based systems engineering (MBSE). A scenario-driven methodology and SysML profile will be introduced to capture and formalise interactive patterns. The study also intends to develop an evaluation framework based on heuristics and practitioner feedback. This research aims to foster a human-centred integration of H-CGenAI.I into systems engineering analysis, enhancing traceability, collaboration, and reliability in the engineering of socio-technical systems.

INTRODUCTION

Defined as "*a transdisciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods*" (INCOSE 2019), the practice of systems engineering is facing new challenges, partly driven by technological revolutions. As presented in the systems engineering roadmap for 2035, systems engineering practitioners are confronted with increasingly complex systems, defined as "*a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change*" (Magee and de Weck 2002), with a stronger request for the systems stakeholders to stay in control and be accountable for its action – for example AI Act.

Identified as artificial intelligence (AI) systems capable of producing "*new and diverse content, in various formats, and for different tasks, by leveraging generative models*" (García-Peñalvo and Vázquez-Ingelmo 2023) with a conversational attribute "*pertaining to an interactive system or mode of operation in which the interaction between the user and the system resembles a human dialog*" (ISO/IEC/IEEE 24765:2017), conversational generative artificial intelligence (CGenAI) has shown growing potential to support systems engineers in handling complex systems development. Integrated into systems engineering, CGenAI has notably demonstrated the potential of analysing and translating natural language statements or informal requirements into structured requirements. Nonetheless, the use of CGenAI in critical systems development, such as aircraft, faces important challenges to ensure the quality of the joint production of the generative software and the design team. Indeed, CGenAI systems can be confronted with various barriers of adoption, which can be summarized as a general lack of curated training data, a lack of model and interaction transparency, and intrinsic technical limitations of GenAI models. For example, difficulties for adaptation to unexpected events without human intervention (Norheim et al. 2024). As such, the partial automation of the system's requirements definition task, coupled with the generative uncertainty inherent to the algorithm, raises questions about the human-CGenAI team's capacity to prevent, detect, and correct potential inaccuracies in their production (Thorne 2024). This research aligns with a growing movement of human-system integration

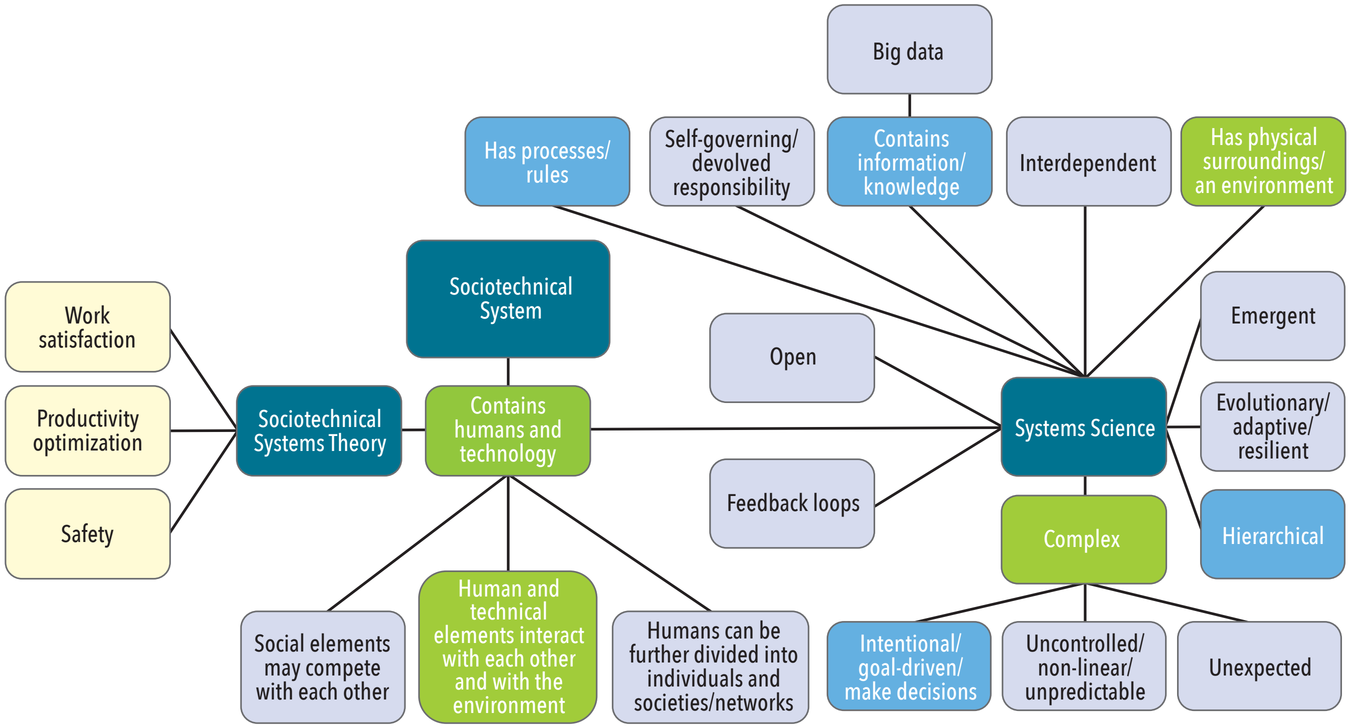

Figure 1. Socio-technical system concept map (Polojärvi et al. 2023)

(HSI), which aims to reduce techno-centric development by considering the role of analysing human-system interaction within the system-of-interest specification process. Looking at recent research, the investigation of human-AI teaming (HAT) in MBSE recognises the conditions of human-CGenAI interaction (H-CGenAI.I) as an influential factor of the system's output (Miller and Rusnock 2024). However, the research community is still lacking clear propositions on how to model H-CGenAI.I, the previous research being generalised to AI systems, without considering the specificities of CGenAI ones. As far as the authors know, the design of CGenAI's interaction with the system engineer, as well as their integration in socio-technical systems, is still considered a black box and is weakly represented in systems engineering research.

This research aims to support H-CGenAI.I design by proposing new tools and methods to enable their consideration at early design phases through MBSE practices. For this purpose, the present work develops the following research axes: what are the interactive elements to consider when designing H-CGenAI.I, and to what extent H-CGenAI.I design could be embedded within systems engineering tools? This article presents (1) an overview of H-CGenAI.I design challenges in system engineering, and (2) develop methodologies to support the integration of H-CGenAI.I in systems engineering modelling practices.

H-CGENAI.I FOR SYSTEMS ENGINEERING ACTIVITIES

Currently at the centre of research attention, the use of CGenAI is also considered to support systems engineering practitioners in their daily tasks, as part of a new wave of ASE (advanced systems engineering) examining the use of new technologies such as AI to enhance systems engineering and MBSE practice (Dumitrescu et al. 2021). In requirements engineering (RE), CGenAI systems are seen as an opportunity for requirements elicitation, analysis, specification, validation, and management. Current work highlights their main contributions in detecting, verifying, and correcting data-related requirements (Cheng et al. 2023). Applied to MBSE for RE, CGenAI systems demonstrate capabilities to support model generation from a set of requirements, notably reducing production time, improving correctness, and decreasing the perceived difficulty of the task (e.g., Crabb and Jones 2024). Despite the exposed claims, the performance of the agent is frequently evaluated from a standardised practice, with pre-structured researcher-CGenAI interactions. Despite their empirical approach, most of the research published in 2023-2024 shows limited end-user integration, resulting in reduced external validity. Researchers such as Johns et al. (2024) exposed the influence of the user's knowledge on control-group results and the high discrepancies between the CGenAI and the human production. Results such as those of Johns et al. illustrate a general need for human-centric design and evaluation. However, the definition of human-centric evaluation scenarios and criteria cannot be achieved without a clear representation of the projected H-CGenAI.I workflow and output expectations.

MODELLING HUMAN-CGENAI INTERACTION IN MBSE

From another perspective, considering AI as an element, systems engineering and MBSE are also seen as an opportunity to improve the CGenAI development phase by considering the requirements of the socio-technical system made by the human interacting with the CGenAI. A comparison with the concepts recognised in the socio-technical definition (see Figure 1) highlighted the need for considering the complexity of HCGenAI.I as a human-machine-controlled and intention-driven system. This process can be improved by using the systems engineering frameworks with MBSE to ensure the consistency and traceability of the HAT factors. Miller and Rusnock (2024) notably developed an approach to include the human-AI team in each step of the model development. The authors propose to extend modelling to new forms of representations (i.e., diagrams) with the inclusion of goal-responsibility diagrams, responsibility-capability diagrams, and agent diagrams based on information flow. Meanwhile, some other researchers, such as Boy (2024), focused on the definition of a human-centred MBSE approach, emphasising multi-agent systems and iterative development of the HAT architecture.

TOWARDS INTEGRATING H-CGENAI.I IN MBSE ANALYSIS

In consideration of the diversity of HAT domains involved in the system analysis, the project adopts a mixed approach, allowing the acknowledgment of the standardisation gap between human sciences and engineering domains. During the first steps, the research gathers and compares standardised documentations, scientific positions, and subjective viewpoints from different disciplines such as ergonomics, psychology, systems engineering, and computer science. This phase will be necessary to select and extend the current ontologies used around the HAT domain to include the concepts of H-CGenAI.I. Our methodology relies on SysML-based tooling and ergonomics activity analysis methods applied for a simulated use case of function and requirements definition of a robot subsystem. The interactions of the human and the GenAI recorded through video and logs during the use case will be instantiated in a model with a prototype of the SysML profile to capture interactive patterns between the engineer and the CGenAI system. The interactive elements will be defined from the elements in the socio-technical system, and the interaction definitions drawn from the different disciplines investigated during the literature review. Modelling output will be a customised SysML profile evaluated through the application of predefined heuristics developed during the thesis and from qualitative feedback from MBSE practitioners. Discrepancies between evaluators will be analysed using inter-rater agreement metrics, and feedback will be integrated into the model proposition. As a final output, the project aims to provide a taxonomy and its comprehensive description of H-CGenAI.I interactions for functions and requirements definition activities. To enable its integration in the early stages of MBSE processes, a customised SysML profile will be developed within the Catia Magic environment.

CONCLUSIONS AND PERSPECTIVES

This project highlights the need to shift from a techno-centred CGenAI system towards recognising H-CGenAI.I as an active factor within socio-technical systems. By positioning H-CGenAI.I as a design element to provide services, this work wishes to contribute to bridging the methodological gap between engineering modelling practices and human-centred systems integration to prevent the risks for CGenAI users and improve the efficiency (e.g., cognitive load, environmental impact) of H-CGenAI.I. The proposed methodology combines ergonomics activity analysis, experimental simulation-driven modelling, cross-disciplinary ontology development, and heuristic-based evaluation to structure the inclusion of GenAI into MBSE workflows. Future work will focus on refining the H-CGenAI.I concepts and heuristics before proposing their integration in MBSE workflows through iterative testing. In parallel, validation will be conducted with engineering teams to assess the practical relevance of the modelling constructs and the impact on design decision-making. Ultimately, this research aims to contribute to the development of supporting tools for Human-CGenAI teaming design in complex engineering contexts. ■

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Towards a Federation Method to Enable Organizations to Interoperate on Complex Systems Engineering Projects

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ABSTRACT
This paper explores the benefits of developing a method to support and enable effective collaboration between organizations involved in complex and large-scale engineering projects, particularly focused on interoperability challenges that represent a classical stake to overcome in such collaborative contexts. The paper highlights particularly issues concerning the requested use of heterogeneous engineering languages, and respect of operational practices of project stakeholders and organizational habits. The goal is to outline the foundations of a method that facilitates seamless data, information, and knowledge exchange while preserving each organization's engineering culture. To do this, the emphasis is placed on the importance of specifying, and comparing organizational habits, practices, and languages, and then finding compromises.

KEYWORDS: systems engineering, interoperability, framework, collaboration, organization

INTRODUCTION

Complex systems engineering projects involve many stakeholders with their own professions, practices, habits, and objectives, themselves being impacted by their enterprise's organization, business processes and procedures, and contractual engagements. These stakeholders must collaborate iteratively and continuously share data, information, and knowledge (DIK) and particularly models of different natures (Alaoui et al. 2023). It is then mandatory to pay attention to classical problems due to variability, veracity, velocity, volume, and value (Ishwarappa and Anuradha 2015) of these DIK at each moment. Interoperability is a requirement defined classically as "*The ability […] to exchange and use the information […]*" (IEEE 1990). So, it is a crucial requirement to ensure mutual, dynamic, and efficient understanding of all exchanged DIK, then to facilitate the requested collaboration. More generally, engineering project context must consider interoperability at different levels: organizational, process, stakeholder, tool, and DIK levels. Particularly, interoperability of practices, habits (processes and stakeholders levels), languages (tool level) and DIK (DIK level) remains a significant challenge in systems engineering projects, particularly due to the diversity of terminologies, standards (Van Ruijven 2013), and processes used by organizations (ISO/TC 184/SC 42023). At the same time, it is crucial to ensure effective communication between stakeholders involved in multiple engineering activities. The starting point of this article is expressed in the following question: "*How to get stakeholders with different practices, habits, DIK, and languages to collaborate?*"

This paper investigates this research question through two barriers (Chen 2006) 1) syntactic and semantic incompatibilities in DIK exchanges, and 2) incompatibilities between organizational structures and management techniques between different organizations.

RELATED WORK

There is abundant scientific literature about both systems engineering projects and interoperability that allows us to precisely identify these barriers as proposed in Daclin (2017). In the context of a complex system engineering project, the stakeholders and organizations involved are multidisciplinary and multi-domain. Collaboration in such a project's context does not just mean working on the same deliverables or the same tasks. It also means working on the same DIK and particularly, on various models that are elaborated throughout the project under consideration, highlighting different views, details, and characteristics of the project's system of interest. Collaboration can be achieved through a wide range of activities e.g., modeling, documenting, verifying, validating, justifying, and deciding together, as promoted for instance, in ISO:15288:2023 systems engineering processes cartography detailed in the INCOSE *Systems Engineering Handbook* (Walden et al. 2023). Effective collaboration depends in part on understanding the implicit meaning of natural language, i.e., the unspoken assumptions, implicit knowledge (Bourdon et al. 2024), and underlying concerns of stakeholders and organizations. These concerns are linked to business domains that may use different paradigms, knowledge and know-how, expertise, and skills. So, stakeholders may be subject to cognitive biases due to their roles and responsibilities during the activities in which they are involved, but also due to their education and work experiences (Walden et al. 2023). The capacity to recognize and comprehend the implicit meaning that organizations and stakeholders use is essential to reducing interoperability problems that are partially brought on by cognitive biases among stakeholders. So, a systematic and continuous specification of stakeholders' and organizations' practices, habits, and languages seems necessary.

This reasoning leads to refining the research question into the following related questions:

Q1: *How to formalize organizational practices, habits, and languages?*
Q2: *How to facilitate the identification of differences in organizational practices, habits, and languages?*
Q3: *How to implement compromises in organizational practices, habits, and languages?*

CONTRIBUTIONS

To help stakeholders fully and accurately identify the design, structure, and behavior of their organization, this section presents a generic framework comprising the necessary and sufficient components to model an organization and contribute to the objective of facilitating interoperability in a collaborative engineering context. The framework aims to define and formalize a machine-readable and interpretable format. Three key concepts are proposed in this article to structure and facilitate the reading of this section:

- A *project organization* as: *A set of processes, people, and tools aligned with strategic objectives, used to plan, coordinate, and execute projects, and characterized by homogeneous practices, habits, and languages*. (e.g., a department within a company can be considered as a "*project organization.*")
- An *engineering framework* as: *A generic reference model representative of a project organization, to be identified and specified to ensure interoperability*.
- A *collaboration space* structures and manages *engineering framework* components to enable better adjustment and arbitration of applicable components and then to optimize the interoperability of *project organizations*.

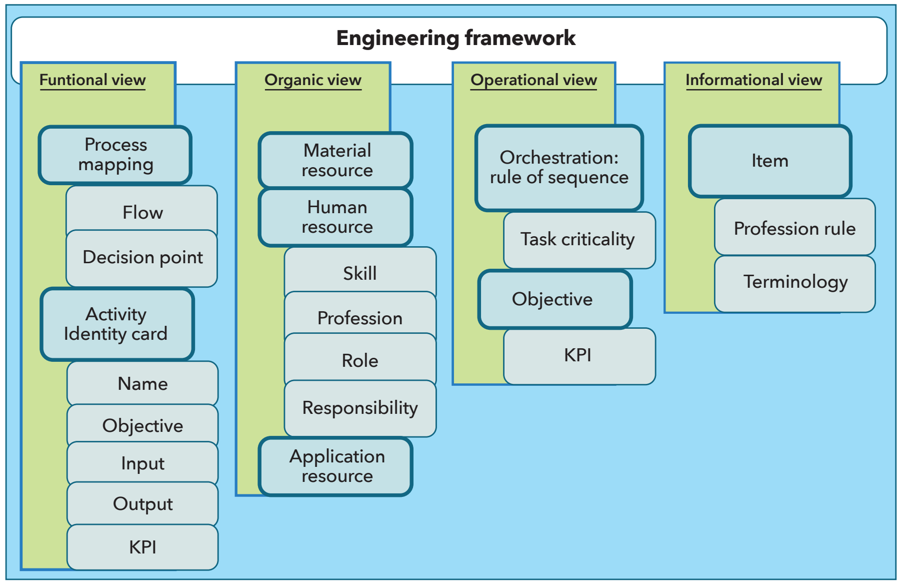

Figure 1. Engineering framework views, components, and attributes

An *engineering framework* aims to facilitate and support the specification of practices, habits, and languages, thereby improving interoperability both in the short and long term within a *project organization*. The framework is represented by four views that provide perspectives on specific concerns.

Three of these views are inspired by the SAGACE grid (Penalva 1990), used as a systemic modeling baseline (functional view, organic view, and operational view). An informational view is also added to address the items (DIK) that are essential for interpreting the first three views. Indeed, this informational view formalizes the terminology required for complete understanding within an organizational context.

As synthesized in Figure 1, the components (represented by rounded rectangles with thick outlines) of an *engineering framework* are described by attributes (represented by other rounded rectangles and attached to a component), which will help in their progressive specification. The relevance and exhaustiveness of these attributes will have to be tested through case studies. For example, an "*activity identity card*" may first be specified by a "*name*" and then progressively specified by its "*inputs*" and "*outputs.*"

In detail:

- Functional view: representation of the *project organization's* activities and processes required to achieve its objectives. This view highlights the key processes, their interactions, and the essential attributes of the activities that make them up (e.g., "*Name,*" "*Objective,*" "*Flow,*" "*KPI.*")
- Organic view: representation of the resources required for the overall operation of the *project organization*. These resources are broken down into three groups: human, application, and materiel resources.
- Operational view: representation of the elements required for day-to-day management of the various processes and resources. These elements depend on the strategic orientations of a *project organization* and support decision-making. They take the form of operational objectives, criteria, KPIs, and chaining rules.
- Information view: representation of the data, information, and knowledge required by a *project organization* to manage and carry out its projects. This includes everything from the vocabulary used to express a problem, through the words used to organize work, to the re-appropriation of formulations found in norms, best practices, standards, and technical documents.

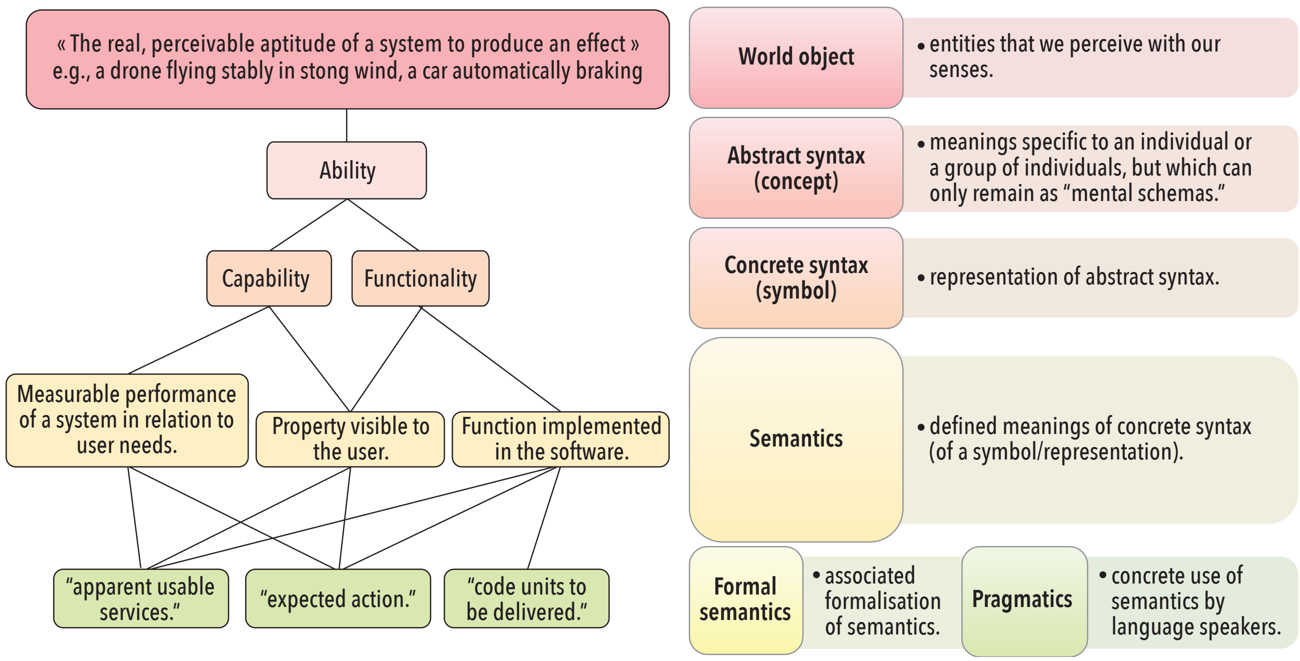

Figure 2. Natural language conceptualization applied to an example

The goal of the *engineering framework* is not to eliminate all ambiguities between the habits, practices, and languages of a given *project organization*. It is rather to make them explicit through concise and precise elements (views, components, and attributes) at various levels of granularity. The work on comparison and compromise will be based on the specifications of the *engineering framework*. The *engineering framework* addresses the issue of federated interoperability by proposing the straightforward idea that *you can't fully use something unless you understand it entirely*.

The formalization of the habits, practices, and languages of *project organizations* within the *engineering framework* is expressed in natural language, which remains a universal, adaptable, and widely used means of communication. However, it is fundamentally ambiguous: a text or expression can be understood in different ways, depending on its structure or formulation. As a result, specifications frequently contain ambiguities (Kwizera 2025). To manage this complexity and carry out the comparison work, the following natural language conceptualization is considered (see Figure 2).

On the right side, natural language is broken down as 1) "*world objects,*" perceptible entities, to which are associated 2) an "*abstract syntax,*" which corresponds to the mental meaning specific to an individual or a group of individuals. This is represented by 3) a graphical or textual "*concrete syntax,*" whose meaning is defined by 4) a "*semantic*." This "*semantic*" can be formalized by 5) a "*formal semantics*" and re-appropriated by the speakers who use the language, called 6) "*pragmatics.*" On the left side, an application example of natural language conceptualization is given. This "*world object*" (defined as "*the real, perceivable aptitude of a system to produce an effect*.") is associated, in a very convenient manner here (to consider "*Capability*" and "*Functionality*") with the abstract term "*Ability*" which arguably has several meanings among collectives and individuals. His "*concrete syntaxes*" are the terms "*Capability*" and "*Functionality.*" It is quite common in industry to talk about systems and use these terms interchangeably. Let us look at some examples of semantics and pragmatics to try to frame their uses and highlight the value of this natural language conceptualization.

The "*semantics*" examples "*Measurable performance of a system in relation to user needs*." and "*Property visible to the user*." are possible definitions of the term "*Capability;*" "*Property visible to the user*." and "*Function implemented in the software*." are possible definitions of the term "Functionality."

As for the "*pragmatics,*" they will vary according to the concerns of the stakeholder manipulating them. In the examples of "*pragmatics*" in Figure 2, "*apparent usable services*" could be the view of a client regarding a "*Capability*" or a "*Functionality.*" The "*pragmatics*" "*code units to be delivered*" could be the perspective of a developer, with a more technical vision of a "*Functionality.*"

This natural language conceptualization is proposed by this work to ease the comparison of several *engineering frameworks*' content. In other words, the comparison of habits, practices, and languages of *project organizations*.

Based on at least two *engineering frameworks*, the *collaboration space* organizes and manages tooled components that aim to facilitate DIK interpretation and sharing, e.g., raw data, contextualized information, business knowledge, and engineering models already established at the system and business levels. To achieve this, these components are structured, relying on a controlled vocabulary (ISO 25964 2013). This controlled vocabulary is built on compromises between the habits, practices, and languages of *project organizations* that collaborate. This is the result of the comparison and arbitration in the search for the best compromise to optimize interoperability. So, a *collaboration space* is then seen as an *physical (i.e., implemented) artifact that is composed of various tools that aim to considers the heterogeneity of involved enterprises' engineering frameworks and to assume their interoperability in terms of DIK exchanges, tool independence (e.g., by technical encapsulation) such as proposed in* FMI-Standard (2024) *and ability of autonomy of practice of stakeholders from various involved enterprises*. A *collaboration space* must be seen as an "*authoritative source of truth*" (Walden et al. 2023) for the stakeholders involved in a project in the context of a collaboration. The *collaboration space* will evolve alongside the project by updating the *engineering framework* specifications, comparisons, and compromises, becoming a vector for continuous improvement.

The *collaboration space* does not aim for "perfect solutions" but rather for practical and operational ones. i.e., it does not seek to achieve a high level of interoperability between organizations at all costs but to master the interoperability of a collaboration by optimizing it. An optimum must be found between the inputs (resource consumption, costs, etc.) and the effective interoperability achieved to derive maximum value for the stakeholders involved. As pointed out by Legner and Wende (2006) "[…] *the highest level of interoperability is not necessarily the optimum level of business interoperability.*"

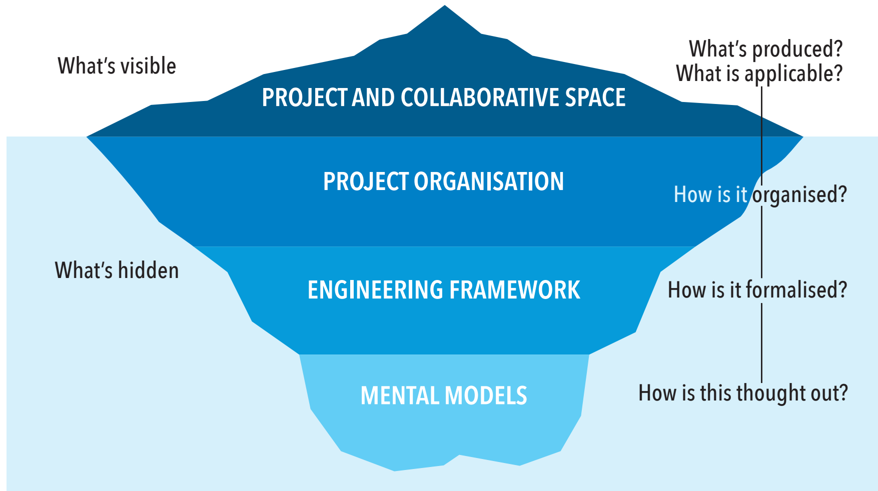

Figure 3. Overview illustration of the main concepts

CONCLUSIONS

This article provides guidance on improving interoperability between organizations by considering their existing *engineering frameworks* and addressing research questions posed above:

Q1: An *engineering framework* is a solution to capture implicit meaning by formalizing organizational practices, habits, and languages, using various element types to specify different levels of detail.

Q2: A natural language conceptualization is a solution to grasp implicit meaning; its use facilitates the identification of differences in organizational practices, habits, and languages.

Q3: A *collaboration space* is a solution to implement compromises in organizational practices, habits, and languages and so become a lever for improving interoperability between organizations.

These solutions are illustrated in Figure 3.

As a synthesis, the goal is to link the mental models of the stakeholders (prone to cognitive biases) with the most visible and concrete realities of the project. This provides a basis to apprehend conceptual barriers and organizational barriers in the context of collaboration on system engineering projects. Finally, this approach serves the goal of mastering interoperability by enabling organizations to work on specification, comparison, compromise, and evolution of their practices, habits, and languages. ■

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Engineering Decisions in MBSE: Insights for a Decision Capture Framework Development

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■ **ABSTRACT**
Decision-making is a core engineering design activity that conveys the engineer's knowledge and translates it into courses of action. Capturing this form of knowledge can reap potential benefits for the engineering teams and enhance development efficiency. Despite its clear value, traditional decision capture often requires a significant amount of effort and still falls short of capturing the necessary context for reuse. Model-based systems engineering (MBSE) can be a promising solution to address these challenges by embedding decisions directly within system models, which can reduce the capture workload while maintaining explicit links to requirements, behaviors, and architectural elements. This article discusses a lightweight framework for integrating decision capture into MBSE workflows by representing decision alternatives as system model slices. Using a simplified industry example from aircraft architecture, we discuss the main challenges associated with decision capture and propose preliminary solutions to address these challenges.

■ **KEYWORDS:** model-based systems engineering, decision capture, design rationale

1. INTRODUCTION

In response to the increasing complexity in engineered systems, model-based systems engineering (MBSE) has emerged as a solution to better manage this complexity by enhancing traceability, consistency, and collaboration. In this context, MBSE promises to help engineering teams work more efficiently by shortening development times through the use of overarching single-source-of-truth models (Campo et al. 2023). However, while traditional MBSE focuses on "what" the system is and how it functions through structural and behavioral modeling, there is little focus on "why" a certain solution is chosen. This article proposes insights on a value-based decision capture framework that can further shorten rework and revisiting time. Decisions translate the engineer's knowledge—whether explicit, implicit, or tacit—into courses of action. This makes them a valuable asset for engineering teams, as they help consolidate and leverage engineering knowledge for future projects. The remainder of this article is structured as follows. Section 2 illustrates the limitations of unstructured decision communication through a simplified example. Section 3 presents a preliminary proposal for the decision capture framework and discusses how it can potentially address the identified challenges. Finally, we conclude with a concise summary of our findings and outline promising directions for future research.

2. PROBLEM STATEMENT AND CHALLENGES

2.1 Motivating Example: An Illustration of Unstructured Decision Capture

To highlight the need for a proper, systematic approach to managing engineering decisions in the industry, we will use a simplified industry example: the implementation of a cabin depressurization function in an overall aircraft design problem. Once the airplane has landed, especially after an emergency landing, the cabin can have some residual differential pressure compared to the ambient pressure. This can lead to significant hazards: opening the aircraft doors in the presence of a pressure differential can be impossible or damage the door structure.

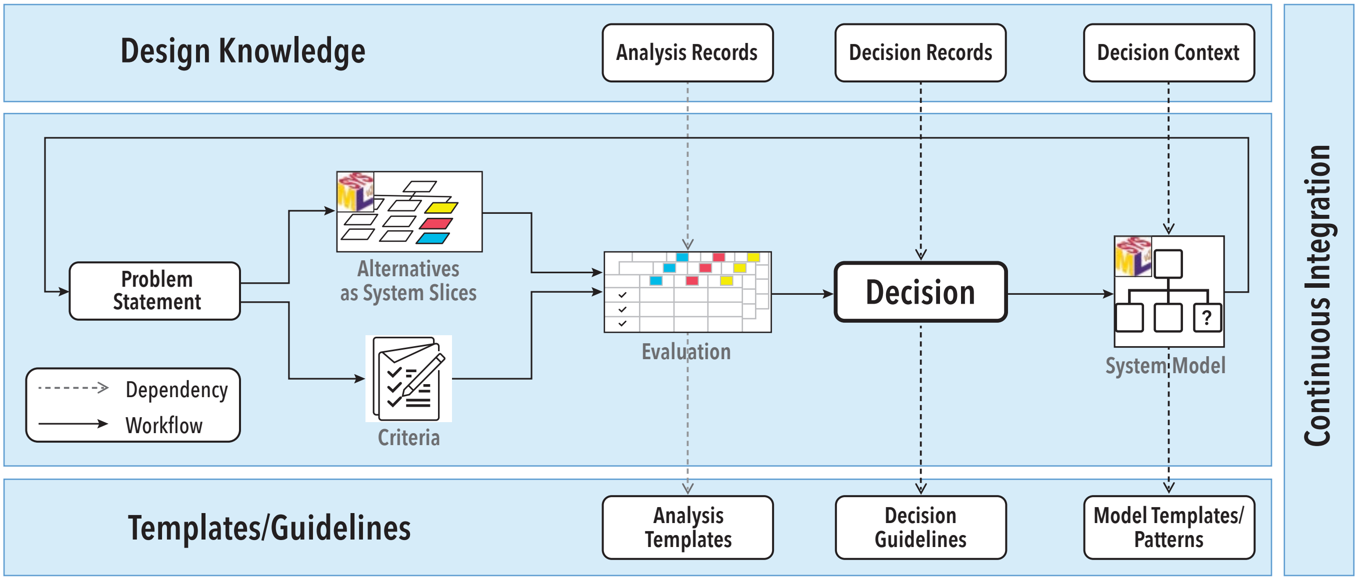

Figure 1. Decision management framework overview

Engineers with different roles in the design team are involved in treating this problem: the aircraft architect, who supports trade-off studies at the aircraft level, suggests two possible alternatives. The first option is to allocate this function to the doors system: the opening and pressure relief mechanisms are connected directly, resulting in a reliable mechanical link and reduced system complexity. The second option is to extend the existing control system to implement this function. Although this increases control complexity, it reduces weight and cost per door. The performance specialist evaluates the impact of both choices on the overall performance of the aircraft. Once evaluated, the overall aircraft architect opts for option one and communicates this choice to the system designer, who refines the architecture based on this choice.

Although the decision-making process and roles of the involved engineers are well-defined, the capture of the decision information has been done in an unstructured manner: the overall weight and performance evaluation carried out by the performance specialist is stored on their machine. The pros and cons of each alternative were communicated in a team meeting and documented in the meeting minutes. The resulting allocation of the function is stored as part of the MBSE model. Later on, if the allocation of the depressurization function is questioned by another member of the design team, they would need to collect this decentralized information from the engineers involved. Especially when developing highly complex, long lifecycle systems like aircraft, this is not straightforward. The responsible engineers might be elsewhere by the time the information is needed. Additionally, the large number of documents, analysis results, and meeting minutes stored in an unstructured manner makes it nearly impossible to find the right information.

Therefore, it is clear that there is potential value in using a more systematic approach to capturing decisions, along with their rationale and analysis. The potential value of such an approach is closely tied to the promised development cost-reduction benefits of model-based systems engineering. Making explicit the traceability between the "whats" and their respective "whys" can make the revisiting, challenging, and understanding of past decisions much more seamless. Another potential benefit is the consolidation of engineering knowledge inside the organization. For instance, reusing decisions based on context similarity can minimize rework time, leading to more efficient development.

To summarize, the decision management approach we aim to implement should focus on reducing the difficulties of revisiting and understanding the reasons behind design results and provide more structured decision information that can be useful for analysis and reuse.

2.2 Main Challenges in Decision Capture

A series of informal discussions was conducted with Airbus engineers to elicit their needs and operational constraints. Based on these discussions and reviews of existing literature (Regli et al., Lee, Harrison et. al. 2000), we identified the following challenges:

- The effort to capture decisions along with their relevant information can be obtrusive to the engineer's main activity: Separately documenting the reasons for design artifacts results in additional workload.
- Access to decision information has to be straightforward and intuitive.
- The context of the decision-making activity is very important for understanding and reusing past decisions in future design problems.
- To ensure an efficient, value-based capture of decisions, it is necessary to identify which decisions are key: A compromise needs to be found to capture only decisions that will likely be questioned, revisited, or reused.

Further challenges include scalability, confidentiality, granularity, and complexity of decisions. These have not been considered in this first proposal and will be investigated in future iterations. Another goal of our research is to leverage past decisions, including their contextual information, to formalize and enhance design knowledge, which is a valuable asset for organizations and design teams. Additionally, we aim to continuously verify the properties of decisions and related artifacts to ensure they follow defined guidelines, e.g., to ensure the completeness of the decision information.

3. STRATEGIC DIRECTIONS FOR A DECISION CAPTURE FRAMEWORK

In this section, we discuss a preliminary proposal for a decision management framework utilizing MBSE model slices. A high-level overview of the proposed decision management framework is illustrated in Figure 1. The main approach is to capture the results of decisions as slices of the system's descriptive model. The primary assumption underlying this approach is that all engineering decisions have a direct impact on the MBSE model. Making explicit this link between the MBSE model artifacts and the underlying decision information has two main benefits: (i) capture and access efficiency and (ii) potential consolidation of knowledge through context elicitation.

We use the example from Section 2 to illustrate how these benefits can be achieved. Both proposed solutions to implement the depressurization function can be identified as subsets of the MBSE model. In this case, the resulting artifact of either alternative is simply an allocation link between the depressurization function and either the cabin door component or the pneumatic and air systems component. The system modeler captures both alternatives in the MBSE model along with the evaluation criteria. Here, it is essential to note that decision rationales can also be strategic rather than merely a technical evaluation. In this example, the performance specialist creates a traceability link to their evaluation results, i.e., analysis, test, and simulation cases, assuming that these results are stored as part of the digital thread and that links can be created between them and the MBSE artifacts. The chosen course of action is simply recorded by labeling one of the alternatives as the preferred option. The capture is more efficient and less obtrusive as the system modeler captures the decisions in the same environment as the descriptive model. If the new team member needs to access the rationale for choosing the allocation to the door system instead of the control system, they can simply navigate to the rationale and disregard alternatives through the allocation link between the activity diagram and the door system. This way of accessing the rationale seems most intuitive, as we first observe what was created, to then ask why and why not.

Different types of interdependencies can be identified to better contextualize decisions. Once defined, these relationships can allow us to analyze the impact of changing one decision on the remaining linked decisions. The ISO 42010 standard for Software, Systems, and Enterprise Architecture provides examples of the possible relationships between decisions (ISO 2022). These relationships include constraints, influences, enables, triggers, forces, and subsumes, among others. For instance, the decision to use door vent flaps could trigger a new design problem concerning the positioning of these vents. Here, the "triggers" relationship is defined as a chronological link between decisions to create a streamlined decision-making process, directing the architect to the next recommended focus point (Zimmermann et al. 2009). Creating these dependencies between decisions can help contextualize a single decision, which is essential for understanding and reuse. Additionally, since the alternatives are captured as slices of the MBSE model, their context within the model and their content regarding artifacts can offer valuable information for categorizing and contextualizing the decision.

4. CONCLUSION AND PERSPECTIVES

Decisions are the translation of engineers' knowledge into courses of action. This knowledge represents an essential asset for engineering teams and organizations. Not only does value-based capture of decisions render the design process more efficient and reduce revisiting times, but it can also potentially help consolidate organizational memory and better leverage design knowledge for future projects. Our approach to capturing decision outcomes as slices of the MBSE model to overcome intrusiveness issues. Another potential benefit is the contextualization of decisions within the system and the design process, which can help gain a better understanding of the rationale and potentially improve knowledge consolidation. ■

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Digital Twin Architecture Design for an Aircraft Seat Mechatronic Testbench

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ABSTRACT
The optimization of the system development process has long been a significant challenge. In the context of aircraft business class seats, the products are mechatronics systems as they incorporate diverse discipline-specific components (mechanical, electrical, and electronic). Therefore, their design, manufacturing, and V&V (verification and validation) are complex. The V&V phase typically occurs later in the development process, adhering to the V-model and ISO 15288 technical processes. However, ensuring system behavior testing early in the development process is essential to prevent extensive rework and physical prototyping iterations. This paper presents an innovative approach integrating virtual testing in the development process of mechatronics systems. This methodology is built upon the traditional V-model, enhanced by a parallel testing process using the digital twin concept. The digital twin architecture is designed following the model-based systems engineering (MBSE) approach.

KEYWORDS: digital twin, V-model, optimization, simulation, testing, MBSE, architecture

INTRODUCTION

The integration of advanced simulation methods and tools has become essential in the complex mechatronic systems development. The virtual testing enables engineers to explore numerous scenarios to predict the system's behaviour under varying conditions without the need for physical prototypes initially. The integration of virtual multi-physics simulations into the mechatronic systems development process has been extensively studied and is recognized as an efficient and cost-effective strategy (Nattermann and Anderl 2013). While most methodologies emphasize the importance of simulation during the detailed design phase, it is important to acknowledge its potential for reducing iterations caused by specification or integration errors. Therefore, this simulation must be a continuous effort across all phases of the development process, facilitating V&V testing of system performance in each phase before progressing to subsequent phases (Bouhali et al. 2023).

Despite the extensive capabilities offered by simulations, they only provide an initial insight into potential system performance. Physical prototyping remains an indispensable step for validating these simulations and making any necessary adjustments. This step increases development costs due to the complex nature of manufacturing physical mechatronic prototypes. Advanced virtual simulations provide an important advantage by minimizing the need for iterative prototyping (Martinez et al. 2024). However, these virtual models can miss out on certain details or interactions that occur in the real world. This is where using digital twins becomes particularly beneficial in reducing gaps between expected and real system state (Grieves, and Vickers 2017). The continuous update of the digital twin based on real data is an iterative process that enhances the reliability of simulations and improves decision-making around system development. A key aspect of the digital twin concept is its reliance on having a physical system to enhance the

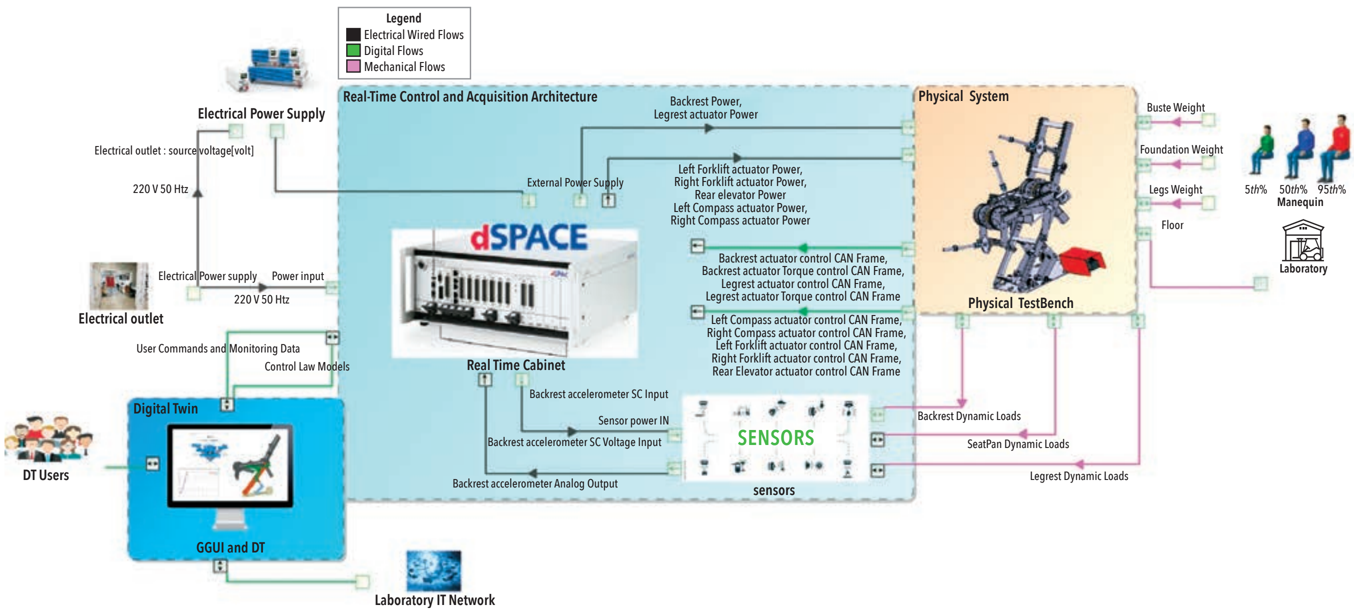

Figure 1.1. Modular and generic testbench

accuracy of virtual simulations, which remains difficult in the early phases of the V-model. Physical testbenches can serve as the physical counterpart for the digital twin, providing the necessary real-time data updates. A significant challenge arises from the diversity of products across various industries, which makes it difficult to develop tailored testbenches for each specific product. To overcome this, there is an increasing need to create a generic and modular testbench that represents a range of the company's products.

TESTBENCH DIGITAL TWIN ARCHITECTURE

One of the main goals of Safran Seats is to optimize the development process of business-class aircraft seats to reduce development cost and time, and to predict the seat's performance, such as the energy consumption (Tsai et al. 2014).

In this context, during the design phase, a physical testbench is developed to represent all the company's products. Multiple sensors instrument this testbench to gather real data, which increases the accuracy of its digital twin. The testbench (presented in Figure 1.1) is composed of:

- Generic seat: seatpan, backrest, and leg rest.
- Multi-kinematics platform: serves as a platform that enables the generic seat to move by various kinematic patterns to represent all company products' kinematics.
- BLDC (brushless direct current) actuators: The test bench contains seven BLDC actuators, controlled using robust control laws designed for position regulation and performance optimization.
- Sensors: The testbench contains several sensors necessary for real data acquisition.

The physical testbench has been designed with a modular mechanical structure, enabling the seamless incorporation of seat subsystems into its structure. This modularity is reflected in its digital twin, where seat subsystems are represented through configurable variant models within the simulation environment. This approach enables the evaluation of seat subsystems integration at an early stage of the design process, thereby reducing reliance on late-stage physical testing.

The testbench digital twin is a virtual representation connected in real-time with the physical testbench. The exchanged flow between virtual and physical entities is bidirectional, i.e., the digital twin controls the physical testbench's actuators using the control model, and the digital twin uses real data acquired from the testbench to adjust the virtual models and provide the feedback data necessary for the actuators' regulation. The interaction between the virtual and physical twins is ensured by the dSpace real-time controller, which interacts with the Simulink environment, where the digital twin models are developed. The digital twin models are initially developed based on the physical components' datasheets and behaviors, and consist of:

- Electrical models: these models predict the electrical behavior of the testbench actuators and compute the seat's electrical performance.
- Electronic models: contain the developed control law and all the necessary electronic components' models (bridges, inverters, etc.).
- Mechanical models: these models serves as the 3D representation of the testbench, which computes the dynamic mechanical performance of the testbench structure.

The interactions of these models with each other form a multiphysics model that represents all the physical testbench aspects. The architecture of this digital twin is designed in detail using the MBSE approach, allowing for the design of such a system throughout its life cycle (Pasquariello et al. 2025).

The digital twin architecture, structured according to the CESAM (composants d'architecture des systèmes d'aménagement et de mobilité) architecture grid, begins with **the operational view**, which defines the digital twin's context and interactions within its environment. This view encompasses a comprehensive analysis of the system's interaction with external entities, including the represented physical system and digital twin users, which facilitate data exchanges and operations. Within this framework, key use cases are articulated; for instance, the digital twin is employed to simulate and assess seat performance under varying conditions, enabling insights and operational improvements. Additionally, this view underscores the importance of stakeholders' requirements, gathering needs from engineers and end-users to ensure that the digital twin provides real-time data visualization, simulation accuracy compared to real data, seamless integration and a user-friendly interface.

The functional view delves into the core and main functions of the digital twin. At

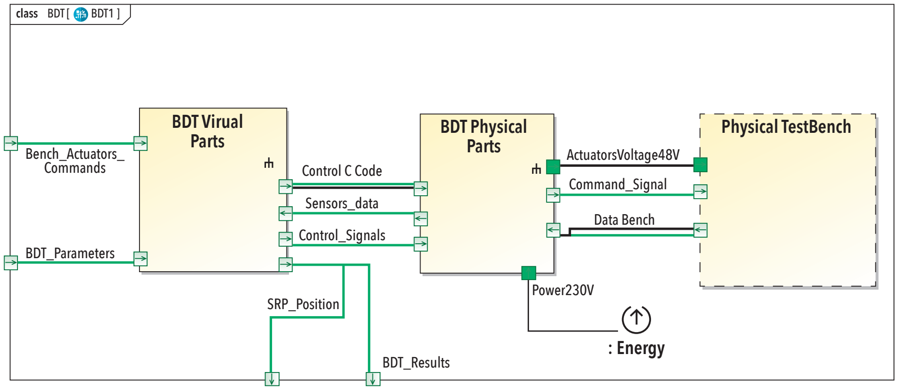

Figure 1.2. Digital twin physical view: physical and virtual parts interactions

the heart of this view is "seat performance simulation," a main function designed to explore various scenarios and adjust parameters to virtually represent real-world conditions accurately. This function is supported by sub-functions necessary to the digital twin's operation. Data acquisition outlines the methodologies for collecting real-time data from sensors, necessary for feeding into the simulation models. Another pivotal sub-function is the communication interface with stakeholders, which ensures that the collected and simulated data are effectively visualized through graphical user interfaces, promoting informed decision-making. The simulation process itself involves virtual models dedicated to replicating seat performance, while the analysis and reporting sub-function transform this data into actionable insights through reports and evaluations.

In **the physical view**, the architecture addresses the composition and integration of both virtual and physical components (Figure 1.2). It describes the virtual models at the core of simulating seat characteristics. These models exchange data with physical components, such as controllers that manage data flow and execute commands (dSpace controller in our case), and sensors that provide real-time data on various metrics, including forces, actuators' speed and current. The seamless interaction between these components is important, ensuring the digital twin's ability to perform real-time simulations and data acquisitions with precision. Owing to the modular nature of the testbench, the digital twin incorporates variant models, and the physical view reflects these variants accordingly.

Throughout the digital twin's life cycle, allocation and derivation matrices ensure continuous traceability between the different views.

To refine the digital twin architecture, the model identity card (MIC) concept is used in this methodology as a structured way to specify and document the characteristics of each model before its implementation (Bouhali et al. 2024). The MIC captures essential information such as model scope, inputs and outputs, assumptions and parameters, ensuring that models are clear, interoperable, and reusable.

TWO PARALLEL V-MODELS METHODOLOGY

The described testbench digital twin is used for business-class seat testing during the development process, following the methodology presented in Figure 2.1. This methodology consists of enhancing the traditional V-model with a parallel V-model, which describes the testing process phases:

- Preliminary virtual testing: consists of using a generic virtual model (GDM) to explore various architecture solutions.
- Virtual and physical testing: consists of using the testbench and its digital twin (BDT) to perform functional and dysfunctional tests to verify and validate the seat requirements.
- System digital twin (SDT) models creation and subsystems integration: these steps consist of creating seat models that represent exactly the produced seat.
- Advanced virtual and physical testing: consists of using the SDT connected in real-time with the manufactured physical seat to validate the seat before production.

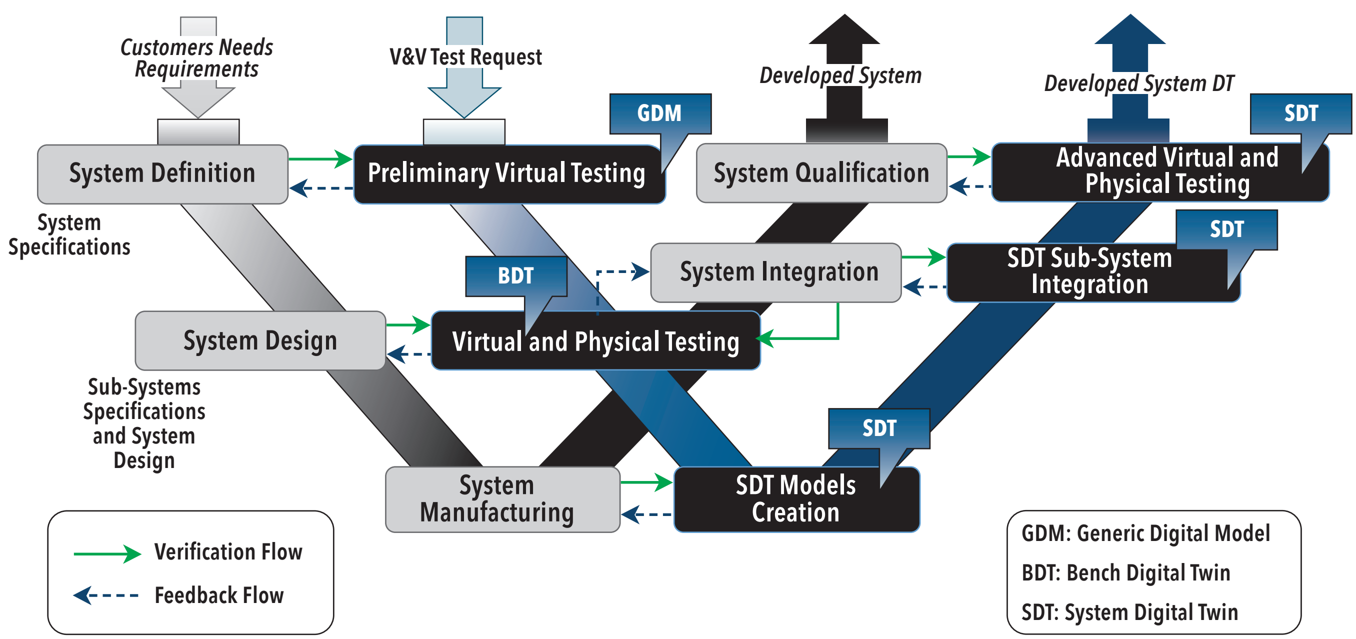

Figure 2.1. Parallel V-models: enhanced V-model with the testing process.

CONCLUSIONS AND PERSPECTIVES

By enabling earlier detection and prediction of design, manufacturing, and integration issues, the described approach promises to significantly optimize the system's development process, reduce costly iterations, and ensure system reliability and compliance with customer requirements. The MBSE approach has demonstrated its capability to design a "modular digital twin" architecture. Moreover, it improves the digital twin models specification and modifications' traceability throughout its life cycle by using the MIC concept.

In future work, we aim to validate the proposed approach through the real-time experimentation of the testbench and its digital twin. This real-time simulation will provide real data to adjust the digital twin models. Thus, increase the digital twin accuracy. ■

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Integration of Architecture and Maintenance Points of View in an MBSE Context

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ABSTRACT

In most cases, over 80% of a system's cost is already committed during the preliminary design review (PDR) of the life cycle (Claxton 1993 and NASA 2017). Overruns often occur because requirements of certain stakeholders, such as those related to maintainability, are not involved in the system design process early enough. Consequently, a collaborative effort during the design stage should involve the requirements of key stakeholders and decision-makers. In this perspective, domain ontologies and the sharing of needs should facilitate a common agreement. Systems engineers are key stakeholders to guarantee the viability of the solution system. The integration of domain ontologies within a model-based systems engineering framework will enable the interconnection of the heterogeneous data needed to integrate maintenance issues into collaborative system design. Adding maintenance requirements earlier in the design process will help limit additional costs and delays.

KEYWORDS: MBSE, ontology, MDAO, IPS, maintenance, and collaborative conception

CONTEXT

System quality usually depends on how they are built and the choices made during their development. Such choices concern several fields and impact both architectural and maintenance levels. One main challenge is dealing with the increasing complexity of systems of interest (SOI) and the increasing strategic role of integrated product support (IPS) constraints on SOI design. IPS' main role is to enable system support throughout the system's life cycle, from concept definition to disposal. IPS optimizes the management of the elements needed to keep a system operational, including maintenance, spare parts management, logistics, and many other aspects. Later, we will focus on the maintenance process, which sustains the system's capability to provide a service (INCOSE 2023).

PROBLEMATIC

Maintenance planners could be involved earlier in the design processes. Figure 1 illustrates the current process (in blue) where architecture and maintenance stakeholders are involved in the current design of an SOI. During the system's development stage, the engineering architects submit a first draft of the design system to the maintenance experts. Depending on whether the maintainability requirements are met, maintenance experts will either accept or reject the proposed architecture. This development process slows down or even prevents the solution's optimization from both financial and technical performance perspectives.

Only 20% of the life cycle cost (LCC) remains optimizable at the preliminary design review (PDR) stage. Furthermore, maintenance requirements are primarily specified in textual documents. Consequently, methods and tools are needed to formalize and integrate maintenance requirements as early as possible in the design process (cf. Figure 1, grey version).

Moreover, the maintenance organization

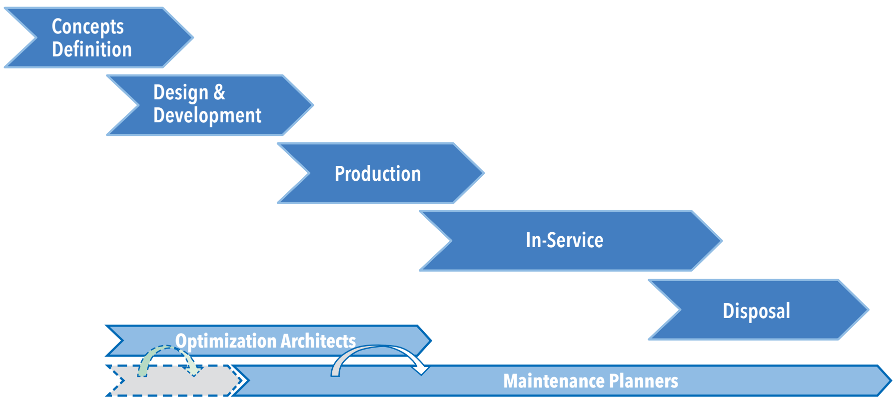

Figure 1. Current (in blue) and intended (in gray) SOI design process

is not the only element that impacts LCC, as spare parts management and logistics, in particular, also influence it. Hence, the following research question:

How can ontologies, in an MBSE framework, enable the interconnection of heterogeneous data required for integrating architecture and IPS points of view in the co-design of systems?

CHALLENGES AND OBJECTIVES

Model-based systems engineering (MBSE) and semantic web technologies provide a better context for managing systems complexity. MBSE aims to shift traditional document-centric development work to model-centric development. Different names can designate the same variables in the architecture and maintenance domains. To align this vocabulary, the current research proposes to use ontologies and knowledge graphs. An MBSE framework with ontology alignment approaches will enable the structuring and alignment of architecture and maintenance requirements. The research objective is thus to define a framework based on requirements models to improve operational and architectural collaborative design optimization.

PROPOSITION

As mentioned above, integrating IPS requirements at the beginning of a system's architectural design would help limit delays and costs. Multi-disciplinary analysis and optimization (MDAO) could be a solution for integrating not only physical phenomena but also economic and human factors, such as IPS requirements at the beginning of a system's architectural design (Martins and Ning 2021). MDAO methodologies facilitate the exploration of possible solutions and provide disciplinary experts with tools for analyzing the performance and trade-offs between selected solutions. This approach is most widely used during the architecture stage. However, IPS operational maintenance rarely deploys MDAO methodologies and is based on the S-Series specifications jointly developed by the AeroSpace and Defence Industries Association of Europe (ASD) and the Aerospace Industries Association of America (AIA) (AeroSpace 2023a).

Among these specifications, the S3000L specification supports the elicitation of the IPS requirements of the development, commissioning, and decommissioning stages during the system's design stage. The S3000L specification also maximizes the system's availability and minimizes costs throughout the life cycle (AeroSapce 2023b). The S3000L specification and the

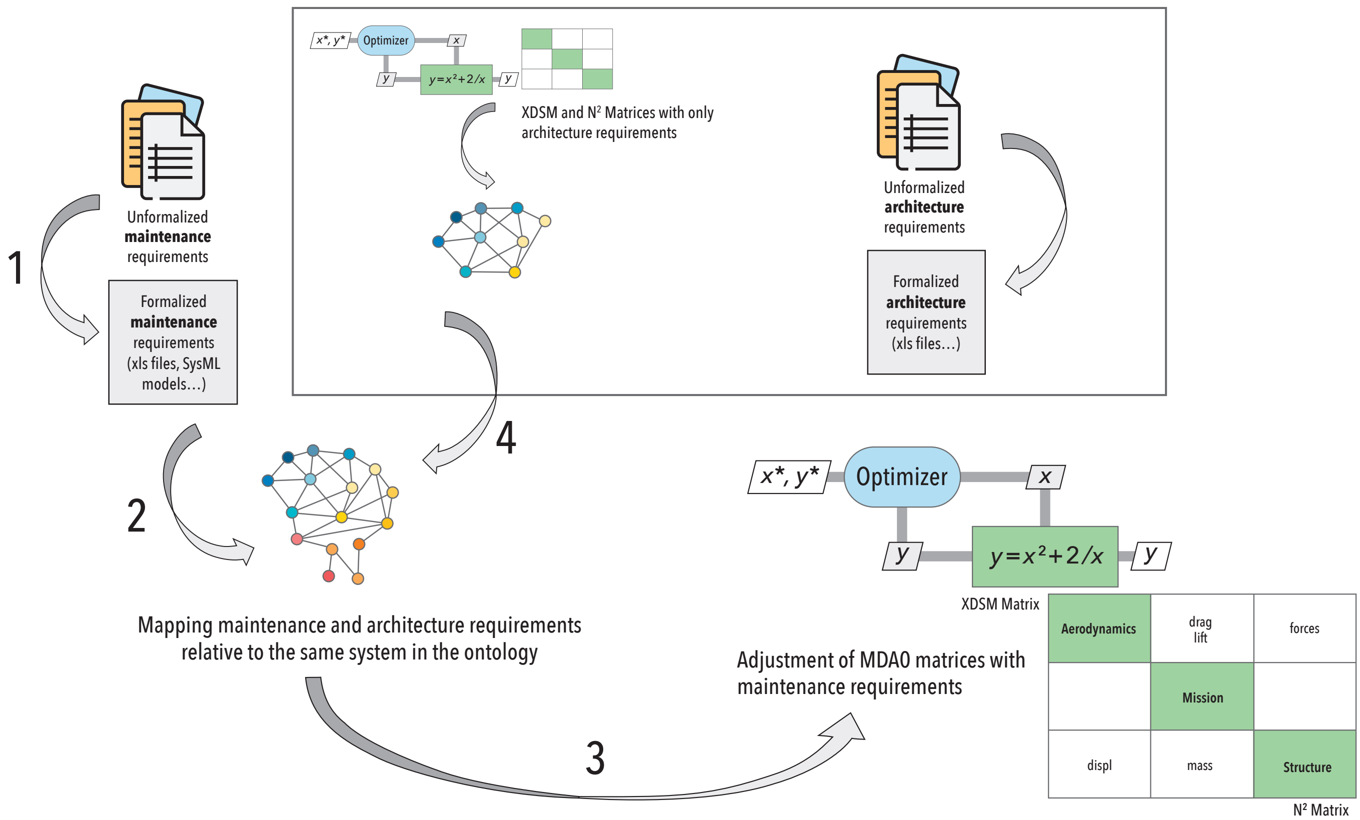

Figure 2. Future design process involving MDAO and maintenance requirements at ADS

ontologies will serve as a framework to represent the dependencies between IPS concepts and the architectural requirements of the same system.

To apply this proposition and provide an initial evaluation, a first proof of concept will be developed, based on an MBike case study, which relies on the design of a bicycle dedicated to a rental fleet. This use case is used by the Aerospace, Security, and Defence Industries Association of Europe (ASD) to demonstrate the power of the S-Series specification. An N^2 matrix is used to co-design an optimized bicycle architecture that combines maintenance and architectural requirements. The N^2 matrix represents the MDAO disciplines and the functional or physical interfaces between the elements of a system (NAS n.d.).

Figure 2 illustrates the methodology for automatically integrating requirements expressed in documents into N^2 matrices during the design process. To begin, architecture requirements are considered already integrated into the ontology, as well as the disciplines and equations that meet these requirements.

Maintenance requirements are primarily expressed in natural language in documents, sometimes in XLS files, and more rarely in SysML diagrams. The first step of the process involves extracting the maintenance requirements from XLS files, documents, or SysML diagrams to formalize them (Arrow 1) and then integrating them into the ontology (Arrow 2). This assumes that the ontology already comprises the architecture requirements and matrix aspects (Inside Frame–Arrow 4).

From the completed ontology, the maintenance constraints are integrated into the matrices (Arrow 3). Maintenance requirements are adapted into disciplines and equations to complete the existing disciplines and equations relating to the architecture requirements.

The current work consists of:

- Linking maintainability and architecture requirements to N^2 matrices to link design variables.
- Providing the Mbike graph by adding the instances relating to the bearing life requirement and instances associated with the matrices.
- Defining the queries that interrogate the graph to generate the matrices, and implementing the Python code to generate a maintenance requirement in the N^2 and XDSM matrix from the results of the queries.

CONCLUSION AND PERSPECTIVES

The proposed methodology aligns ontologies and heterogeneous models to support an early, optimized collaborative design. The MBike case study will establish the links between a system of interest (e.g., bicycles) and the integrated maintenance aspects via an MDAO and MBSE formalism. The proof of concept will result in an optimized collaborative design of an MBike in N^2 matrices, including maintenance requirements. The developed tool will support the inclusion of heterogeneous requirements early in the collaborative design of the system to provide an optimized architecture. A first validation of the proof of concept will be done through the MBike use case. ■

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Proposal of a Model- and Pattern-Based Method for the Engineering of a Digital Twin System

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■ **ABSTRACT**
The engineering and maintenance in operational conditions (MOC) of a digital twin system (DTS) remains today a difficult, time-consuming, costly and resource-intensive task. This paper proposes a method to support the stakeholders involved in such activity. It combines the principles and processes of model-based systems and software engineering (MBSSE), is inspired by the pattern-based systems engineering (PBSE) approach and is in line with the recent norms and standardization. An application on a real use case of the method is presented to illustrate the practical benefits of this contribution.

■ **KEYWORDS:** digital twin system, method, model-based systems and software engineering, pattern-based systems engineering

INTRODUCTION AND CONTEXT

In many industrial sectors, production systems are undergoing a digital transition, featuring sophisticated technologies capable of galvanizing their productivity, effectiveness and efficiency. These include the digital twin (DT), classically seen as a virtual replica of a physical entity (e.g., a production system, logistics network, or product), which is then referred to a physical twin (PT). The aim is to serve a particular purpose (ISO 23247-1:2021 2021), e.g., to control the physical entity in real time, analyze, and anticipate its possible behavioral drifts, organize and manage its maintenance or train operators. Norms and standards have expanded, and ISO/IEC 30173:2023 defines this DT as a "*Digital representation of a target entity with data connections that enable convergence between physical and digital states at an appropriate rate of synchronization.*" The same standard also put forward the concept of a digital twin system (DTS), which is a "*System providing functionality for the digital twin consisting of interoperable target entities, digital entities, data connections and models, data and interfaces involved in the data connection process.*" However, the engineering and maintenance in operational conditions (MOC) of a DTS remains a difficult, time-consuming, costly, and resource-intensive task, often in line with the MOC of the PT which is the system of interest of DTS. They therefore require the definition of sufficiently robust and adequate techniques and methodologies (Agrawal, Fischer, and Singh 2022; Hua, Lazarova-Molnar, and Francis 2022; Shao 2024; and Ali et al. 2024).

In this sense, to facilitate these engineering and MOC, the work presented here is positioned on: 1) an engineering of a DTS that follows the processes and principles of model-based systems and software engineering or MBSSE (ISO/IEC/IEEE 24641:2023; Gregory et al. 2024; Ladzinski and Tolle 2019; andTekinerdogan 2022), and 2) an engineering also aiming at leveraging the pattern concept and approaches of pattern-based systems engineering (PBSE) (Schindel and Peterson 2013; and Schindel 2024) to facilitate reusability and thus reduce the efforts of the DTS stakeholders involved.

A DTS ENGINEERING METHOD BASED ON MODELS, DATA, AND PATTERNS

Today, the engineering of a DTS is the subject of several works and references.

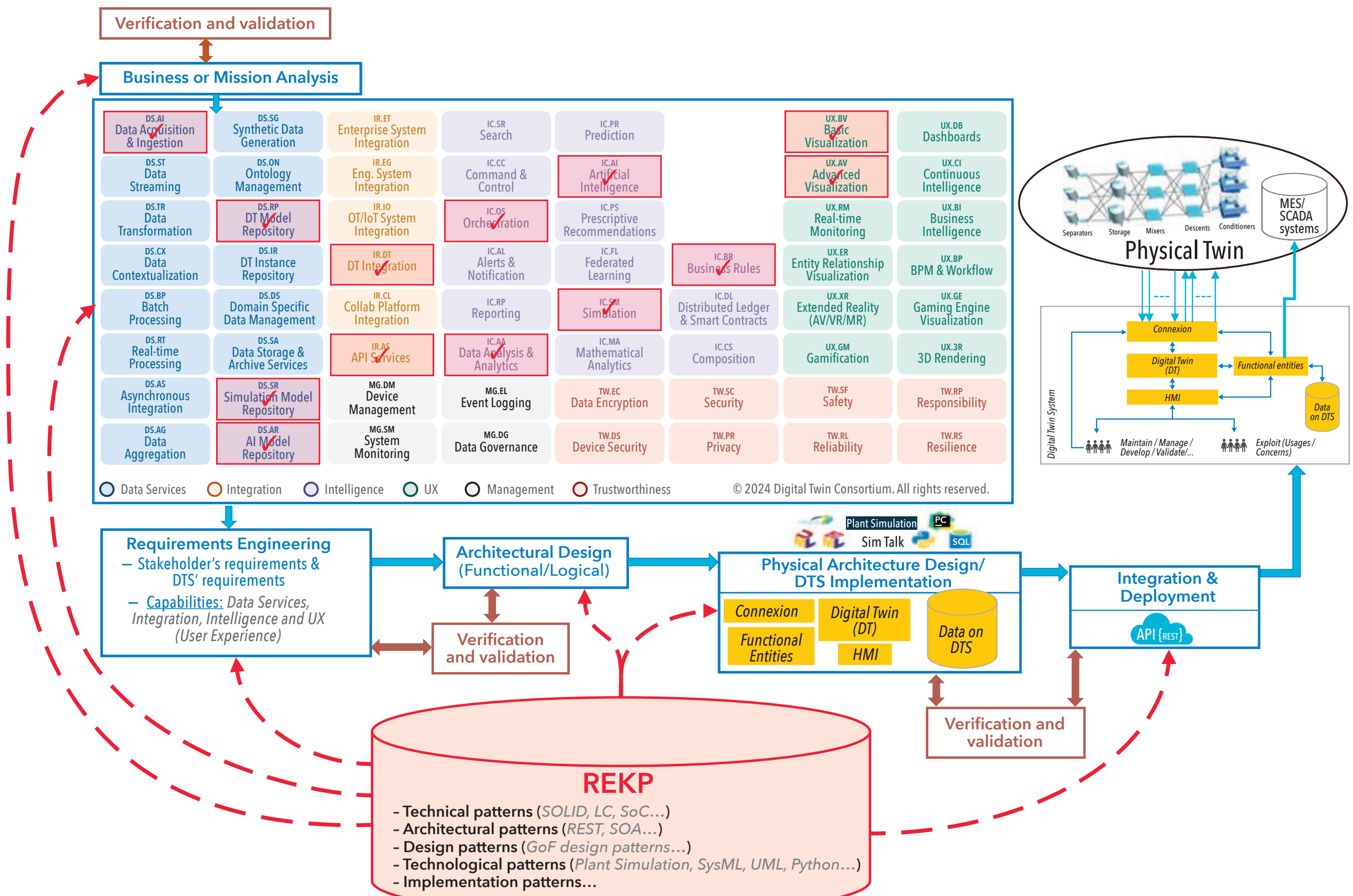

Figure 1. Summary of the application of the method on a DTS for the optimization of a workshop's production schedule

A notable contribution is the digital twin capabilities periodic table (DT-CPT) proposed by the Digital Twin Consortium (van Schalkwyk et al. 2024) which provides a comprehensive framework to classify and structure DTS capabilities. From an engineering point of view, those capabilities evoke needs that depend, among other things, on the desired use or the type and nature of the PT. They may also induce requirements to be met, both functional and non-functional. Finally, they may evoke proven solutions that can be implemented to meet the requirements. These capabilities are organized into 6 distinct groups: data services (DS), integration (IR), intelligence (IN), user experience (UX), management (MN) and trustworthiness (TW). Focusing on the contribution of this repository, the elements of the proposed method are then structured while considering the following elements.

Firstly, MBSSE is the "*formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and subsequent phases of its life cycle.*" In addition to the systems principles and processes promoted by systems engineering (INCOSE 2023), which structure and orchestrate engineering, MBSSE promotes and recommends the creation and use of models, in this case those of the DTS, to better master the system complexity. Similarly, this model orientation enables and facilitates the capitalization, reuse, and transfer of data-information-knowledge (DIK) across projects (El Alaoui et al. 2022).

Finally, a pattern is a principle associating the description of a problem encountered during design, development or MOC, with a space of solution(s), both being valid in a well-defined context (Alexander 1979; Cloutier 2005; Schindel and Peterson 2013; and Mbolamananamalala et al. 2025). It is therefore the expression of proven know-how, or even part of a company's systems engineering culture, which can be reused and continuously enriched to reduce recurring costs, errors, and delays in project implementation. Their use improves returns on investment, the quality of results, understanding and, above all, the confidence of stakeholders.

In summary, this method must promote modeling principles, activities and tools in line with the MBSSE principles incorporating the DT-CPT framework, then continuously feed, ensure consistency and make available in all DTS engineering projects a catalog of patterns structured according to:

- The very nature of the physical twin (PT), the specific needs of stakeholders (For example, designers, future users, and maintainers).
- Classes and types of problems already encountered in other projects, expressed at a generic or specific level. For example, conceptual, methodological or technical, and solutions to these problems deemed satisfactory and proven. As a reminder, the aim here is to promote the reuse and capitalization of knowledge, not by hindering but by guiding the creativity of stakeholders, and to detect errors and omissions as early as possible.
- The intended use of the DTS during the engineering phase, and the recommended capabilities.

This method is formalized by five components: 1) **concepts/attributes/relationships**, thus defining a unified and sufficient vocabulary for DTS engineering; 2) **languages** for modeling, simulation, programming, analysis,… which will use these concepts to build, analyze, improve, maintain and optimize a DTS; 3) **an operational approach** explaining how the method is implemented in concrete terms. This involves defining four master processes: acculturation, deployment, application, and continuous improvement of the method, 4) the **tools** (in this case IT tools, existing or to be created) supporting this approach in its entirety, and 5) the **REKP** (repository of expertise, knowledge and practices), which plays a crucial role in that it contains, provides access to and structures the patterns, as well as user guides, best practices and feedback on the method (ISO/IEC/IEEE 24641:2023).

ILLUSTRATION OF THE APPLICATION OF THE METHOD

In terms of illustration, the following use case consists of developing a DTS in charge (as its usage) of dynamically calculating, optimizing and then recommending a schedule for a food production workshop (Mbolamananamalala et al. 2025).

Figure 1 summarizes the essential stages of the proposed method.

A first version of the identified stakeholders' needs and system requirements repository is based on an initial interpretation of the capabilities listed in the DT-CPT (van Schalkwyk et al. 2024). The MBSSE processes of business or mission analysis, needs engineering, and requirements engineering are then implemented. Similarly, the requirements repository is expanded by the list of capabilities required for this DTS, which are identified and classified as: DS *(models repositories, etc.*), IR (*API services, etc.*), IN (*simulation, artificial intelligence (AI), etc.*), and UX (*basic and advanced visualizations*).

Architectural design can then take place (functional, then logical and physical, culminating in the actual implementation of the DTS). From then on, the REKP proposes a set of patterns likely to be useful and usable by designers, taking into account the requirements specified (for example, design Gang of Four Design Patterns aka GoF (Gamma et al. 1995) for concerns of maintainability, reusability, etc.), architectural (REpresentational State Transfer aka REST (for concerns of interoperability), technical SOLID (single responsibility, open/closed, Liskov's substitution, interface segregation, dependency inversion) principles (Martin 2000), loose-coupling (LC) principle (Mämmelä et al. 2023), separation of concerns principle (SoC) (De Win et al. 2002)… for maintainability, reusability, flexibility, modularity… concerns), and technological (Tecnomatix PlantSimulation tool and Siemens Simtalk language for simulation concerns, Python language and environment for AI concerns, SQL language for database (DB) concerns, etc.). These patterns guide and support the designers in the architectural design, implementation and integration of the subsystems (DT, connexion layer, HMIs (human-machine interfaces), functional entities and DB). At the end of the architectural design process, the first version of the DTS is proposed, before iterating through the previous stages (induced requirements, detailed architectural design, then software and hardware implementation). Verification and validation activities naturally punctuate each activity in each process, drawing on techniques for proving, simulating, and evaluating the characteristics of the DTS obtained at each iteration. Convergence toward an implemented DTS, consistent with the initial requirements and expected use, will then lead to the deployment of the DTS in its supersystem (connected to the PT and allocated to the software and hardware architecture planned to move into the installation, parameterization and production phase). Here, this DTS is mainly made up of a federation of simulation models and AI recommending improved scheduling. At this stage, its maintainability, interoperability and reusability are guaranteed by the upstream application of appropriate patterns (SOLID, SoC, LC, GoF, REST...).

This operational approach is intended to be iterative, incremental and collaborative. The same processes as those used during the engineering phase are then used during that of the MOC. Depending on the new needs/requirements to be considered and current state of the DTS, the application of those processes for MOC-related activities might be adapted and even lighted.

CONCLUSIONS AND FUTURE WORK

The DTS engineering and MOC method proposed in this paper favors the reuse of tried-and-tested solutions, thus reducing errors and project costs, in line with the expected uses of the DTS. Future work will focus on a series of iterations between formalization, development and validation of all the components of this method, through the use cases proposed by the industrial partners within the framework of the "digital twins for industrial systems" chair. ■

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Digital Thread Based Federated Interoperability for Complex Systems Engineering

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■ **ABSTRACT**
Large amounts of heterogeneous data are generated, used and managed all along engineering projects. The concept of digital thread (DTH) is therefore evoked to assume digital continuity, consistency, and traceability of these data. To this purpose, this paper proposes an approach to address data, tool, and processes interoperability problems in the DTH.

■ **KEYWORDS:** digital thread, digital twin, federated interoperability, model-based systems and software engineering

INTRODUCTION

All along systems engineering projects, stakeholders (architects, engineers, business engineers, …) are involved in different modelling, analysing, checking, and decision activities, hereafter driven by systems engineering methodologies, principles, and processes (ISO/IEC/IEEE 15288:2023) reinforced by role and relevance of modeling in model-based systems and software engineering (MBSSE) (ISO/IEC/IEEE 24641:2023) . These activities generate various digital elements (e.g., data, models, documents, or simulation results). These are defined as 'items' (El Alaoui et al. 2022) and must be used and shared without ambiguity. These items are semantically differentiated, defined by using different tools, stored under various formats and rules, but they describe the system of interest view by view, at different levels of details and for various analysis and decision perspectives. Items evolving at various paces, serve diverse, interdependent and questionable modelling and analysis objectives. However, at a given time, they represent the system of interest (SoI) to be designed and implemented under a specific view at a given level of details. Despite heterogeneity factors, the items form a complete digital modelling environment enabling to define, characterize, argue, and explain the choices made along the engineering of SoI.

The concept of digital thread (DTH) is then evoked to ensure consistency and traceability of items (AIAA Digital Engineering Integration Committee 2023), participating in improving items' trustworthiness, interoperability, traceability, and consistency, becoming an authoritative source of truth. The DTH purpose is to gather, structure, organize, manage, and provide items from and to stakeholders. The DTH is then crucial to support engineering activities and processes such as modelling, manufacturing, or inspection (Kwon et al. 2020) and linking items together (Kasper, Pfenning, and Eigner 2024). However, managing items' variability, veracity, velocity, volume, and value (Ishwarappa et al. 2015) face interoperability challenges at different levels. This paper focuses on an approach to address these challenges, and to propose a first step towards DTH implementation solution. The aim is to leverage items during different phases of SoI lifecycle, or for the engineering of other associated entities such as a SoI digital twin (DT) (Semeraro et al. 2021).

PROBLEM STATEMENT

Models are considered as a particular kind of item, formalising among other SoI as conceived or envisioned by stakeholders. Models are themselves heterogeneous in terms of type, purposes, nature, used modelling language or tool, or level of maturity, or also version.

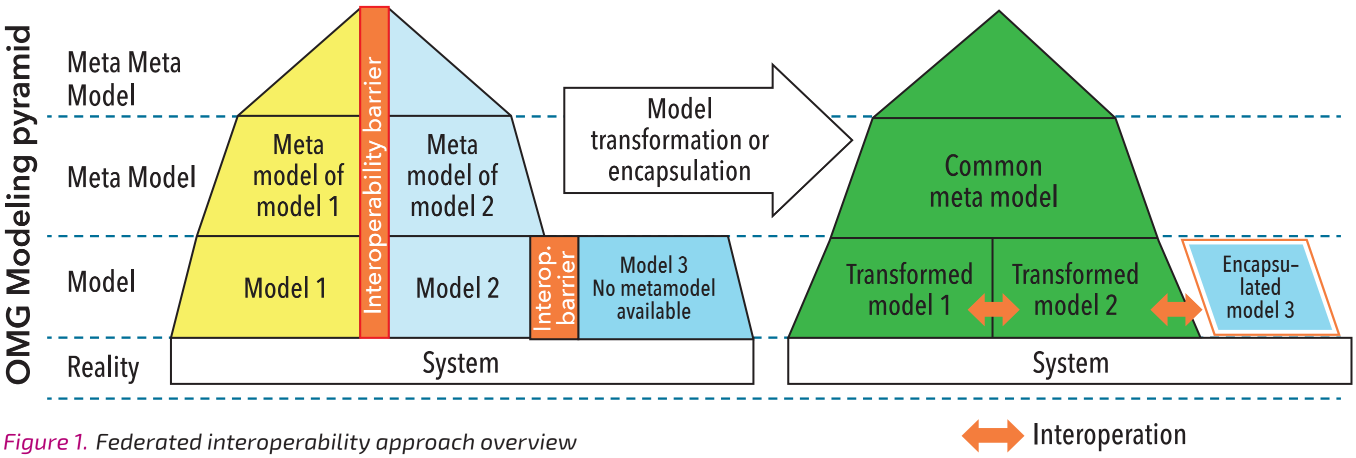

Figure 1. Federated interoperability approach overview

Many items in general, and particularly models are currently not necessarily reused outside a particular engineering activity's context or for different objectives due to limited trustworthiness or fear of ambiguity. At a given moment, each item could be indeed perceived by any stakeholder as a data, an information or a knowledge (DIK) as proposed in El Alaoui et al. (2022) depending on the context, skills, and objectives of this stakeholder. ISO/IEC/IEEE 24641:2023 defines such DIK status as follows: a data is perceived without any consideration of the context (e.g., a sensor measure or a pattern model), an information once verified and validated and considered along its associated context (e.g., production data or preliminary architectural model), and a knowledge if it is used for decision-making (e.g., a completely validated physical architecture model).

In addition, all items are generated and consumed from the beginning of the SoI engineering process until SoI dismantling. For instance, SoI operations are guided considering both generated and requested items for optimisation, control, or maintenance in operational conditions. Some are obtained at the cost of considerable efforts.

The challenge of DTH implementation is to support the management of a high volume of items that constantly evolve. The DTH ensures consistency and traceability of items, but implementation remains difficult as noticed by Hedberg et al. (2022). Interoperability approaches, creating relations between items, tools, processes and organisation (Labreche 2023), will contribute to solve the DTH implementation problem. On one hand, it will enable stakeholders to carry out their work around the SoI by leveraging items together, without semantic ambiguities or confusion. On the other hand, interoperability approaches will maintain the link between items despites their evolution over time.

To achieve better reuse, sharing, traceability of items in the context of the DTH, while ensuring DIK management in confidence, requires an improvement of overall interoperability. Labreche (2023) updates the state of the art related to interoperability problems depending on the level they occur data, service, process, or enterprise level. It characterizes the barriers preventing interoperability: conceptual, methodological, or organisational. For every level and barrier of interoperability, three types of interoperability are defined:

- *Integrated interoperability*: all elements are designed on purpose to be interoperable.
- *Unified interoperability*: interfaces are designed to enable collaboration.
- *Federated interoperability*: in the case collaboration is possible as-is, on the fly, without modification, nor sharing methods and tools it is federated interoperability.

An application of interoperability approach is the reduction of the SoI digital twin engineering effort by reusing as it is engineering material from the SoI, produced by numerous stakeholders and varying over time, and that must be maintained across SoI lifecycle. Applying integrated or unified interoperability approaches that require processing items individually, would involve tremendous efforts and be a costly process. Therefore, federation is the most relevant interoperability approach for reuse of DTH items while preserving stakeholders' practices.

CONTRIBUTION

Federated interoperability exhibits several requirements to make collaboration feasible, while maintaining the autonomy of the federated elements and without modifying them permanently (Mallek, Daclin, and Chapurlat 2012). This article focuses on models' interoperability to ensure stakeholders collaboration in MBSSE. Two methods have been identified to achieve model interoperability:

- *Model transformation* is applicable to any modelling language of which meta-model is known, to which the Object Management Group (OMG) pyramid (OMG 2019) is applicable. This approach is based on formal transformations. Both meta-models of the original modelling languages, in which the models are written, are converted to a third common meta-model thanks to established formal transformation rules, translating the model in the target modelling language. The strength of this approach is the preservation of the model internal structure. However, during transforming, it is impossible to keep all the properties of the original modelling language. Therefore, the modeler keeps a predominant role in the interpretation of transformed models, ensuring the modifications of properties are not contradicting the original model and that it remains representative with a sufficient level of confidence.
- *Model encapsulation* is achieved using standards such as the functional mock-up interface (FMI) and can be federated by distributed simulations such as the high-level architecture (HLA) (El Kassis et al. 2024). This approach does not require knowledge or access to the modelling language meta-model and guarantees to stakeholders the confidentiality of their models. However, encapsulation does not allow the internal workings of the model to be controlled, as only inputs and outputs are accessible, limiting the explainability of models, taken individually as well as in the federation.

A first possibility for federating is combining transformation and encapsulation approaches. It is summarised in Figure 1.

CONCLUSIONS AND PERSPECTIVES

The introduced method focuses on the modelling language interoperability problem, by proposing an adaptive approach integrating any modelling language, relying on model transformation or model encapsulation. It can be extended in two ways. A first improvement opportunity is to consider the interoperability barriers generated by modelling tools, views (system, requirements, architectures, etc.) on the SoI. Reconciling them will make it possible to facilitate heterogeneous items management and use, thus facilitating circulation and traceability of items within and between organizations.

A second improvement opportunity is to seek to improve the conservation of modelling assumptions and properties during model transformation using formal approaches. It will lead to greater reversibility of collaboration and interoperation. A formal approach based on graph theory and category theory seems promising to bridge these gaps (Wach et al. 2024). Such approaches can formally enhance stakeholders' collaboration by bridging semantic and conceptual gaps using mathematically consistent tools. Developing formal approaches, to transform models into mathematical objects, can improve the understanding and management of models' properties. As modifying these properties can affect model relevance, careful management and traceability of model properties is of primary importance for models to remain representative despite undergoing transformations for interoperable. ■

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A Requirement Conceptual Model to Support Requirements Writing and Early Verification

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■ **ABSTRACT**
Performing verification and validation (V&V) as early as possible has become a critical challenge for companies. Requirements and their associated models, elaborated during the engineering phase, often present quality issues that must be systematically verified. This paper introduces a conceptual model of requirements, together with writing patterns specifically designed for system requirements. These contributions provide a structured approach to writing system requirements and will form a foundation for future work on requirements modeling and verification.

■ **KEYWORDS:** requirements engineering, systems engineering, model-based systems engineering, verification, validation

INTRODUCTION

The development of complex industrial systems must follow rigorous processes, such as those defined in ISO 15288 (2023). These processes encompass requirements engineering (RE), architecture definition, and verification and validation (V&V). As companies strive to accelerate time to market and reduce design errors, engineers increasingly need early and collaborative methods for verifying and validating system requirements and architectures (Chapurlat and Bonjour 2014).

Micouin (2014) introduced the concept of property-based requirements (PBR) and showed that PBR, considered as executable requirement models, can be integrated into a model-based systems engineering (MBSE) approach to strengthen system V&V. This reinforced the value of incorporating executable requirement models within the RE process. Nevertheless, in practice, most product defects are still discovered during system integration. The main causes stem from errors introduced earlier in the process, specifically in the specification of natural language requirements (NLRs), which often lack sufficient quality.

Poorly written requirements hinder system modelers from confidently translating NLRs into executable requirement models. Instead, they must rely on personal interpretation while navigating the constraints of modeling languages and tools. This often leads to semantic discrepancies between the modeled requirements and the original stakeholder intent. To improve requirement quality and systematically verify key attributes of requirement sets, such as consistency and completeness, as defined in ISO 29148 (2018), requirements should be expressed through structured patterns. Such patterns enable V&V of requirement quality while serving as a bridge between NLRs and model-based requirements.

To address this challenge, a new approach called executable model-based requirements engineering (eMBRE) is proposed in our work. This approach is built upon a requirement conceptual model that links requirement semantics to system logic and the system environment. It also introduces writing patterns derived from the conceptual model, designed to improve requirement formulation and to support both modeling and verification of individual requirements and requirement sets.

In the remainder of this paper, the requirement conceptual model along with instances of this model is presented, then instantiated as patterns for writing NLRs that meet the conditions for model-based representation and enable early V&V.

DEFINING THE REQUIREMENT CONCEPTUAL MODEL

The proposed model (Figure 1) is com-

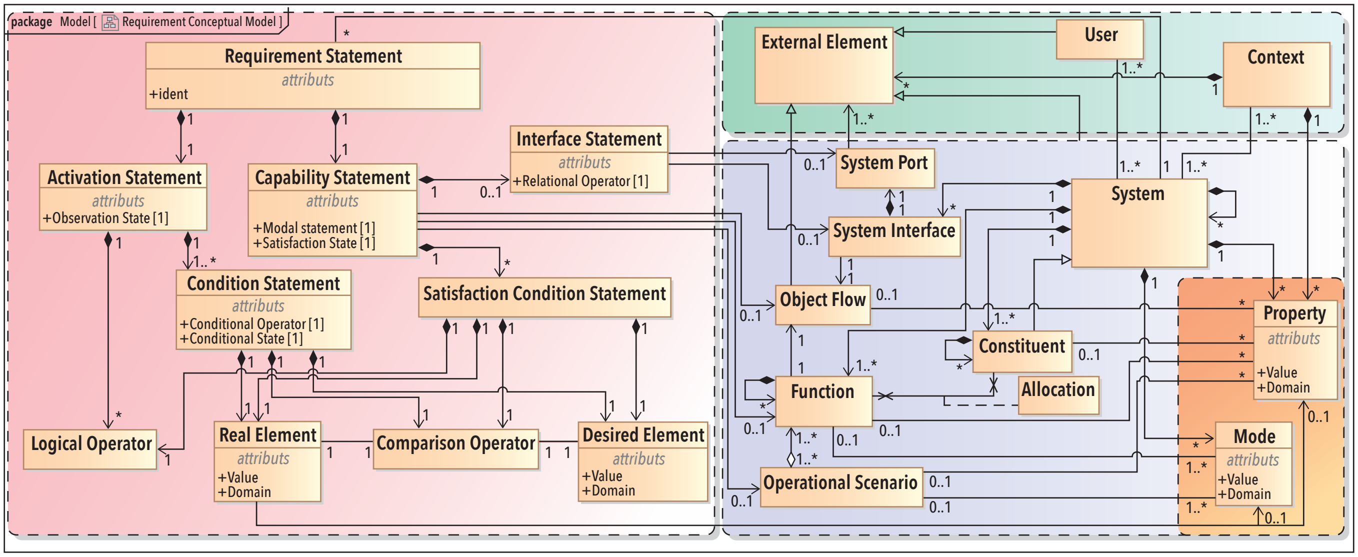

Figure 1. Requirement conceptual model

posed of four main parts: the requirement statement structure, the system's interactor, the system structure, and the observable elements.

The description of the model begins by first focusing on the system's interactor elements. The "context" includes various "external elements," which may themselves be external "system"s, "object flow"s, or "user"s. The "context" is also in direct link with the "system" interpreted as the system of interest. This "system" of interest then interacts with one or more surrounding "users," and indirectly with external "systems" both from the "context" or "object flow"s through the "system interface"s.

The proposed system structure is built upon elements from Faisandier's system ontology (Faisandier 2012) and Pfister's metamodel for systems engineering (Pfister et al. 2011). An "operational scenario" represents a sequence or set of "functions" executed to achieve a specific goal. A "function" is a process that transforms input objects into output objects, thereby transforming an "object flow." Each function is also linked to a system "constituent" through an "allocation." The "object flow" is exchanged at the behavioral level via a "system interface." The "system interface" enables the exchange of flows through its "system port" on the physical side, interacting with "external elements" such as a "user," another external "system," or an external "system interface."

The observable part is composed by a "property" that is a named and, observable or measurable, characteristic. It may relate to the "system" itself or its "constituent"s (e.g., physical properties such as mass), to a "function" or an "operational scenario" (e.g., time or quantity), or to an "object flow" (e.g., temperature, concentration, or the volume of a coffee). The "property" also may relate to a specific "context". The "mode" represents a specific system state. Modes are used to define situations under which an "operational scenario" or a "function" may occur. "Property" and "mode" have both a "domain" and an associated "value."

The requirement statement structure part highlights its relationships to the system. The "requirement statement" has an "ident" (unique identifier), an "observation state" and a "satisfaction state." It is composed of an "activation statement" related to the "observation state" that contains one or more "condition statements" combined using a "logical statement" typically via Boolean operators (e.g., 'And,' 'Or'). The "capability statement" related to the "satisfaction state" includes a "modal statement" (typically 'shall') and refers to system elements such as an "operational scenario," a "function," or an "object flow." It can be extended with an "interface statement" to specify exchanges between functions and components. In addition, one (or more) "satisfaction condition statement(s)" may be included to express expected performance levels or characteristics of a "function," an "operational scenario," or an "object flow."

Additionally, semantic elements lie in the previously defined "condition statement" and "satisfaction condition statement" with different operators. The "conditional operator" structures the logic of the requirement using temporal logic. The "comparison operator" connects a "real element," a measured or observed "value" of a "property" or "mode," to a "desired element" as a defined "value" (or range) within the same "domain." It may take the form of a temporal comparator (e.g., Allen's interval algebra) or a mathematical comparator. Finally, in the "interface statement," the "relational operator" defines the direction of interaction between system elements.

APPLYING WRITING PATTERNS TO SYSTEM REQUIREMENTS

To illustrate the applicability of the requirement conceptual model, an example involving a coffee machine and the formulation of its system requirements is provided. A set of syntactic patterns is introduced to express various types of requirements, including functional, performance, and interface requirements.

At an abstract level, the "activation statement" follows a generic structural pattern: [<conditional statement> + N (<logical statement> + <conditional statement>)]. Where "conditional statement" will follow the pattern: [<conditional operator> + <real element> + <comparison operator> + <desired element>].

For example: <When> <the button state> <is> <pressed>.

The "activation statement" is mandatory for expressing any system requirement. For clarity and simplicity, this component will be omitted in subsequent examples.

Functional requirements describe the transformation, transport, or storage of input resources into output resources. To express such requirements, the following pattern can be used to construct the "capability statement": [<system> + <modal statement> + <function> + <object flow>].

For example: <The System> <shall> <heat> <water>.

Performance requirements specify the expected performance or quality attributes of an "object flow". To express such expectations, the following "satisfaction condition statement" pattern is used, with : [<logical operator> + <real element> + <comparison operator> + <desired element>.

For example: The System shall heat

<with> <a heating time> <inferior to> <10 seconds> water <with> < a water temperature> <strictly between> < 50 to 65°C>.

Interface requirements define the exchanges between the system and external elements in its operational context, either from a physical or functional perspective. In this case, the associated function in the "capability statement" may be of the "transportation" or "transfer" type, as defined by Stone and Wood (2000). The following pattern is used to construct the corresponding "interface statement": [< relational operator > + <system port>].

For example: The system shall send water <to><the water dispenser>.

Since functional interface requirements are considered a refined form of functional requirements, they must also describe the performance characteristics of the associated flow.

For example: The system shall send water with a transfer rate of 20 mL/s to the water dispenser.

The proposed writing patterns are designed to bridge the gap between NLRs and formal requirement models by relying on the structure defined in the requirement conceptual model. In contrast to existing approaches, such as boilerplates (Marvin and Wilkinson 2010; Rupp and Pohl 2016; Hull et al. 2005; and Dick and Llorens 2012), the proposed patterns provide finer precision in the granularity of the concepts they use. Furthermore, since the concepts are system-related and structurally interconnected, they can be seamlessly integrated into an MBSE approach.

CONCLUSION

Although the proposed writing patterns provide a structured basis for expressing system requirements, they are not exhaustive. Project-level and business requirements were not addressed in this study and may require adjustments to the conceptual model or the development of additional patterns. This work opens up promising directions, including the integration of linguistic templates and product-specific ontologies into the conceptual framework. It also creates opportunities for leveraging AI, whether to extract system or operator-related concepts from textual sources or to support engineers in writing structured requirements.

Once operator semantics are formally defined, the approach supports a more rigorous expression of requirements, facilitating their modeling and enabling systematic verification and validation (V&V) of requirement quality within an eMBRE process. Future research will concentrate on formally characterizing essential quality attributes of requirement sets, such as consistency, completeness, and correctness, based on the proposed conceptual model. This will provide the foundation for developing a practical methodology and user-oriented guidance to support the application of V&V processes within a simulation environment. ■

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Éric Bonjour is a full professor specialized in systems engineering, at Université de Lorraine/Graduate School of Innovation and Systems Engineering (ENSGSI). His main research interests touch upon the fields of model-based systems engineering (formalization of requirements, product architecture, safe systems engineering, adoption of MBSE frameworks), innovation (acceptability, adoption) and knowledge management. He has supervised 19 PhD theses related to these topics. He has been a vice-chair of the French chapter of INCOSE (from 2012 to 2017). In 2015, he received the INCOSE outstanding service award.

Alain Kerbrat is contributing to the Airbus transformation project DDMS (digital design, manufacturing and support), with an aircraft architect's perspective. His current focus is model-based systems engineering, definition of modeled specifications (adequate combination of models with textual requirements), to support more mature and efficient contractual exchanges with suppliers, as well as early verification and validation of systems.

The Regeneration Ecosystems as a Holistic Approach to Overcoming the Barriers of the Circular Economy

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■ **ABSTRACT**
Circular economy (CE) is widely promoted as a sustainable alternative to the traditional linear economy. However, its industrial implementation faces persistent challenges, notably due to the lack adaptability and holistic integration of the current solutions. This paper identifies eight major barriers to CE deployment, considering the products in their changing technical, social, and financial environment. While closed-loop supply chains have emerged as a partial solution to these barriers, they often fall short in addressing systemic complexity and dynamic adaptation needs. To overcome the remaining limitations, we propose the concept of regeneration ecosystems. These ecosystems aim to support the sustainable valorisation of product across multiple use phases, while considering social, environmental, and economic impacts. This paper highlights the properties of regeneration ecosystems and argues for their potential to enable an evolutive implementation of CE at the industrial level.

■ **KEYWORDS:** circular economy, regeneration ecosystem, system of systems, sustainability, holistic approach

INTRODUCTION

The transition from a linear to a circular economic model has become a priority in both research and practice, aiming to align industrial activity with long-term sustainability. The circular economy (CE), as introduced by the Ellen MacArthur Foundation (2013), promotes a regenerative system that preserves products' value over multiple use phases through strategies such as reusing, recycling, and remanufacturing. Revalorisation constitutes a foundational principle of the CE, referring to the process of restoring functional and economic value of end-of-use products by reintegrating them into subsequent usage cycles, thus extending their lifespan. Despite having many advantages, the industrial implementation of CE still lacks a systemic vision and faces many barriers (Sautereau et al. 2025). Numerous current approaches of CE rely on rigid closed-loop systems, which lack adaptability and holistic vision required to deal with real-world complexity and change. These limitations justify the need for a broader perspective at system level that can address the diverse and evolving nature of industrial systems. This paper addresses the challenge of CE implementation at industrial level by first analysing barriers identified in recent literature. The discussion then turns to the strengths and limitations of closed-loop supply chains (CLSCs), a widely discussed concept offering insufficient solution in the case of CE's industrial implementation. To address this shortcoming, the paper introduces the concept of a regeneration ecosystem: a flexible and holistic approach that enables dynamic coordination, supports multiple circular strategies, and responds effectively to changes in context, in technology, and in stakeholder needs.

THE BARRIERS TO INDUSTRIAL CIRCULAR ECONOMY IMPLEMENTATION

Despite proposing a solution to the sustainability challenge of our era, CE is still not broadly spread at an industrial level. A review of the literature (Guldmann and Dorothea Huulgaard 2019, Kayikci et al. 2021, Mejía-Moncayo et al. 2023, Simonetto et al. 2022), reveals eight key barriers that hinder the effective implementation of CE. From a systemic perspective, the barriers hindering the implementation of CE principles can be organized across different system scales, from product-level issues to those concerning inter-organizational coordination and adaptability to contextual dynamics.

1. **Product design constraints**: Most industrial products are not conceived with revalorisation in mind. While design-for-circularity methodologies do exist, they are not systematically applied and often lack the flexibility to support multiple lifecycles.
2. **Process and technological limitations**: Transitioning to CE requires the deployment of specific circular manufacturing and administrative processes, which in turn demand new skills, infrastructures, and technologies that are not yet fully available or standardized because not anticipated (Vanson et al. 2023).
3. **Logistical complexity and environmental impact**: CE relies on reverse logistics for the collection, sorting, and reintegration of used products. These operations are often poorly anticipated and must be designed to minimize their negative impacts.
4. **Financial constraints**: Implementing circular strategies often requires significant upfront investment. Accessing sufficient funding remains a key obstacle, particularly in the absence of immediate economic gains.
5. **Human factors**: The transition to a circular model requires changes in mindset, skills, and practices across all levels of the organisation. Resistance to change and lack of training can significantly hinder progress.
6. **Systemic complexity**: Implementing a CE requires the alignment of all stakeholders around the revalorisation network. Inadequate data management and underdeveloped infrastructure often hinder this coordination, limiting the system's effectiveness.
7. **Misalignment of policies**: policies, through subsidies and regulations, can strongly influence the success of circular strategies. However, many current frameworks remain incompatible with the shift required by the CE and may prevent its development.
8. **Lack of adaptability**: The effective functioning of CE depends on the ability of the implemented system to adapt to a dynamic context. Managing these changes at multiple scales requires a high level of adaptability, which is often lacking in current circular systems.

CLOSED-LOOP SUPPLY CHAINS

CLSCs are often considered as basis for implementing CE in industry. By combining forward and reverse logistics, CLSCs support the planned revalorisation of end-of-life products through for instance reuse, remanufacturing, and recycling strategies, thereby enhancing resource efficiency and extending product lifespan (MahmoumGonbadi et al. 2021). Although operationally relevant, CLSCs remain insufficient to address the full complexity of CE implementation (MahmoumGonbadi et al. 2021). While CLSCs enable the deployment of circular processes, several hampering barriers remain unaddressed. The rigidity of CLSCs' architecture limits adaptation to technological, regulatory, or economic changes (MahmoumGonbadi et al. 2021), which would nevertheless be necessary to respond to the evolving context of revalorisation systems. Moreover, CLSCs tend to focus primarily on optimising economic performance (MahmoumGonbadi et al. 2021), often at the expense of the social and environmental dimensions. This narrow focus hinders the systemic integration required to coordinate stakeholders, manage data effectively, and adapt infrastructures. Therefore, although CLSCs represent a step toward circularity, they are insufficient for realizing the development of more holistic, adaptable, and resilient industrial systems. holistic, adaptable, and resilient industrial systems.

REGENERATION ECOSYSTEMS

To address the limitations of CLSCs, we propose an extended model: the regeneration ecosystem. This approach builds upon CLSCs but incorporates additional components and capabilities to overcome the barriers of CLSCs and to present a complete, dynamic, and stakeholder-inclusive system. Therefore, the regeneration ecosystems extend the CLSCs by including the same elements of CLSC who ensure the role of handling the products, but also some auxiliary components in charge for instance of information collection, processing and sharing among the system components. The mission of regeneration ecosystems is to allow not only the implementation of a circular process, but also to enter products into new use phases where they will fulfil most of the needs while keeping the smallest social, environmental, and financial impacts (to regenerate the value of the product). Connecting all these components in a network, by physical and virtual flows, allows optimized decisions making. One of the specificities of a regeneration ecosystems is to be made mainly of independent components (these being mostly companies) which for most already existed before and were integrated as off-the-shelf components. This independency is a reason to consider the components of the regeneration ecosystems as systems and the whole as a system of systems (SoS) (Sautereau et al. 2024).

A Holistic Solution:

Regeneration ecosystems offer a more holistic and systemic approach than CLSCs, by systematically incorporating broader decision-making criteria and engaging more stakeholders in the governance of product regeneration. This approach considers the product users' needs across multiple usage phases, the current state of health of the product, and the necessary interventions to transition it toward the desired functional state. Unlike CLSCs, which prioritize economic performance, the regeneration ecosystem relies on the three pillars of sustainable development: environmental, social, and economic. A multi-criteria assessment enables a more holistic evaluation of revalorization trajectories, ensuring the alignment of product regeneration with long-term sustainability objectives and real usage conditions. Achieving a global vision necessitates the integration of enabling layers, including data acquisition, information exchange, and system cohesion mechanisms that foster collaboration among stakeholders engaged in product regeneration. The relevant data may encompass product state of health information, operating conditions, environmental footprint, and financial performance metrics. While these aspects are often overlooked in CLSCs, they are critical for the robustness and efficiency of regeneration. The inherent complexity of the whole system requires appropriate methodological tools, especially of systems engineering, to support system design, orchestration, and adaptability (Sautereau et al. 2024).

An evolutive solution:

Regeneration ecosystems are, by nature, evolutive and reconfigurable, adaptable to a wide range of changes. These changes may be external to the regeneration ecosystem (such as new regulations or the emergence or disappearance of market demands), or internal (including the withdrawal of a participating company, contractual

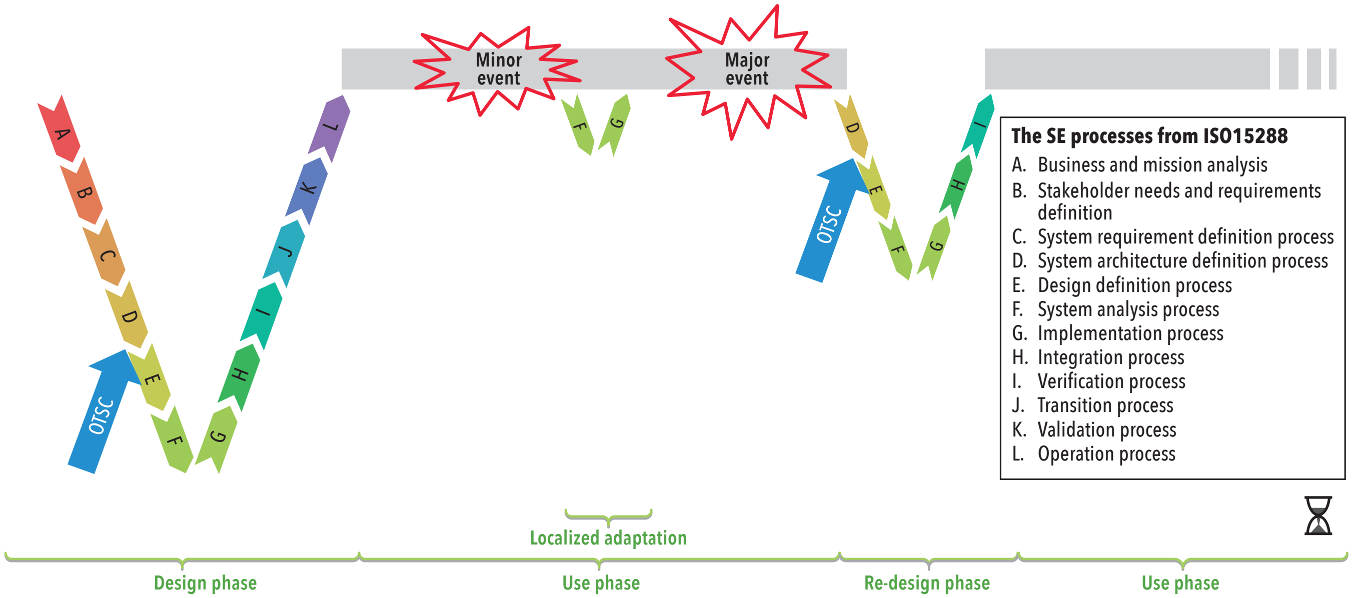

Figure 1. Regeneration ecosystem's lifecycle

modifications, or the integration of a new actor introducing an innovative technology). The regeneration ecosystem follows its own lifecycle, as illustrated in Figure 1, starting first by its design, following the whole Vee-model (Sautereau et al. 2024). Depending on the nature and severity of the changes, different phases of this design process may need to be reactivated. For example, a significant regulatory shift or a structural change in market demand may require a return to upstream processes such as requirements elicitation or functional architecture redefinition, to adjust ecosystem objectives (at the SoS level) during a re-design phase. In other cases, more localised adaptations may suffice, for instance, adjustments to the organic architecture to integrate a new component or to reallocate existing functions. The ability to distinguish and respond appropriately to different levels of change depends directly on the modularity and resilience of the system's architecture. As such, a given perturbation may be perceived as minor or major depending on the flexibility of the system concerned. This capacity to absorb or restructure in response to evolving conditions reinforces the characterisation of regeneration ecosystems as SoS. They rely on autonomous, interoperable components capable of cooperating and evolving within a coordinated whole (Sautereau et al. 2024).

CONCLUSIONS AND PERSPECTIVES

The industrial implementation of the CE continues to face barriers. While CLSCs represent a first try of industrial CE implementation, their limited adaptability and narrow focus hinder their effectiveness realizing sustainable and resilient circular systems. This paper introduces the regeneration ecosystem as a more complete and evolutive alternative to CLSCs, grounded in a system-of-systems perspective, and aiming (as shown in Table 1) to mitigate the eight major barriers to CE's industrial implementation identified. ■

Table 1. The comparison of the responses of CLSC and regenation ecosystem to the CE barriers

Barrier	CLSC	Regeneration ecosystem
Product design constraints	Product design is an input data to deal with	Product and regeneration are jointly designed
Process and technological limitations	Both solutions are aiming to implement these processes	
Logistical complexity and environmental impact	Purely focused on the logistical processes	Consideration of the impact of these stocks and flows
Financial constraints	Both solutions are considering it by trying to reduce the financial costs	
Human factors	Focus is being made on the process forgetting the humans implied	the humans are taken into consideration as changing
Systemic complexity	The system is reduced to the operating components	Taking a broad environment under several points of view in a SoS point of view
Misalignment of policies	Suffered with no influence on	Suffered with no influence on but followed
Lack of adaptability	Fix architecture	Adaptability of the ecosystem through its own lifecycle

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Towards a CuSEF (CubeSat Systems Engineering Framework)

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■ **ABSTRACT**
CubeSat missions are increasingly adopted by NewSpace actors despite their limited resources and fast-paced development cycles, often leading to high failure rates. Traditional systems engineering standards such as ISO/IEC/IEEE 15288 and ECSS-E-ST-10C are rarely applied because they are considered too complex for very small entities (VSEs). This paper introduces the CubeSat systems engineering framework (CuSEF), a lightweight yet rigorous framework tailored for CubeSat class IV/V missions. CuSEF adapts ISO 29110 as a structural foundation and incorporates selected ECSS requirements to ensure mission reliability. The framework combines a simplified lifecycle model with model-based systems engineering (MBSE) practices and leverages artificial intelligence (AI) to accelerate tasks such as requirements drafting and test case generation. Early application of CuSEF demonstrates improvements in cost, schedule, and robustness without compromising agility. Future work includes large-scale validation across diverse CubeSat teams and enhanced integration of digital continuity and AI-driven design optimization.

■ **KEYWORDS:** CubeSat, systems engineering, ISO 29110, ECSS-E-ST-10C, NewSpace, MBSE, artificial intelligence, lightweight processes, small satellite development

INTRODUCTION

CubeSat technology has lowered the barrier to entry into space, enabling small organizations and universities to rapidly design and launch miniature satellites. This trend has also created a market in which companies are jostling to sell these systems and the services they provide.

CubeSat projects are very often carried out in very specific contexts with small teams and limited budgets. What's more, in the face of stiff competition, industry players are trying to compress development time to keep costs down and deliver the product as quickly as possible. This leads to a very high mission failure rate.

A key factor of this high failure rate is the lack of a rigorous yet lightweight systems engineering process adapted to these small, fast-paced projects. Traditional standards for systems engineering (such as the ISO/IEC/IEEE 15288 lifecycle standard or space agency process standards like the European Cooperation for Space Standardization (ECSS)) are often not applied on CubeSat projects, as they can be overly complex, resource-intensive, or ill-suited to the constraints of CubeSat-class missions. NewSpace teams (small start-ups or academic groups with limited budgets and personnel) typically operate in a "garage development" style – **ad hoc** design-build efforts using off-the-shelf parts (Venturini 2018) – which can result in missed engineering steps and inadequate testing. This observation raises the following research question: *How can a systems engineering framework be designed to preserve the methodological rigor of space standards while remaining lightweight and practical enough for CubeSat-scale projects?*

This paper introduces the **CubeSat Systems Engineering Framework (CuSEF)**, tailored for NewSpace, that bridges the gap between heavyweight standards and the practical realities of CubeSat development. CuSEF combines a simplified **process** model with modern **methods** and **tools** to provide structure without undue burden. By adapting the ISO 29110 standard for very small entities and integrating essential requirements from the ECSS space engineering guidelines, the framework aims to enhance the reliability of CubeSat missions while optimizing development cost and time (Ndao 2024a). The following sections review the state of the art, detail the CuSEF framework (its process, methods, and toolset), discuss expected benefits, and conclude with future perspectives.

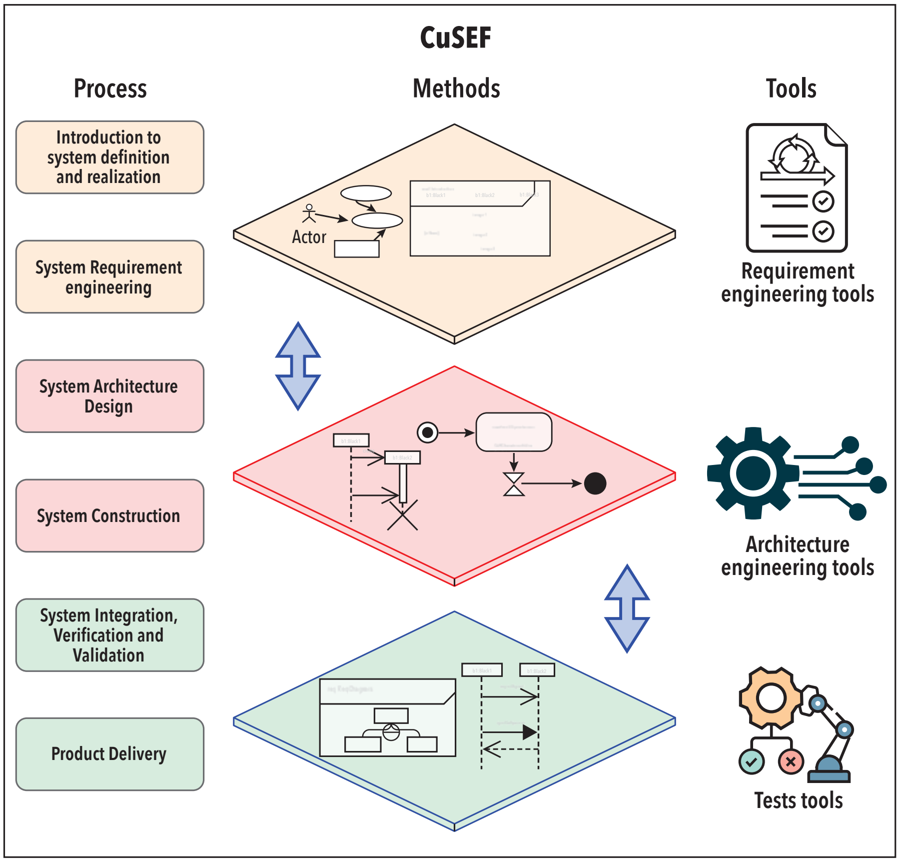

Figure 1. CuSEF framework presentation

STATE OF THE ART AND FOUNDATION OF THE CUSEF

CubeSats were initially developed as educational tools in academic environments, but over the past decade they have been increasingly adopted by commercial NewSpace companies and governmental programs for operational missions. These projects are typically carried out by small teams – often micro-enterprises or student groups – working with limited resources and tight schedules. However, numerous studies have shown that such missions suffer from a **high failure rate**, particularly in academic contexts. According to an analysis by the Aerospace Corporation, only about **45% of academic CubeSat missions** achieve full success, compared to **77% for commercial projects** where teams are more experienced and processes more structured (NASA 2018, Venturini 2018). The causes are well known compressed development cycles, poor documentation, incomplete testing, and the lack of systems engineering expertise in teams.

In this context of CubeSat projects, **full-scale systems engineering standards are rarely applied**. Standards such as **ISO 15288**, which defines a comprehensive lifecycle for complex systems, are often considered disproportionate to the scope of CubeSat missions. Similarly, the **ECSS-E-ST-10C** standard, while highly relevant to space projects, contains a dense set of prescriptive requirements and documentation deliverables. As Ndao (2024b) highlights, it is "not suitable for systems engineering for Class IV and V CubeSats due to the high number and complexity of requirements." Class IV and V CubeSats are nanosatellites of low (Class IV) to very low (Class V) complexity, generally small in size (1U to 3U), with a simple architecture, using commercial technologies (COTS) and developed with lean processes, typical of educational missions, technology demonstrators, or low-criticality projects. Full compliance would overwhelm small development teams and exceed available time and resources – especially considering ECSS was originally designed for large institutional programs.

To overcome this, some initiatives have sought to create **tailored frameworks for very small teams**. One promising foundation is **ISO/IEC 29110-4-1:2018**, a standard specifically aimed at **Very Small Entities** or VSEs. (VSEs are organizations with fewer than 25 people.) It offers **simplified lifecycle processes** that are more accessible and less burdensome than traditional standards (ECSS 2023). ISO 29110 defines lightweight project management and engineering practices suitable for software and systems development in small structures. In theory, ISO 29110 can help structure CubeSat projects. In practice, its generic form lacks key **domain-specific elements** essential for space missions – such as space environmental testing, model philosophy, or mission-level verification strategies. Therefore, to truly support CubeSat Class IV and V projects, a new approach is needed: **building on the ISO 29110 process baseline**, while **enriching it with selected ECSS requirements**, and **complementing them with appropriate methods and tools**. This allows for the development of an engineering framework that is both realistic and robust.

CUSEF FRAMEWORK PRESENTATION

CuSEF aligns processes, methods, and tools to provide a small CubeSat team with an appropriate level of rigor, avoiding the complexity of traditional standards (see Figure 1).

a. Process: ISO 29110 framework + ECSS supplements

The CuSEF process is built upon the **ISO/IEC 29110-4-1:2018** framework, which is structured into six lightweight phases: **introduction to system definition and realization, system requirements engineering, system architecture design, system construction, system integration verification and validation**, and **product delivery**. This lifecycle is specifically suited for VSEs (ISO 29110 2023). To ensure relevance for space missions, the process is enriched with targeted contributions from the ECSS standards, focusing only on high-value elements such as design reviews, mission analysis, and selected document requirements definitions (ECSS 2023). The result is a "minimum viable process" process flow that retains all critical milestones and deliverables (Ndao 2024b) without inflating cost or duration.

b. Methods

CuSEF is based on a **model-based systems engineering (MBSE)** approach that centralizes requirements, design, and analysis within a coherent digital model. The process begins with simplified diagrams. – the *horned beast* to define mission needs and the *octopus* to map external context–followed by functional decomposition and allocation to subsystems. Key trade-off analyses (mass, power, thermal) are performed early in the model. This structured yet lightweight method ensures coherence, traceability, and design rigor, while remaining suited to the constraints of small CubeSat teams.

c. Tools: MBSE + AI

To support these methods, CuSEF integrates a toolchain that includes MBSE platforms like **Capella** or **Cameo Systems Modeler**, which facilitate architecture modeling, automatic document generation, and consistency checks. Artificial intelligence is also leveraged to accelerate engineering tasks: large language models assist in drafting requirement sets, and tools like **Expleo Sophia** can generate test procedures fully traceable to the system requirements in just a few seconds (Expleo 2023). Finally, CuSEF promotes the use of **open APIs** to link requirement management tools, system models, and test benches – ensuring continuous data synchronization across the engineering lifecycle.

With these bricks, a small team has a "just enough" framework: discipline, visibility, and automation without bureaucracy.

CONCLUSIONS

CuSEF demonstrates that a well-balanced mix of ISO 29110 processes, tailored ECSS requirements, MBSE models, and AI support can increase CubeSat reliability without stifling agility. Ongoing missions will provide quantitative measures of success; meanwhile, early results show gains in cost, schedule, and robustness.

Future work will focus on extending the validation of the framework through experiments with small enterprises and university CubeSat teams, to consolidate its applicability across diverse NewSpace contexts. In parallel, the MBSE dimension of CuSEF will be expanded and detailed – including the specification of modeling languages, toolchains, and traceability mechanisms – to reinforce digital continuity throughout the engineering lifecycle. Additional research will also explore AI-driven design space exploration and the publication of open-access models so that the broader NewSpace community can adopt, validate, and evolve the framework collaboratively. ■

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