INSIGHT

This Issue's Feature:

New Challenges and Advances in Systems Engineering at French Universities

DECEMBER 2023
VOLUME 26 / ISSUE 4

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

INSIGHT

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

DECEMBER 2023 VOLUME 26 / ISSUE 4

Inside this issue

About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 20,000 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.

For more information, click here:
The International Council on Systems Engineering
(www.incose.org)

OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four 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, 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*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

PERMISSIONS

ARTICLE SUBMISSION insight@incose.net

Publication Schedule. ***INSIGHT*** is published four times per year. Issue and article submission deadlines are as follows:

- February 2024 issue – 1 November 2023
- April 2024 issue – 2 January 2024
- June 2024 issue – 1 March 2024
- August 2024 issue – 1 May 2024
- October 2024 – 1 July 2024
- December 2024 – 1 September 2024

For further information on submissions and issue themes, visit the INCOSE website: www.incose.org

 ISSN 2156-485X; (print) ISSN 2156-4868 (online)

ADVERTISE

Readership

INSIGHT reaches over 20,000 members and CAB associates and uncounted employees and students of more than 100 CAB organizations worldwide. Readership includes engineers, manufacturers/purchasers, scientists, research and development professionals, presidents and chief executive officers, students, and other professionals in systems engineering.

Issuance	Circulation
2023, Vol 26, 4 Issues	100% Paid

Contact us for Advertising and Corporate Sales Services

We have a complete range of advertising and publishing solutions professionally managed within our global team. From traditional print-based solutions to cutting-edge online technology the Wiley-Blackwell corporate sales service is your connection to minds that matter. For an overview of all our services please browse our site which is located under the Resources section. Contact our corporate sales team today to discuss the range of services available:

- Print advertising for non-US journals
- Email Table of Contents Sponsorship
- Reprints
- Supplement and sponsorship opportunities
- Books
- Custom Projects
- Online advertising

Click on the option below to email your enquiry to your nearest office:

- Asia and Australia corporatesalesaustralia@wiley.com
- Europe, Middle East and Africa (EMEA) corporatesaleseurope@wiley.com
- Japan corporatesalesjapan@wiley.com
- Korea corporatesaleskorea@wiley.com

USA (also Canada, and South/Central America):

- Healthcare Advertising corporatesalesusa@wiley.com
- Science Advertising Ads_sciences@wiley.com
- Reprints Commercialreprints@wiley.com
- Supplements, Sponsorship, Books and Custom Projects busdev@wiley.com

Or please contact:
Marcom@incose.net

CONTACT

Questions or comments concerning:

Submissions, Editorial Policy, or Publication Management
Please contact: William Miller, Editor-in-Chief
insight@incose.net

Advertising—*please contact:*
Marcom@incose.net

Member Services – *please contact:* info@incose.org

ADVERTISER INDEX September Volume 26-4

CORPORATE ADVISORY BOARD — MEMBER COMPANIES

FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to publish the December 2023 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 eighth 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), and December 2021 (Volume 24, Issue 4). Articles were selected after peer reviews from a larger set of doctoral presentations in collaboration with French universities and industry. The authors address the following topics:

1. New Challenges and Advances in Systems Engineering at French Universities (theme editorial)
2. AFIS Report on Challenges for the Near Future
3. Challenges in Early Verification and Validation of System Requirements
4. Challenges in Developing a Method to Support the Adoption of a Model-Based Systems Engineering Methodology
5. Understanding the Indirect Effects of Interactive Systems Within Systems of Systems
6. WONKA: An Ontology-Aided Model-Based Systems Engineering Analysis for Early V&V on Heterogeneous Systems and Applications
7. Project Engineering for the Depollution of Industrial Sites: A Model-Based and Systems-of-Systems Approach
8. Early Validation of Functional Requirements
9. Interoperability Forum for Requirements Exchange
10. Model-Based Systems Engineering Approach for an Indoor Multi-Usages System Development.

The editors of *INSIGHT* would be pleased to accept proposals from INCOSE chapters, working groups, and affiliated bodies for themed issues centered on the future of systems engineering (FuSE) practices to realize the *Systems Engineering Vision 2035* published by INCOSE in 2021.

We thank our theme editors in 2023, Chuck Eng for layout and design, the INCOSE publications office, and the staff at Wiley.

Feedback from readers is critical to the quality of *INSIGHT*. We encourage letters to the editor at insight@incose.org. Please include "letter to the editor" in the subject line. We hope you continue to find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. ■

New Challenges and Advances in Systems Engineering at French Universities

Jean-Marie Gauthier, jean-marie.gauthier@irt-saintexupery.com; and **Hervé Panetto,** herve.panetto@univ-lorraine.fr

INTRODUCTION

This themed issue of *INSIGHT* is dedicated to the ninth occurrence of the French Systems Engineering Academia-Industry meetings, organized by AFIS (Association Française d'Ingénierie Système), the French chapter of INCOSE, and supported by French universities as a regular series, usually every two years. This event was held in December 2022.

These meetings are composed of workshops and plenary lectures that provide the opportunity for both academics and industrials to:

- debate on systems engineering practices, education, and competences development for professional situations, and
- develop and promote research in systems engineering.

The articles of this themed issue are related to research works that have been presented during the doctoral seminar, aiming to provide an overview of the French research in the domain of systems engineering. For this special issue of *INSIGHT*, doctoral students and their supervisors have been invited to submit an extended version of their presentations to emphasize the research aspects of systems engineering. Nine research papers have been selected to be included in this issue to promote research on systems engineering approaches.

The first paper, entitled *AFIS* "Report on Challenges for the Near Future" by Christophe Alix, Jean-Luc Garnier, Rob Vingerhoeds, Lauren Alt, Mikaël Le Mouëllic, and Mickael Bouyaud, discusses the challenges faced by systems engineering in the near future and outlines the vision and strategies proposed by the French Chapter of INCOSE (AFIS) to address these challenges. The authors emphasize the need for systems engineering to adapt to changes in the world, especially in the context of autonomous systems. The paper highlights the importance of integrating systems engineering at the enterprise level, ensuring collaboration across projects, and incorporating systems engineering principles into the governance of projects. It also addresses the role of leadership in systems engineering, emphasizing the need for both vertical and horizontal consistency in decision-making processes. The paper further explores how systems engineering can deal with modern uncertainties, manage unknowns, and incorporate human values into the engineering process, considering the impact of evolving technologies on human behaviour and societal values.

In the second paper, entitled *Challenges in* "Developing a Method to Support the Adoption of an MBSE Methodology," Kozak et al. explore the challenges involved in developing a method to support the adoption of a model-based systems engineering (MBSE) methodology within organizations. MBSE offers a systemic framework for integrating models, enhancing early verification and validation, and improving communication among project stakeholders. The authors identify the complexities of this transformation, emphasizing the need for customized change interventions that consider individual mindsets, roles, and contextual factors. The research delves into barriers and facilitators for MBSE adoption, drawing from diverse scientific fields like management, psychology, sociology, industrial engineering, and social psychology.

In the third research paper, entitled "Challenges in Early Verification and Validation of System Requirements," by Cyril Bacquet, Pascale Marangé, Eric Bonjour, and Alain Kerbrat, presents the challenges associated with early verification and validation of system requirements in the context of model-based requirements engineering (MBRE). Ambiguous or inconsistent requirements can lead to errors in system design, causing project delays and cost overruns. The authors propose an executable model-based requirements engineering (eMBRE) process, focusing on formal modeling of requirements to facilitate early and collaborative validation and verification (V&V).

Laëtitit Bornes, Catherine Letondal, and Rob Vingerhoeads provide the paper

"Understanding the Indirect Effects of Interactive Systems Within Systems of Systems." Interactive systems have impacts beyond their direct physical effects, including rebound effects and systemic changes in practices. The authors propose a qualitative-quantitative modeling methodology to understand these effects, drawing on system dynamics and systemic design. The methodology involves a collaborative approach, including stakeholders and experts, to analyze and model the effects of interactive systems.

The WONKA framework is introduced by Romain Delabeye, Olivia Penas, and Regis Plateaux in the paper entitled "WONKA: an Ontology-Aided MBSE Analysis for Early V&V on Heterogeneous Systems and Applications." The WONKA framework developed as part of the EU-funded EnerMan project, aimed at enhancing the energy sustainability of manufacturing systems. In this large-scale collaboration involving 22 partners across 10 countries, the researchers faced challenges in designing a flexible energy management system (EnMS) and verifying and validating (V&V) scientific approaches on diverse industrial cases. To address these challenges, the study introduces two methodologies: an MBSE analysis, using SysML, to specify and position scientific challenges, and the WONKA framework, an ontology-based approach integrating semantic reasoning and recommendation systems for scalable V&V.

The sixth research paper by Mayssa Chebbi introduces the DEPOSE (DEPollution model-based system engineering) method, designed to address the complexity of depollution projects for industrial sites. These projects involve intricate challenges due to varying pollution sources, site architectures, and collaboration among multiple stakeholders. DEPOSE employs a model-based systems-of-systems engineering (MBSoSE) approach, combining systemic principles with rigorous structuring. The method includes multiple modeling views, such as contextual, lifecycle, operational requirements, functional, physical, data, and risk management views.

Assioua et al. present a systematic process for early validation of functional requirements in the automotive industry, particularly focusing on the development of safe autonomous vehicles. As digital technology replaces mechanical systems, the complexity of embedded electronic and computer systems in vehicles increases. To ensure the safety and reliability of these systems, the authors propose a method where formal verification is introduced at the earliest stages of the software development life cycle. They introduce the SARA framework (safety analysis for requirements in automotive) which transforms textual requirements, expressed in a language called SARA-L, into formal models.

The systems engineering interoperability forum (SE-IF) of the ATLAS program is discussed by Christian Koumalah Mbey, Frédéric Darré, El-Mehdi El Amrani, Albert Levy, and Pascal Hubert. This forum focuses on the exchange of requirements using the STEP AP242 application protocol. The SE-IF, sponsored by the French industry and government, aims to facilitate the exchange of requirements and their attributes in a tool-agnostic manner within the extended enterprise. The STEP format, an ISO standard for product data exchange, is employed to create a common ground for communication and collaboration in system operation and certification. The article outlines the SE-IF's use cases, emphasizing the importance of standardized transfers of systems engineering data, and explores future perspectives, including testing with more complex requirements and integration with other engineering domains using MBSE and collaborative platforms like MoSSEC.

The last research paper, by Eric Razafimahazon, Pierre de Saqui-Sannes, Rob Vingerhoerds, Julien Soula, and Romain Mège, is entitled "Model-Based Systems Engineering Approach for an Indoor Multi-Usages System Development." The paper discusses the design of indoor multi-usage systems capable of performing various tasks within buildings, such as inspection, digitization, and monitoring construction work. To address the complexities of these systems, the authors propose a MBSE approach, providing multiple comprehensive views of the system. The MBSE method, outlined in seven steps, includes mission and requirement analysis, operational analysis, functional and logical architecture design, physical architecture implementation, and verification and validation. The proposed method allows for customizable system architectures and considers diverse operational scenarios.

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*. ■

ABOUT THE THEME EDITORS

Dr. Jean-Marie Gauthier is a researcher in systems engineering at the French Institute of Research and Technology (IRT) Saint Exupéry of Toulouse. His research interests are modelling and simulation, system theory, requirements engineering, and human factors for model-based systems engineering. He received his PhD in November 2015 at the Femto-ST Institute. He is a member of the French chapter of the International Council of Systems Engineering, and Associate Systems Engineering Professional.

Dr. Hervé Panetto is a professor of enterprise information systems at the 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 modelling, semantics modelling and discovery, and database development. His research field is based on information systems modelling 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 outstand ing service award. He is a supporter of ELLIS, and member of DAIRO, TAILOR, and CLAIRE Networks.

AFIS Report on Challenges for the Near Future

Christophe Alix, christophe.alix@thalesgroup.com; **Jean-Luc Garnier,** jean-luc.garnier@thalesgroup.com; **Mikael Le Mouëllic**; **Laurent Alt**; **Rob Vingerhoeds,** rob.vingerhoeds@isae-supaero.fr; and **Mickaël Bouyaud,** mickael.bouyaud@worldline.com

ABSTRACT

Systems engineering shall adapt itself with the changes of the world. System engineering communities like (AFIS 2022) and (INCOSE 2021) have been developing their visions with the identification of needs that systems engineering shall integrate to address new challenges. The systems engineering discipline shall be now considered at the enterprise level and be included in the governance of the project. Systems engineering and system thinking shall be deployed on all layers of the organization and horizontally to ensure the consistency the definition, production, and all phases of the lifecycle of the system within all involved organizations.

The future is paved with unknowns. Systems engineering can integrate new methodologies, new posture to complete its analytical based tools to better face new kinds of complexity. These new challenges are often due to the reallocation of functions and responsibilities between human and machine in the context of autonomous systems. These collaborative socio-technical systems induce new questions for systems engineering which needs to integrate new domain of skills and interacts with new disciplines from the soft sciences.

INTRODUCTION

AFIS, the French chapter of INCOSE, leads the promotion and the development of systems engineering in France. Every year, AFIS publishes a roadmap to update the strategic directions, the overall action plan, the partnership, and evolutions of operational structure (including working groups, projects, and initiatives). This realignment is jointly performed by technical committees themselves and a strategic action led by the technical directorate with AFIS stakeholders. This article is an intermediate delivery of this activity, the final study will be presented at the annual AFIS congress. The definition of the roadmap takes the "as is" situation (that is, the systems engineering ecosystem in France) as input and the short-term visions (including the INCOSE and AFIS visions). Elements in this roadmap aim to close the gaps. This article elaborates on the INCOSE vision for implementation in the French ecosystem. It also provides an analysis of what can be considered and developed, from an AFIS perspective.

AN AFIS INTERPRETATION OF THE "ENTERPRISE TRENDS" OF THE INCOSE VISION 2035

The Systems Engineering Vision 2035 (INCOSE 2021) defines very ambitious enterprise trends. The AFIS analysis of these trends shows an opportunity to clarify what a reference system should include in an enterprise, including:

- Policies and directives to be applied in the enterprise processes performed by the disciplines and specialties. These enterprise references should include a code of conduct in line with the enterprise values and engagement (ethics, social, environmental, etc.)
- Libraries of processes descriptions, methods, standards, patterns, and assets usable across the enterprise.

Governance of the systems engineering activities, at the enterprise level, should be performed across the projects.

- All enterprise processes including systems engineering should be performed collaboratively, in line with a shared business model towards the enterprise goals, strategy, and roadmap, including digital transformation.
- Research, technology development, and innovation should be performed consistently with the business plan, reflecting market demands.
- Assets (including on-the-shelf products, technologies, and tools), human resources and competencies, and strategic partnership must be developed in order to anticipate the needs of the projects.
- Analysis across the needs of products should allow defining product-lines.

At project level, consideration of the enterprise strategy should include:

- An orientation phase based on the complexity analysis of the solution to be worked, based on competence (knowledge, experience, and skills) of the enterprise teams, the available enterprise assets, and partnership.

- System specifications and designs should formalize the commitment of the enterprise to fulfill the requirements of the stakeholders, the enterprise policies and directive, known regulatory constraints, and the state of the art.

SYSTEMS ENGINEERING AND LEADERSHIP

Management and organization play an important role in the development of systems. Even if systems engineering is intended to model all the issues and therefore to describe and rationalize the choices, the human aspect can significantly influence the perception of risks and issues, the level of collaboration between stakeholders, or even the decision. Let's look at the problem from two directions: vertical (hierarchy) and horizontal (inter-disciplinarity).

From a vertical point of view, whether at the level of the internal hierarchy of the organization or the principal/subcontractor relationships, it is important to maintain consistency and alignment within even than a single discipline, to guarantee the best result, and accelerate development. Systems engineering methods provide all the tools to make this possible, the question is rather to know to what level of detail it should be applied,

From a horizontal point of view, as systems are increasingly interconnected, this requires more frequent contact between disciplines to enable better decisions to be made and more alternatives to be explored sooner rather than later. To support these discussions, it is therefore necessary to have relevant and up-to-date inter-disciplinary information. This requires covering product information at the engineering level, but also the integration of other organizations which are increasingly involved in choices. And with the increase in sustainability issues, new expertise must be present in decisions, which are not currently involved in systems engineering.

However, leaders are at the intersection of these two dimensions, and must constantly make decisions both as guarantors of coherence within their field, and as committed actors of good collaboration with their peers. Systems engineering is clearly at the heart of the processes and data that are necessary for their activity, and if it easily makes it possible to model problems and their solutions within silos, its use for transversal coordination often comes up against a problem. Heterogeneity of practices and maturity, especially from a certain hierarchical level, which ends up designating PowerPoint as the only common language. In fact, most of the necessary concepts for management exist in systems engineering, whether in MBSE or existing architecture framework like the Unified Architecture Framework (UAF)® (OMG 2022) but are difficult for the non-educated. There are therefore new communication models to be created to democratize, without distorting the systems engineering within the entire organization. Inspiring agile methods, involving dissemination and reaction to high frequency information are certainly ways to perform better, but above all to bring about the necessary incremental change in behavior and culture.

Finally, given the speed of evolution of the issues, it is important today to also consider the organizations themselves as systems, or systems of systems, and to apply similar methodologies to them, to better define their mission, the functions they must perform, the way in which they are carried out by humans or computer or physical tools.

Indeed, as the systems to be built and operated become more and more complex, the concerns (security, sustainability, etc.), the number of contributing organizations is increasing and therefore requires formalizing relationships between them. Applying a framework like UAF is an important asset.

THE SYSTEMS ENGINEERING POSTURE AGAINST MODERN UNKNOWNS

Our time has shown without ambiguity that our world has many surprises for us. We have learned to be humble with respect to uncertainties and unknowns. Managing knowledge and dealing with the non-knowledge is part of systems engineering. Managing unknowns is fundamental for engineering systems facing adversity and competition.

Rumsfeld dichotomy can help to classify the approaches (Rumsfeld 2002). Known knowns are the foundations of requirements and needs analysis. Known unknowns are usually treated as uncertainty. Dealing with unknown knowns is managing risk. Unknown unknowns, with emergencies "appearing" at any time of a system lifecycle, requires adaptation of the approaches, such as for example:

- Adopt additional methodologies in activities and processes based on soft or combination of soft and hard systems thinking as per developed following methodologies in Jackson (2019) or Snowden (n.d.).
- Monitor emergences of patterns and phenomena, align impacts with stakeholders and define remediations actions (correction, adaptation, transformation, failure) following OODA loop concepts (observe, orient, decide, act) and its derivatives.
- Influence unknown entities with an act-sense-adapt loop.
- Develop scenario planning, creating and analyzing multiple plausible future scenarios to anticipate potential outcomes, and make better informed decisions.

A system is the entity of interest for systems engineers and developing knowledge about the systems of interest is the objective. However, the context (or environment) is equally important for engineering a good system in its operational contexts.

- "Known context" is by nature evolutive but such evolutions are known and characterized. The stakes are to build future architecture increments.
- "Uncertain context" is evolutive and such evolutions may be foreseen through prospective effort, but without certainty on which evolutions will come into reality (probabilities) and when. The stakes are to make relevant projections on the future, and master all along the system lifecycle the gap between reality and the project assumptions.

  "Unknown context" is evolutive in an unforeseeable way or in a manner that had not been foreseen. The stakes are to have the capability at project/enterprise level to manage the new situation impact on the project (or get opportunities from the new situation). For example, requirements are evolving all the time over a systems development and will stabilize at the moment a system goes into production / service. Such evolutions may be due to changes in the expectations of the stakeholders, due to technical evolutions, etc.

Controlling uncertainties and managing unknowns may require:

- Qualifying systems against out of expected range interaction of the context,
- Exploring possible futures scenarios based on FOE (future operating environment) sci fi methodology, and red team books developed by French defense (Red Team n.d.), or
- Developing uncertainty perspectives with appropriate languages in architecture frameworks.

(SYSTEMS) ENGINEERING FOR HUMAN VALUES

The Systems Engineering Vision 2035 (INCOSE 2021) is both very ambitious and incorporates the 17 UN sustainment development goals (SDGs) as well as major future trends (Megatrends, Industry 4.0, Society 5.0, etc.). But alongside this laudable ambition, we find a bias which weakens its scope, since the systems are essentially considered cyber-physical. Humans intervene in several places, but indirectly: that of a "stakeholder" with expectations on the systems. It is an actor in the company, or the creator of regulations or policies. However, with the growing presence of software in cyber-physical systems, and the omnipresence of AI, we can no longer neglect that systems will modify human behavior in feedback, nor that human behavior wherever they intervene in the systems, will be altered by the permanent evolution of technologies.

The bandwagon of technologies in all directions, fuelled by advances in artificial intelligence, is on the move, upending the world at an infernal pace, to the point of destabilizing human and political relations, the perception of science, and so on. Some trust indicators can be severely undermined as a result (Ortiz-Ospina and Roser 2016).

The reaction is taking shape around major players like the European Commission via new regulations such as the GDPR, the European AI act. This trend can be found in the proposed US AI legislation(OSTP n.d.) in a civilian but also military context (example of NATO's principles of responsible use (PRU), part of the NATO artificial intelligence strategy). It's all about protecting human values, ethical values, including trust but others too, cf. (IEEE 2021) and including sustainability.

The aim is to transform these concepts, which usually belong to the human and social sciences, into tangible, measurable elements that can be manipulated by a community of engineers and technologists, with the aim of incorporating these values into present and future systems, from design to retirement, with the ability to adapt according to observations made during operations.

Putting human at the heart of the approach, in the field of investigation, within the scope of design and modelling, is the challenge. Bringing humans into the system, as partners of the machine, as part of a team! This is the objective of the human autonomy teaming (HAT) approach, a structuring activity right from the start, in terms of identifying appropriate levels of autonomy, the balance of responsibilities between machine and human, acceptable levels of industrial and societal risk, and in other words, the engineering trade-offs to be made.

This HAT engineering skill must find its place at the crossroads of engineering disciplines and specialties, in relation to current or future regulatory requirements and associated standards.

CONCLUSION

Analysis of the modern challenges drove AFIS to define its drivers for developing new products, starting new initiatives. Main axes are the integration of the systems engineering in the enterprise systems, development a systems engineering and system thinking culture in the different parts of the organization.

After decades of self-deception, systems engineering shall now address the question of the human model and its inherent complexity especially when it must be addressed at different scale at personal, group, organization, and social environment.

This frame will serve AFIS to define its projects for year 2024. Topics are new and a single group cannot achieve a single of the mentioned objective. AFIS members will look after other disciplines, collaborate with partners having already engaged projects. AFIS members will be encouraged to contribute to INCOSE projects. ■

REFERENCES

- AFIS (Association Française d'Ingénierie Système). 2022. *Vision 2030+ de l'Ingénierie Système*
- IEEE (Institute of Electrical and Electronic Engineers). 2021. IEEE 7000-2021. Standard Model Process for Addressing Ethical Concerns during System Design. https://standards.ieee.org/ieee/7000/6781/.
- INCOSE (International Council on Systems Engineering). 2021. *Systems Engineering Vision 2035*. https://www.incose.org/publications/se-vision-2035.
- Jackson, M. C. 2019. *Critical Systems Thinking and the Management of Complexity*. John Wiley & Sons, Ltd. Chichester, UK.
- OMG (Object Management Group). 2022. "Unified Architecture Framework (UAF®)" https://www.omg.org/uaf/.
- Ortiz-Ospina, E., and M. Roser. 2016. "Trust". https://ourworldindata.org/trust.
- OSTP (Office of Science and Technology Policy). "Blueprint for an AI Bill of Rights." The White House, Washington US:DC. https://www.whitehouse.gov/ostp/ai-bill-of-rights/.
- Red Team. n.d. "Red Team Defense Scenarios." https://redteamdefense.org/saison-1/red-team-defense-saison-1.
- Rumsfeld, D. 2002. "There Are Unknown Unknowns." https://en.wikipedia.org/wiki/There_are_unknown_unknowns.
- Snowden, J. n.d. "Cynefin." https://thecynefin.co/about-us/about-cynefin-framework/.

ABOUT THE AUTHORS

Christophe Alix is senior systems architect, autonomous systems expert) within the Thales Technical Directorate. He joined Thales in 1991. After 20 years of systems engineering and architecting of large military radars and weapon (systems of) systems, for export, NATO, or French MoD, he is now involved in strategy and innovation for systems at Thales Technical Directorate, particularly as coordinator for autonomous systems initiatives. He is contributing to different working groups within French organizations like AFIS, the French Chapter of INCOSE, and GIFAS French Aerospace Industry Group.

Jean Luc Garnier is systems engineering and architecting director within the Thales Technical Directorate. He is president of the French chapter of INCOSE (AFIS). He chairs architecture working groups within INCOSE, AFNOR (French Chapter of ISO), and EDA (European Defence Agency). With the joint ISO/IEC sub-committee "Software and Systems Engineering" (ISO JTC1/SC7), he is a member of the Standard Management Group (AG4) and Architecture Working Group (WG42). And he is co-editor of the NATO Architecture Framework.

Rob Vingerhoeds is a full professor of systems engineering at ISAE-SUPAERO, Université de Toulouse, France. Rob's research interests include systems engineering and architecture, model-based systems engineering, concept design, and artificial intelligence techniques for engineering applications. Rob is deputy editor of the international scientific journal *Systems Engineering*.

Laurent Alt is a seasoned leader (CTO, CEO) in technology development and innovation (notably at Dassault Systèmes and Lectra), and is an expert in enterprise agility and systems engineering at BCG Paris, mainly supporting the move of automotive and aerospace companies towards software and agility, leveraging systems engineering practices.

Mikaël Le Mouëllic is a managing director and partner, at BCG Paris in the last 10 years, after 6 years in charge of production management at Vallourec. Mikaël is the head of BCG's R&D practice in Europe, helping automotive and aerospace companies in their transformation towards agile.

Mickael Bouyaud is a business architect at Worldline for 8 years, leader in payment systems after 10 years in the mobile phone industry. He is also technical director of AFIS, the French chapter of INCOSE.

Challenges in Early Verification and Validation of System Requirements

Cyril Bacquet, cyril.bacquet@univ-lorraine.fr; **Pascale Marangé,** pascale.marange@univ-lorraine.fr; **Éric Bonjour,** eric.bonjour@univ-lorraine.fr; and **Alain Kerbrat,** alain.kerbrat@airbus.com

■ **ABSTRACT**
Today, requirements engineering (RE) is a key process in the development of complex systems (ISO/IEC/IEEE 2015). Requirements containing quality issues such as ambiguity or inconsistency can lead to late error detection in systems design, resulting in high project cost overruns. This paper presents challenges for early system requirements verification and validation associated to an executable model-based requirements engineering (eMBRE) process proposal.

INTRODUCTION

Requirements engineering (RE) is a key process in the development of complex systems (ISO/IEC/IEEE 2015). RE is characterized by the iterative, recursive, and collaborative activities, analysis and management. This process takes as input a list of needs and constraints from stakeholders (for example, airline companies, pilots, flight attendants, passengers, maintenance experts, and certification authorities), and transforms this list into technical system requirements baseline that the system must satisfy to meet the needs.

To reduce time to market, designers need models and methods to perform early and collaborative validation and verification (V&V) respectively of system requirements and architectures (Chapurlat and Bonjour 2014), to detect specification and design errors and to avoid late and costly modifications during the ground and flight-testing phase or even worse when the system is in operation.

A text-based description, expressed in natural language, is an ambiguous way to capture and communicate system requirements. It leads system development teams to exchange incomplete, inconsistent and incorrect descriptions of system requirements whereas executable model-based system requirements engineering (eMBRE) coupled with executable concept of operations opens the opportunity to system requirements V&V: formally with proof-checking and factually with simulations reviewed with stakeholders. In similar works, Micouin (2014) proposes a model-based system engineering (MBSE) framework that includes requirements encoded as "property-based requirement" and a factual validation of these requirements models using manually defined validation scenarios.

The system requirements validation process aims to ensure that the right system is built. The design verification process aims to ensure the system is built right. A standard (ISO/IEC/IEEE 2015) defines verification of a system as a "confirmation, through the provision of objective evidence, that specified requirements have been fulfilled". The provision of objective evidence is a key point in the V&V process. Another standard (Landi and Nicholson 2011), which provides guidelines for the development of civil aircraft, also insists on the provision of evidence to prepare the aircraft system for certification.

Requirements qualities (RQ) correspond to attributes that a requirement and a set of requirements must have to be considered of good quality. They could be called "requirements applied to requirements". Authors have pointed out that consistency, completeness, and correctness are the most used RQ (Atoum et al. 2021 and Montgomery et al. 2022).

Problems in RQ lead to errors in product design, resulting in delivery delays, re-engineering cost overruns, and potentially catastrophic events in operation (Bahill and Henderson 2005). As requirements are mainly expressed in natural language, problems with RQ such as ambiguity and consistency arise (Brasoveanu, Moodie, and Agrawal 2020).

eMBRE uses languages for modelling requirements (Micaëlli et al. 2013). These languages have been developed over many years to support semi-formal (for example,

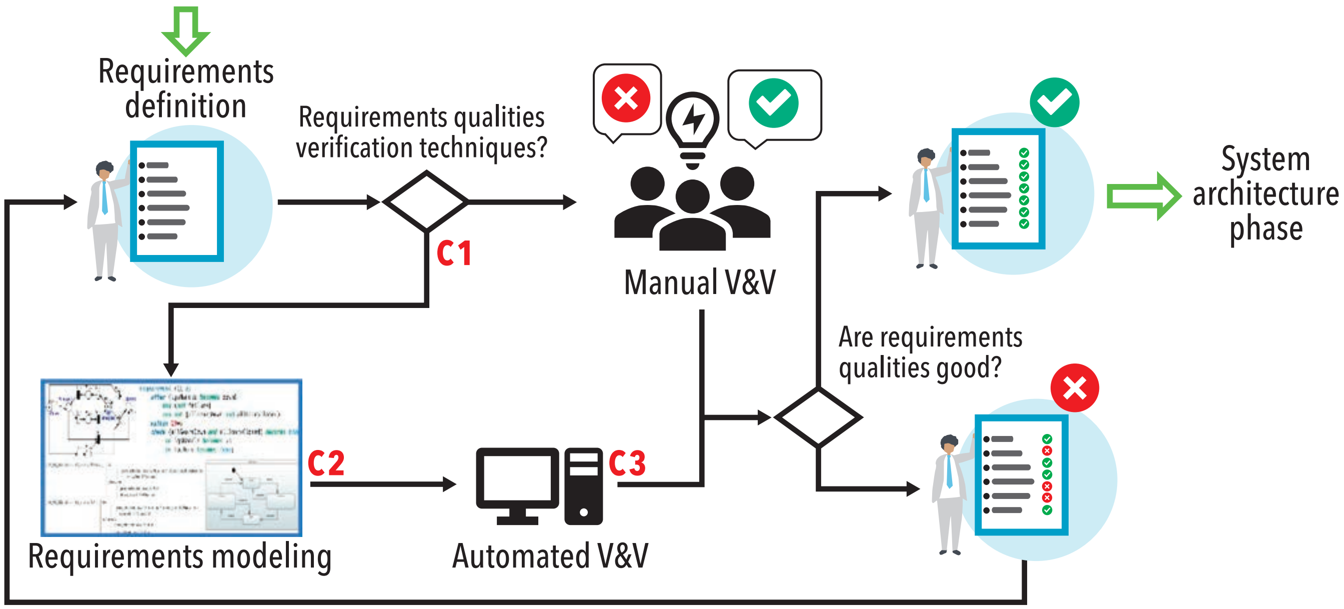

Figure 1. Simplified proposed eMBRE process

SysML) or formal (for example, B method, CTL, and VDM) requirements modelling. Formal languages allow verification techniques to be applied using model checking and theorem proving tools (for example, UppAal and ISABELLE). Several model-based development processes have been proposed in the literature (Brygida Thrower 2012), often as an extension of systems engineering standards.

This article identifies and positions the challenges associated with early verification and validation of systems requirements through a proposal of an eMBRE simplified process.

EMBRE PROCESS

The scope of an eMBRE process can extend throughout the system development process. For an early application of V&V and requirements, eMBRE needs to be upstream of the design or architecture phase.

Figure 1 shows a simplified version of a proposed eMBRE process. The RE process starts with requirements definition from the stakeholders' needs or the over-system specification. These requirements are usually expressed in natural language. The classic RE process involves expert review for manual verification of the RQ.

The alternative way, based on an eMBRE process, aims to model requirements with a formal language. Then to verify and validate requirements models (with automated means). Regarding the qualities of a good requirement, the activity shall verify the requirements model also respects the RQ to ensure that the requirements and the model are usable for other activities.

This eMBRE process raises challenges and questions on its implementation, represented with C1, C2, and C3 in Figure 1: (C1) which requirements should be verified formally according to the concerned RQ? (C2) Which formalism(s) is (are) adapted to model the requirements? (C3) How to verify that each quality of requirements is satisfied?

We will discuss these topics in the following sections:

- C1 in select a requirement V&V approach section
- C2 in select a requirement modelling approach section
- C3 in select an automated V&V techniques section.

SELECT A REQUIREMENTS V&V APPROACH

The first challenge (C1) is to decide which requirements and RQ need to be modelled and formally verified. To do this, the engineers need a means of assessing the intrinsic value of the requirements. The type of requirements may influence this. For example, safety requirements may be prioritized to be modelled due to the potential consequences of errors. The time consumption for an automated means to verify RQ (and implicitly an execution cost) may also be an important criterion linked to the computational processing technologies. Other elements shall be taken into consideration, such as the engineering effort that an engineer should put into the requirement modelling activity. Depending on the impact and return on investment, some requirements may or may not be interesting to model. Using an automated means can also make it possible to review a large number of requirements and identify problematic requirements that may be difficult for the human reason to identify in a large set of requirements. Based on the evaluation of the intrinsic value, the engineers would prefer to use the classical RE approach, or the eMBRE approach in a full or hybrid way.

SELECT A REQUIREMENT MODELLING APPROACH

Another challenge (C2) is to determine which formalism is adapted to requirements modelling (Brasoveanu, Moodie, and Agrawal 2020). There are many existing languages to model requirements (for example, Stimulus, Form-L, Matlab, and Event-B). Each language is designed to support a specific application domain.

In the literature, the landing gear case study (Boniol et al. 2017) aims to test the application of formal techniques for system modelling and formal system verification. This case study does not fully cover the formal modelling and V&V of requirements. We can qualify the landing gear (and aircraft in general) as a cyber-physical system (CPS). Rajkumar et al. (2010) define CPS as: "physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core". We have a particular interest in CPS as the literature is primarily focused on software development. To our knowledge, there is no case study of requirements modelling for CPS with a representative (quality and quantity) requirements dataset that could support the comparison of formalisms and methods. CPS characteristics may not be easily and fully represented with languages in requirements models. Also, the capabilities of the tools supporting these languages may not be developed enough to allow an efficient automation of requirements model V&V.

SELECT AN AUTOMATED V&V TECHNIQUE

The last challenge we identify (C3) is related to the automation and the way of verifying that the requirements models satisfy the RQ.

The requirements formalism chosen beforehand can influence the ability of the automation tools to evaluate the RQ. The three main techniques for RQ V&V are simulation, model-checking, and theorem proving. Depending on the verification capabilities, one technique or another may be preferable. The formalization of RQ is a task to be performed prior to the implementation of the eMBRE process.

From a usage perspective, requirement models need to be compatible with each other to apply V&V on a set of requirements, but also with design and architecture models or any external sources of relevant data to verify designs. Knowing this heterogeneity in the modelling environment, the question of interoperability arises and a standard such as FMI (Functional Mock-up Interface 3.0 Standard 2022) could be a key enabler to support and make eMBRE truly usable.

However, the application of verification techniques may have some scaling limitations when applied to complex CPSs that combine both continuous and discrete behavior in large model environments and may require co-simulation capabilities.

As a complement to the challenge (C2), further work is required to propose a benchmark (or an experimentation framework) to evaluate the performance of the RQ verification capability.

CONCLUSION

This paper highlights the challenges that an eMBRE process will address for early V&V. It first presents the difficulties the engineers may encounter in deciding whether they need to model requirements based on their intrinsic value and the modelling effort (C1). We then consider the challenge of choosing the appropriate formalism(s) to model requirements and to verify their qualities (C2). Finally, the third challenge we identify is to verify that the requirements satisfy these qualities (C3).

Further work will propose a benchmarking (or an experimentation framework) approach to compare the performance of different formalisms and methods for requirements modelling and to verify their qualities, in the specific case of CPS. ■

REFERENCES

- Atoum, Issa, Mahmoud Khalid Baklizi, Izzat Alsmadi, Ahmed Ali Otoom, Taha Alhersh, Jafar Ababneh, Jameel Almalki, and Saeed Masoud Alshahrani. 2021. “Challenges of Software Requirements Quality Assurance and Validation: A Systematic Literature Review.” IEEE Access. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ACCESS.2021.3117989.
- Bahill, A. Terry, and Steven J. Henderson. 2005. “Requirements Development, Verification, and Validation Exhibited in Famous Failures.” Systems Engineering 8 (1): 1–14. https://doi.org/10.1002/sys.20017.
- Boniol, Frédéric, Virginie Wiels, Yamine Aït-Ameur, and Klaus Dieter Schewe. 2017. “The Landing Gear Case Study: Challenges and Experiments.” International Journal on Software Tools for Technology Transfer 19 (2): 133–40. https://doi.org/10.1007/s10009-016-0431-4.
- Brasoveanu, Adrian, Megan Moodie, and Rakshit Agrawal. 2020. “The Role of Formalism in System Requirements.” CEUR Workshop Proceedings 2657 (1): 1–9. https://doi.org/10.48550/arXiv.1911.02564.
- Brygida Thrower, Bozena. 2012. “Model-Based Development and Verification Supplement to ED-12C AND ED-109A The European Organisation for Civil Aviation Equipment L’Organisation Européenne Pour l’Equipement de l’Aviation Civile,” no. January. www.eurocae.net.
- Chapurlat, Vincent, and Eric Bonjour. 2014. “From Model Based Systems Engineering to Model Based System Realization: Role and Relevance of IVTV Plan.” In IFIP Advances in Information and Communication Technology, 438:109–16. Springer New York LLC. https://doi.org/10.1007/978-3-662-44739-0_14.
- “Functional Mock-up Interface 3.0 Standard.” 2022. 2022. https://fmi-standard.org.
- ISO/IEC/IEEE. 2015. “ISO/IEC/IEEE 15288:Systems and Software Engineering System Life Cycle Processes.” ISO/IEC 15288:2008(E), IEEE Std 15288-2008 (Revision of IEEE Std 15288-2004). https://standards.ieee.org/standard/15288-2015.html.
- Landi, Alessandro, and Mark Nicholson. 2011. “ARP4754A/ED-79A–Guidelines for Development of Civil Aircraft and Systems–Enhancements, Novelties and Key Topics.” SAE International Journal of Aerospace 4 (2): 871–79. https://doi.org/10.4271/2011-01-2564.
- Micaëlli, Jean Pierre, Samuel Deniaud, Éric Bonjour, and Dominique Loise. 2013. “How to Implement the Abstract Design Paradigm: The Case of Requirements Engineering.” International Journal of Product Development 18 (2): 147. https://doi.org/10.1504/IJPD.2013.053498.
- Micouin, Patrice. 2014. Model-Based Systems Engineering: Fundamentals and Methods. https://doi.org/10.1016/b978-0-12-385206-9.00002-8.
- Montgomery, Lloyd, Davide Fucci, Abir Bouraffa, Lisa Scholz, and Walid Maalej. 2022. “Empirical Research on Requirements Quality: A Systematic Mapping Study.” Requirements Engineering 27 (2): 183–209. https://doi.org/10.1007/s00766-021-00367-z.
- Rajkumar, Ragunathan, Insup Lee, Lui Sha, and John Stankovic. 2010. “Cyber-Physical Systems: The next Computing Revolution.” Proceedings–Design Automation Conference, 731–36. https://doi.org/10.1145/1837274.1837461.

ABOUT THE AUTHORS

Cyril Bacquet has a Master’s in complex system engineering in 2020. After graduation, he worked as a system engineering consultant with projects in requirements engineering, systems modelling, and PLM systems technologies for two years. He started his PhD in systems engineering in 2022 with the thesis topic of “Executable Model-Based System Requirements Engineering (eMBRE) for early system requirements validation and design verification (V&V)” in an industrial research chair between Airbus and University of Lorraine.

Eric Bonjour is a full professor specialized in systems engineering, at the University of Lorraine/Graduate School of Innovation and Systems Engineering (ENSGSI). His main research interests touch upon the fields of innovation (acceptability, adoption), model-based systems engineering (formalization of requirements, product architecture, safe systems engineering, adoption of MBSE frameworks), and knowledge management. He has supervised 15

> continued on page 25

Challenges in Developing a Method to Support the Adoption of a Model-Based Systems Engineering Methodology

Léa Kozak, lea.kozak@univ-lorraine.fr; **Eric Bonjour,** eric.bonjour@univ-lorraine.fr; **Frédérique Mayer,** frederique.mayer@univ-lorraine.fr; and **Jean-Pierre Micaëlli,** jean-pierre.micaelli@univ-lyon3.fr

■ **ABSTRACT**

To improve design performance and achieve sustainability, organisations are looking to change their systems engineering practices. A model-based systems engineering (MBSE) methodology provides a framework for integrating, associating, orchestrating, and connecting executable and interactive models. It improves early verification and validation of system specifications and architectures, as well as communication and collaboration between project stakeholders. In this sense, MBSE has a truly systemic aspect. The variables to be considered when designing a support strategy are numerous and multidimensional. As a result, this situation can lead to contradictions in the choice of actions to be implemented, or to paradoxes that are likely to slow down the progress of the deployment project with the engineers. Currently, there is no method to support teams in charge of a methodological transformation (for example, in MBSE) to facilitate the adoption of this methodology. This article identifies the main challenges involved in developing such a methodology.

INTRODUCTION

The implementation of a new engineering methodology transforms the knowledge, practices, tools, roles, and exchanges between the actors involved (Sánchez Garzón 2019). This transformation requires appropriate support. Today, change interventions are often one-size-fits-all and do not really support change, but rather its management (Chahir 2021).

Change management often considers a single starting point and a single path to implementation. However, with the proliferation of digital practices, customisation is more than necessary if a change project is to be successful.

Support for change, on the other hand, looks at the mindset of the individual, from their fears to their sense of purpose. The possible paths are as unique as the individuals themselves. The individual's path through the change process depends on several factors, such as the individual's role and the way in which the methodology is applied to his or her activity, as well as certain invisible cognitive mechanisms linked to the individual's beliefs, experience and confidence in the change.

This process of change also faces resistance. This resistance often stems from a lack of knowledge on the part of stakeholders about their own development needs. Through change, the organisation often seeks to make progress in terms of competitive advantage, but this is only possible by developing the knowledge and skills of its people. However, this opportunity for development is often misunderstood and interpreted as a constraint imposed by management through an abstract strategy for teams.

The research question of the thesis is "How to support the adoption of MBSE" and the contribution of this article is to identify the various challenges that make the research question complex.

METHODOLOGY

To contribute to this research question, it is necessary to study the barriers and levers to the implementation of MBSE and the existing gaps in the literature in different scientific fields related to our problem: management, psychology, sociology, industrial engineering, and social psychology. There is an abundance of scientific literature on the subject. One

Table 1. Challenges identified by scientific field and management level

Steering level/Areas	Strategic	Organisational	Operational/Business
Industrial engineering	The initial investment is significant while we are in situations where budgets are quite tight. (Chami et al. 2018)	There is no explanation of the progression between the different stages of development in the SE / MBSE maturity grid proposed by INCOSE.(Hale and Hoheb 2020)	MBSE practices require SE prerequisites that are not clearly spelled out at present (referring to operational invariants linked to SE activities).
Change management	The notion of adhesion is rarely taken into account in change management. (Autissier and Moutot 2019)	There is no definition of the process of adopting a methodology. (Acosta Salgado, Bonjour, and Rakotondranaivo 2020)	The individuals who will occupy the new roles in the new methodology are generally from different cultures, and the means and resources to support this diversity in order to deploy the process correctly have not been identified.
Sociology	It is difficult to measure the level of evidence and of trust when these factors are in the level of adheson. (Sauvayre 2012)	The concept of the learning organisation is considered a theoretical black box. (Denancé 2017)	It is difficult to move from the individual to the collective level in terms of dynamic analysis of change. (Quiger 2013)
Management	There is no method for analysing and taking into account human constraints in order to adjust the strategy.	Management models are based on activating the driving forces of change and neglect the moderating forces linked to constraints. (Denancé 2017).	There are a number of obstacles to the adoption of MBSE. These may include a lack of perceived value and support for its deployment, but also the availability of skills or some kind of cultural and general resistance to change. (Cloutier 2019)
Social psychology	There is no method for developing a culture, which makes it difficult to adjust the necessary actions.	Culture is at the heart of the change process (the biggest obstacle) but remains intangible/inaccessible in its entirety, and so this spectrum is often not considered in the action plan.	Coalitions and networks of influence play an essential role, but are difficult to model. (Buttet 2019)
Psychology	Invisible cognitive mechanisms play a major role in decision-making and therefore in the understanding of change, but to date they have not been taken into account in deployment constraints.	There is no method for including individual beliefs in the understanding of large-scale collective systems.	The link between evidence and cognitive mechanisms is not obvious. (Sauvayre 2012)

difficulty is to establish coherent links between existing works to propose a relevant support method.

What's more, adoption is a complex and ambivalent subject, depending on the approach we take to understanding it. It can be approached from the top down, the bottom up, or a mixture of the two. The decision to deploy MBSE in its true sense is more of a top-down approach; the challenge for true adoption is for engineers to adhere to that vision and contribute to the process of bringing about the bottom-up approach.

Refocusing attention on the human element seems essential to any transformation. Individuals need to be able to see what the change means to them before they will commit to it. The challenge is to support them in this development. By helping change agents to understand the different views and needs of individuals, they can then work together to develop the goals and the most appropriate path for each individual, leading to a positive decision to adopt the change.

This article identifies the challenges that define the boundaries (scientific gaps and barriers) by domain and by level of management, making it possible to highlight the missing links between these domains in order to move towards a holistic approach.

RESULTS

As part of the introduction of MBSE, it was mentioned that the notion of meaning is important. And it can be considered in two ways:

- The meaning behind collaboration: understanding their development needs, those of their team and those of the organisation. It is important that they understand that they are part of a system and that they are contributing to the development of that system.

- The importance of change for their work. They need to be able to conceptualise and abstract. In other words, the change needs to be understood by the people involved, but more than that, it needs to make sense to them if they are to contribute to and commit to it.

To take these aspects into account, it seems appropriate to examine the issues at three levels of management: strategic, organisational and operational/activity. Table 1 identifies the issues according to scientific fields (in the rows) and management levels (in the columns).

With our current knowledge of the subject, we can say that there is no method of measuring and monitoring adhesion. However, it is important to be able to monitor the progress of the individual or team to provide the appropriate support.

There are 3 conceptual solutions to meet these different challenges: systems thinking, co-construction, and maturity. The latest change management models show their limitations when it comes to acting in complexity, and the recommendations are to be able to put this complexity into dialogue to better understand it before acting (Morin 1990). We then move from "simple" thinking (guessing, preferring, believing, etc.) to "complex" thinking (proposing hypotheses for solutions, creating relationships, looking for criteria, relying on valid justifications, and self-correction).

This systems thinking allows us to better understand, question, and deepen the definition phase of the needs of the stakeholders in the change process from a variety of perspectives. It can be broken down into six main concepts: interconnection, synthesis, emergence, feedback loop, causality, and mapping (DeMarce 2020). There is a link here with the concept of co-construction. It is defined as a process "based on the design of interactions between actors so that, as they interact, they develop agreements aimed at making definitions in relation to a change, a project or a compatible way of working" (Foudriat 2014). It is through the development of these agreements that trust is built in the change agent and in the proposed solution. Trust is one of the essential elements of acceptance, along with evidence and acceptability (Sauvayre, 2012).

Finally, there is a link with the notion of maturity, in the sense that co-construction leads players to develop their maturity in MBSE with different (non-exhaustive) levels of ability to adapt, collaborate, evolve, and change things. By measuring this maturity through a diagnostic, we can then monitor the development of the teams as the actions are implemented and readjust their development together.

CONCLUSION

For each of these areas, we have been able to identify the various limitations in relation to our subject. And it is within these limits that the hypotheses for solving our problem are to be found.

From this study, the article highlights the different challenges that we hope to resolve in the future, namely: understanding the complexity involved and how to transcribe it; identifying the positive and negative conditions for emergence; understanding how the factors for emergence and buy-in influence each other and how to adapt the action plan; and finally, being able to monitor the progress of the teams in the ownership process according to the actions taken. ■

REFERENCES

- Acosta Salgado, Linda, Eric Bonjour, and Auguste Rakotondranaivo. 2020. "Towards an Improved Acceptability Assessment Model of Innovative Solutions in the Design Phase." *International Journal of Business Information Systems* 1 (1): 1. https://doi.org/10.1504/ijbis.2020.10029802.
- Autissier, David, and Jean Michel Moutot. 2019. "Le Changement Agile." In *La Boîte à Outils de La Conduite Du Changement et de La Transformation*, edited by Dunod, 2ème editi, 40-41.
- Buttet, Loïc. 2019. "Enjeux et Facteurs Clés de Succès de La Conduite Du Changement Pour Un Projet d'évolution SIRH: Exemple d'une Solution Personnalisée Vers Une Solution Standard."
- Chahir, Mehdi. 2021. "Proposition et Évaluation d'une Méthode d'accompagnement Du Changement Induit Par Le Déploiement d'une Nouvelle Technologie Dans Les Organisations." PhD thesis, University of Rennes 2.
- Chami, Mohammad, Aiste Aleksandraviciene, Aurelijus Morkevicius, and Jean-Michel Bruel. 2018. "Towards Solving MBSE Adoption Challenges: The D3 MBSE Adoption Toolbox." *INCOSE International Symposium* 28 (1): 1463-77. https://doi.org/10.1002/j.2334-5837.2018.00561.x.
- Cloutier, Robert. 2019. "2018 Model-Based Systems Engineering Survey." Internal report, University of South Alabama.
- Denancé, Victor. 2017. "Accompagnement Du Changement Individuel et Collectif Par Le Développement Des Compétences." PhD thesis, Université Rennes 2.
- Foudriat, Michel. 2014. "La Co-Construction–Une Option Managériale Pour Les Chefs de Service." In.
- Hale, Joe, and Al Hoheb. 2020. "INCOSE Model-Based Capabilities Matrix and User's Guide." *INCOSE International Symposium*.
- M. DeMarce, Gabriella. 2020. "The Great Turning: A Call for Systems-Thinkers."
- Morin, Edgar. 1990. *Science Avec Conscience*.
- Quiger, Stéphanie. 2013. "Acceptability, Acceptance and Appropriation Des Systèmes de Transport Intelligents: Elaboration d'un Canevas de Co-Conception Multidimensionnelle Orientée Par l'activité." Thesis, 1-294.
- Sánchez Garzón, Felipe. 2019. "Supporting a company's project management transformation by developing a project management maturity model based on invariants and a causal predictive model between maturity criteria and project performance." PhD, Université de Lorraine.
- Sauvayre, Romy. 2012. *The Mechanisms of Membership*.

ABOUT THE AUTHORS

Léa Kozak has an engineering degree in innovation and systems engineering (ENSGSI) and a master's degree in human and social sciences (IUVTT). She is currently a doctoral student at the ACTE MBSE Chair where she is developing a method to support the adoption of MBSE.

Frédérique Mayer is associate professor HDR (accreditation to direct research) of information systems and systems engineering at the graduate School of Innovation and Systems Engineering (ENSGSI) of the University of Lorraine. She is member of the research team on innovation process (ERPI). She has a strong research experience in systems modelling process and enterprise modelling, with special interests in systems dynamics and systems approaches. She has supervised 10 PhD theses related to these topics. Frédérique Mayer was the chairwoman of the technical committee 9.2 on "Social Impact of Automation" of the International Federation of Automatic Control (IFAC). She was

> continued on page 25

Understanding the Indirect Effects of Interactive Systems Within Systems of Systems

Laetitia Bornes, laetitia.bornes@isae-supaero.fr; **Catherine Letondal,** catherine.letondal@enac.fr; and **Rob Vingerhoeds,** rob.vingerhoeds@isae-supaero.fr

■ **ABSTRACT**
Until recently, research into the sustainable design of interactive systems has primarily focused on the direct material impact of a system, through improving its energy efficiency and optimizing its lifecycle. Yet the way a system is designed and marketed often has wider repercussions, such as rebound effects, and systemic change in practices. These effects are harder to assess (and to anticipate) than the direct physical impact of the construction and use of the system itself. Current tools are unable to account for the complexity of these effects: the underlying causal mechanisms, their multi-level nature, their different temporalities, and the variety of their consequences (environmental and societal). This is why we are seeking to develop a specific methodology and tool, inspired by systemic design and system dynamics. These are intended for decision-makers and designers of interactive systems within systems of systems (for example, in the fields of agricultural robotics or public transportation). In this paper, we present this modeling approach and our prototype tool through the example of a second-hand clothing sales platform.

■ **KEYWORDS:** sustainability, systems of systems, sociotechnical systems, rebound effect, systemic, methodology, modeling tool

THE INDIRECT EFFECTS OF AN INTERACTIVE SYSTEM WITHIN A SOCIOTECHNICAL SYSTEM

In interactive systems engineering, until recently, efforts to move towards a more sustainable future have mainly focused on the direct material impact of a system, by improving energy efficiency during its use and optimizing its lifecycle to reduce waste, pollution, and greenhouse gas emissions. (In this context, "interactive system" refers to a computerized system whose behavior adapts to users' actions.) However, the impact of an interactive system is not limited to the direct physical impact of its manufacturing, use, maintenance, and end of life (first order effect). In fact, the introduction of a new product (or a new technology) into society very often has indirect consequences, due to how it is used and the changes in societal practices it induces (Coroamă 2019). A simple example is the rebound effect, first identified by William Stanley Jevons in 1865 in relation to the steam train (Jevons 1865). The rebound effect occurs when the optimization of a system leads to a saving (in time or cost) which has the effect of increasing overall consumption.

In addition to direct (first order) effects, there are several indirect effects, including:

- **direct rebound (second order) effect**: A rebound effect where increased efficiency, associated cost reduction and/or convenience of a product or service results in its increased use because it is cheaper or otherwise more convenient. (ITU 2022)

  Example: In the case of the car, improved engine efficiency enables drivers to save fuel: they can drive more often or for longer, and, for example, live further away from their work, which results in an overall increase in fuel consumption.
- **indirect rebound (second order) effect**: A type of rebound effect where savings from efficiency cost reductions enable more income to be spent on other products and services. (ITU 2022)

  Example: Some drivers will spend their fuel savings on other activities, such as flying on holiday.
- **systemic (higher order) effect**: The indirect effect (including but not limited to rebound effects) other than first and second order effects occurring through changes in consumption patterns, lifestyles, and value systems. (ITU 2022)

  Example: The introduction of the car has completely changed the way cities are organized and how people get

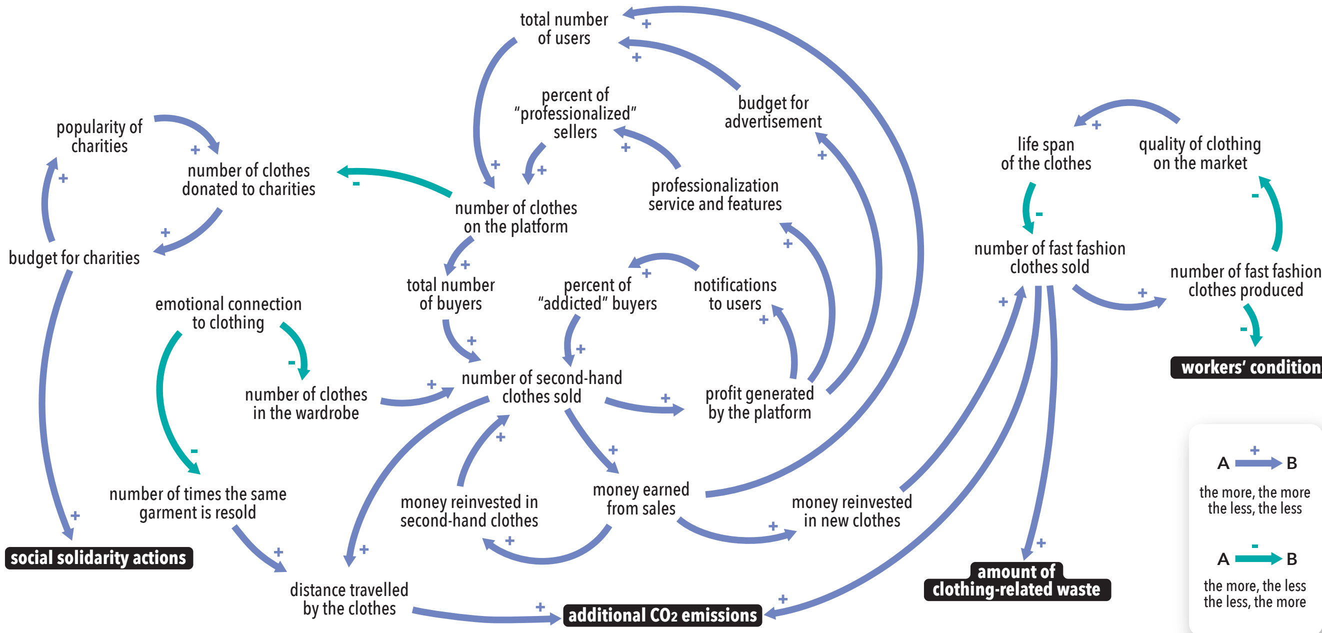

Figure 1. Causal loop diagram (Kim, 1992) representing the influences between the different variables

around, to the extent that it is difficult to do without a car in certain regions or for certain professions.

Second order and higher order effects do not necessarily exceed efficiency gains and are not even necessarily negative. Nevertheless, it is imperative to understand them, as they are now perceived as potentially very impactful, in terms of intensity and duration, hence the recent interest in sustainability research (Coroamă 2020). These effects are on a much larger scale (the higher the order, the larger the scale), and are interwoven with social dynamics, practices, and lifestyles, making them very difficult to assess, let alone anticipate.

"Systemic effects have wider boundaries of analysis and are more difficult to quantify and investigate but are nonetheless very relevant" as stated by the IPCC (Pathak 2021) in the Working Group III report and described by Gauthier Roussilhe (2022).

A 'QUALI-QUANTITATIVE' MODELING METHODOLOGY

Designers, decision-makers, and policymakers lack the tools and methods to understand these effects and to visualize the dynamics of sociotechnical systems (systems of systems). The ITU-T L. I480 methodology proposes mapping these effects using a consequence tree (ITU 2022), which consists of listing the various possible effects and ranking them in the form of a tree. This representation does not shed light on certain feedback dynamics when consequences can themselves become causes. In addition, this tool is qualitative and does not allow orders of magnitude to be represented. Yet many of the problems we face are physical and quantifiable (CO_2 emissions, depletion of resources, land artificialization, etc.). Other existing tools mainly focus on environmental impacts (particularly GHG) and ignore societal impacts (working conditions, access to healthcare, etc.). However, it is necessary to adopt a systemic approach if one intends to respect the planetary boundaries, as well as the social foundations, as described in the doughnut model (Raworth 2017).

Drawing on system dynamics (Sterman 2000) and systemic design (Jones 2020), we are seeking to develop a 'quali-quantitative' modeling methodology (Bornes et al. 2022) and tool (Bornes 2023). To develop this methodology, we rely on the activities of group model building (Bérard 2010), which we integrate into the interactive systems design process. We conducted interviews with systemic designers and continuously assess and refine this methodology by applying it to case studies. Specifically, we held two workshops with professional user experience designers on the case of a second-hand clothing platform (partially presented in the next section), and we also plan two new workshops with systemic designers (Bornes et al. 2023). Additionally, we are currently collaborating with political stakeholders on a real-world project to study the possible impacts of a low-carbon train within a rural transportation system of systems (Une étude sur l'écomobilité menée à Lectoure 2023).

The objective is to enable designers and decision-makers to represent scenarios of potential environmental and societal effects of design alternatives, to inform their design or strategy decisions. The ambition is to enable them to build their own model, to understand the sociotechnical dynamics, to get quick insights, and to be able to communicate it. The objective is to project scenarios of possible futures and to compare these scenarios relatively, with the help of indicators. Considering the uncertainty of the future, we propose a prospective approach: it is not a matter of predicting the most probable future, but of exploring several possible (and desirable) scenarios. To do so, we favor human understanding and intuition over quantitative data, building the model not only on quantitative data, but also on expert opinion, documentary studies, and mixed data collection methods (qualitative and quantitative surveys).

PRACTICAL CASE OF A SECOND-HAND CLOTHING PLATFORM

Let's take the simple example of a second-hand clothing platform. At first glance, we might imagine that it supports more sustainable practices and has a positive impact on society. However, it can have detrimental effects (Juge et al. 2022):

- Transporting clothes from seller to buyer and using the platform causes carbon emissions (first order).
- On average, buyers buy more items because they cost less or because they feel less guilty about buying second-hand (direct rebound).

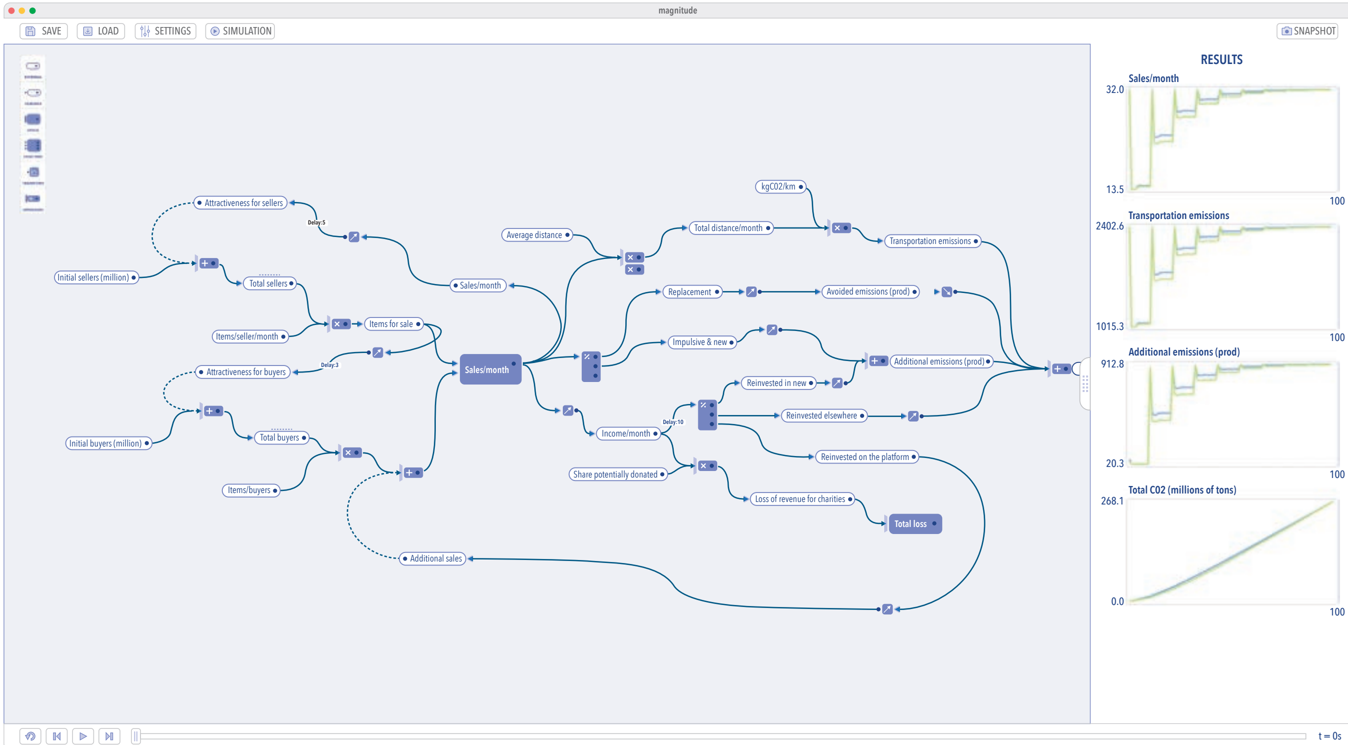

Figure 2. Example of model building in the 'quali-quantitative' modeling tool

- Some sellers use the money from sales to buy unnecessary new fast-fashion clothes (indirect rebound).
- Charities are suffering from a drop in donations because people are changing their habits and preferring to sell rather than donate (higher order rebound).

Identifying these effects can help define mitigation levers at the product design, service, and business model levels. For example, filtering the results to show only items that are close to the buyer, offering sellers the option of donating their item rather than selling it in certain cases, encouraging users to use the proceeds from sales on the platform through incentives, offering services to extend the lifespan of clothes through repair, and so on. However, this does not allow designers and decision-makers to determine which lever or combination of levers will have the most significant impact over time.

As part of a project to redesign the platform, its business model and associated services, our methodology consists of the following steps (this process is nonlinear and iterative):

1. Bring together stakeholders from the company and experts from the fashion and second-hand industries (including environmental economists and sociologists).
2. Collectively carry out a qualitative analysis of the various effects of the platform.
3. Collectively identify the variables of interest (for example, CO_2 emissions, amount donated to associations, etc.), and the influencing variables (for example, number of garments sold, number of users, revenue generated by sales, etc.).
4. Collectively construct a diagram representing the influences between the different variables (see a simplified example in Figure 1).
5. Collectively define a strategy for quantifying these influences:
   a) by drawing on existing studies (for example, average emissions per km travelled),
   b) by deducing from existing quantitative data measured on the platform (for example, the average percentage of sales revenue used to buy other second-hand clothes on the platform),
   c) by carrying out a specific study (observations, qualitative interviews, quantitative surveys, etc.) with consumers (for example, emotional link to second-hand clothes and number of clothes in the wardrobe),
   d) by testing various hypotheses based on expert opinions.
6. Iteratively build a 'quali-quantitative' model using Magnitude, the prototype modeling tool (see the prototype in Figure 2), and explore several scenarios through simulation, not forgetting to represent possible rebound effects due to the mitigation measures.
7. Relatively compare the scenarios to collectively define a strategy at several levels (design, services, and business), possibly including other stakeholders such as users, charities, etc.
8. Monitor the effects of this strategy over time, in comparison with the projected scenario, and iterate on the strategy and model based on observed changes over time.

This 'quali-quantitative' modeling is seen as a tool for collaborative thinking and decision support between different stakeholders. The relevance of the results depends on the model validity. However, the stakeholders are aware of the model's limitations since they have participated to its construction.

MAGNITUDE: OUR PROTOTYPE MODELING TOOL

To propose a simplified formalism that requires minimal or no coding, and to delve into the concept of a modeling tool tailored to interactions between product/service design and the associated sociotechnical system, we decided not to use generic system dynamics tools like

InsightMaker, Stella, or Vensim. Instead, we developed our own prospective modeling tool (see Figure 2). For this tool, we opted to draw inspiration from the simplicity of causal loop diagrams and the calculation principles of stock-and-flow modeling.

Our prototype provides a toolbox that allows loading data from files, creating variables and stocks (cumulative variables) calculated at each time step, applying transformations and delays, and forming feedback loops. The curves of the values of variables of interest can be displayed on-demand in the results panel on the right. It is also possible to compare the curves of multiple simulations.

PERSPECTIVES

The results of our initial practical cases seem promising, with good engagement from the involved designers. We also plan to apply this modeling methodology to other practical cases in the ICT (information and communication technology) industry and compare the contribution in comparison to the methods and tools mentioned in Section 2. ■

REFERENCES

- Bérard, C. 2010. "Group Model Building Using System Dynamics: An Analysis of Methodological Frameworks." *Electronic Journal of Business Research Methods* 8 (1): 35-45.
- Bornes, L. 2023. "A Methodology and a Tool to Support the Sustainable Design of Interactive Systems: Adapting Systemic Design Tools to Model Complexity in Interaction Design." Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems, 1–5. Hamburg, DE: ACM. doi:10.1145/3544549.3577055.
- Bornes, L., C. Letondal, and R. Vingerhoeds. 2022. "Could Systemic Design Methods Support Sustainable Design of Interactive Systems?" Proceedings of Relating Systems Thinking and Design RSD11. ISSN 2371-8404. https://rsdsymposium.org/could-systemic-design-methods-support-sustainable-design-of-interactive-systems.
- Bornes, L., C. Letondal, and R. Vingerhoeds. 2023. "Using a Quali-Quantitative Modelling Tool to Explore Scenarios for More-Than-Sustainable Design." Proceedings of Relating Systems Thinking and Design RSD12. https://rsdsymposium.org/quali-quantitative-modelling (pre-release).
- Coroamă, V. C., P. Bergmark, M. Höjer, and J. Malmodin. 2020. "A Methodology for Assessing the Environmental Effects Induced by ICT Services: Part I: Single Services." Proceedings of the 7th International Conference on ICT for Sustainability, 36–45. Bristol, UK: ACM. doi:10.1145/3401335.3401716.
- Coroamă, V.C. and F. Mattern. 2019. "Digital Rebound–Why Digitalization Will Not Redeem Us Our Environmental Sins." Proceedings 6th International Conference on ICT for Sustainability. Lappeenranta, FI. http://ceur-ws.org (Vol. 2382).
- ITU (International Telecommunication Union). 2022. ITU-T L.1420. Enabling the Net Zero transition: Assessing How the Use of Information and Communication Technology Solutions Impact Greenhouse Gas Emissions of Other Sectors.
- Jevons, S. 1865. The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines. London, Macmillan and Co.
- Jones, P. 2020. "Systemic Design: Design for Complex, Social, and Sociotechnical Systems." In *Handbook of Systems Sciences*, edited by Gary S. Metcalf, Kyoichi Kijima, and Hiroshi Deguchi, 1–25. SG: Springer Singapore. doi:10.1007/978-981-13-0370-8_60-1.
- Juge, E., A. Pomiès, and I. Collin-Lachaud. 2022. 'Plateformes digitales et concurrence par la rapidité. Le cas des vêtements d'occasion'. Recherche et Applications en Marketing (French Edition) 37 (1): 37–60. doi:10.1177/0767370121994831.
- Kim, D. H. 1992. "Guidelines for Drawing Causal Loop Diagrams." *The Systems Thinker* 3 (1): 5–6.
- Pathak, M., et al. 2021. "Working group III contribution to the IPCC Sixth Assessment Report (AR6) – Technical Summary." IPCC, 132-133.
- Raworth, K. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st Century Economist*. Chelsea Green Publishing. ISBN:9781603586740.
- Roussilhe, G. 2022. Les Effets Environnementaux Indirects de la Numérisation. Septembre 2022. https://gauthierroussilhe.com/articles/comprendre-et-estimer-les-effets-indirects-de-la-numerisation.
- Sterman, J. D. 2000. *Business Dynamics—Systems Thinking and Modeling for a Complex World* 53. US.
- 'Une Étude Sur l'écomobilité Menée à Lectoure'. 2023. La Dépêche. https://www.ladepeche.fr/2023/07/18/une-etude-sur-lecomobilite-menee-a-lectoure-11347331.php.

ABOUT THE AUTHORS

Laetitia Bornes, PhD student, ENAC & ISAE-SUPAERO. After a master's degree in engineering, architecture, and digital design, Laetitia Bornes worked for 5 years as a UX designer. During her PhD, she is exploring the potential of modeling to support the more-than-sustainable design of interactive systems. Her research aims to enable designers and decision-makers to represent the systemic effects of their design and explore scenarios to make informed decisions.

Catherine Letondal, Assistant Professor, ENAC. Catherine Letondal has been conducting research into human-computer interaction and human-centred design for 25 years. She initially specialised in end-user development, participatory design, and tangible interaction for complex critical domains such as aeronautics. For the past five years, she has been exploring HMI-based research directions for systemic approaches.

Rob Vingerhoeds, Professor, ISAE-SUPAERO. Rob Vingerhoeds is a full professor of systems engineering at ISAE-SUPAERO, Université de Toulouse, France. Rob's research interests include systems engineering and architecture, model-based systems engineering, concept design, and artificial intelligence techniques for engineering applications. Rob is deputy editor of the International Scientific Journal *Systems Engineering*.

WONKA: An Ontology-Aided Model-Based Systems Engineering Analysis for Early V&V on Heterogeneous Systems and Applications

Romain Delabeye, romain.delabeye@isae-supmeca.fr; **Olivia Penas,** olivia.penas@isae-supmeca.fr; and **Régis Plateaux,** regis.plateaux@isae-supmeca.fr

ABSTRACT
This research is undertaken as part of the EU-funded EnerMan project aiming at improving the energy sustainability of manufacturing systems. In such a large project, with 22 partners over 10 countries, a first challenge addresses the collaborative design of an energy management system (EnMS) for the improvement of energy sustainability, while offering the flexibility and agility necessary for the diversity of the industrial cases studied and the partners involved. In a second stage, industrial use cases are generally too constrained to easily proceed to the verification and validation (V&V) of the scientific approaches tackling their challenges. In this context, our research contributions consist of methodologies and automated approaches to: (i) ensure the consistent collaborative integrability of developments, in a sustainable manufacturing context, and (ii) perform the verification and validation of such contributions on multiple systems, assessing their scalability on heterogeneous systems, environments, and missions in a V&V context.

CONTEXT

The EnerMan project aims to design and implement a series of energy sustainability enhancements for production plants (EnerMan H2020 2021). Indeed, as industry is inherently energy-intensive, accounting for 38% of global energy consumption in 2021 (International Energy Agency 2022), this project aims to develop a holistic energy management system (EnMS) (ISO 2023), made of monitoring and control systems, models, and decision aids, acting as an "energy digital twin" of a plant (Hehenberger et al. 2023). As a result, this EnMS is jointly designed by 22 academic and industrial partners. Each partner provides scientific approaches and technological developments that must be validated on real-world industrial case studies and should be applicable to most use cases in the manufacturing industry. This collaborative environment induces new constraints with respect to state-of-the-art collaborative design approaches (Roumili et al. 2021) and V&V processes (Milis, Panayiotou, and Polycarpou 2019).

Many efforts are undertaken to bind research contributions with industrial technological developments, to lead to high value-added innovation. Still, due to the constraints dictated by the industrial environment in which these elements of innovation will eventually be implemented, the overall design may be arduous to be verified and validated in real conditions. Indeed, V&V activities encounter multiple difficulties in practice: wide domain of application, low availability of the industrial systems, cost of experiments, and time required to implement reliable V&V processes.

Thus, the first challenge concerns the positioning of various solutions in a large-scale project, which we propose to address by means of a model-based systems engineering (MBSE) analysis (Delabeye et al. 2021). Then the second challenge deals with the verification and validation of these solutions – from the earliest design phases – as applicable to all targeted use cases (beyond the ones that are the most accessible) and similar applications. To meet this challenge, an automated and scalable V&V process for heterogeneous systems and applications was developed (Delabeye, Penas, and Plateaux 2022). An ontology was designed to formally represent the use cases and scientific approaches to be validated. Reasoning is then used to assess the extent

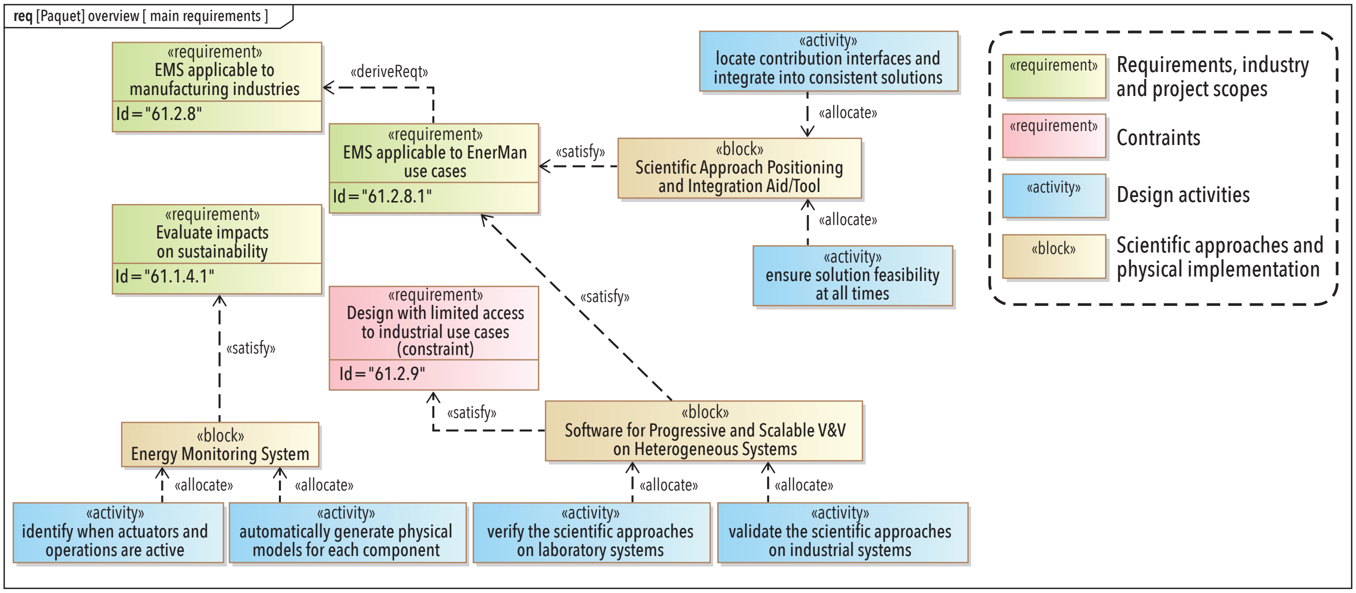

Figure 1. Traceability links between the four views: requirements and constraints, design activities, scientific approaches, and physical implementation

to which a given scientific approach can be verified on a laboratory system (selected using semantic similarity with respect to the industrial use cases) different from the industrial scenarios on which it must finally be validated. A recommendation system, pinpointing missing components or interactions within the use case, was designed to augment the systems so as to increase the degree of validation of the studied scientific approach and its ability to scale to other use cases.

MBSE ANALYSIS TO FORMALISE THE PROBLEM AS REGARDS THE RESEARCH QUESTIONS OF A LARGE PROJECT

Following a scientific methodology, a systems engineering approach made it possible to specify and position the scientific challenges of the research project (Delabeye et al. 2021). This approach allows to identify interactions between research teams, research topics and communities, underlying scientific approaches and enabling technologies, as well as their compliance to existing contracts, standards, and regulations. This methodology relies on an MBSE analysis, implemented with the System Modeling Language (SysML).

The workflow of this developed MBSE analysis is based on four main top-down steps: (i) the derivation of the energy sustainability requirements limited to the scope and constraints of the project (in part stemming from application requirements); (ii) an analysis of the macro-functions (corresponding to the different energy sustainability improvement paths) that the EnMS to be developed must have in order to meet these requirements; (iii) the scientific research areas that can contribute to these macro-functions; and (iv) the solutions/technologies for the implementation of these approaches (Figure 2). Finally, the traceability of the dependencies between these four views, conducted all along this workflow (Figure 1), allows to identify during the project, for a given modelling element, all the ins and outs and in particular the interfaces to be foreseen and defined with other interacting parties, but also to facilitate the crucial steps of verification and validation.

As a result, this SysML model captures multiple system design aspects, classified into requirements, constraints, design activities, and physical implementations. Traceability between these views ensures the consistency of the complex product in development in a collaborative context. Figure 1 presents this mechanism in a synthetic view, as applied to one partner's solutions contributing to the final EnMS envisioned by the EnerMan project.

THE WONKA FRAMEWORK

To converge towards joint academic and industrial developments tackling the above-mentioned crucial aspects, we propose a generic while highly interpretable framework to cover all stages of a verification and validation process: from early V&V to full validation and continuous verification, as illustrated in Figure 2. The WONKA (Verification & Validation with an ONtology and Knowledge-based Approach) methodology is an ontology-based framework with a methodology assessing the scalability of heterogeneous systems, environments, and missions in a V&V context. This methodology has been implemented and tested on laboratory systems (an instrumented automatic coffee machine, a 3D printer, and a robot arm with additional sensors) and industrial use cases (a vehicle testbed's heating, ventilation and air conditioning system, and a chocolate production line). Projecting these industrial and laboratory applications onto a meaningful ontology allows them to be flattened out to the same scale from a semantic point of view. The SAREF ontology (de Roode et al. 2020) was refined to represent all the cyber-physical systems under consideration, as its concepts and properties accurately captures monitoring, production systems, and processes. The framework has been implemented using Protégé and Owlready2, and applied to a scientific approach focused on a blind source separation technique used to identify system operating modes in a black box manner (Delabeye, Penas, and Plateaux 2022), tested on the coffee machine and both industrial case studies. Using description logic, a subset of first order logic, an inference mechanism enables an automatic and quantified assessment of the ability of a scientific approach to be verified on a laboratory use case different from the industrial scenario on which it will have to be validated.

CONCLUSIONS AND PERSPECTIVES

Two intricate methodologies have been proposed to cover the development lifecycle of a scientific approach, software, and tools to be applied to multiple systems of different nature, in a constrained industrial environment. An MBSE analysis was led to identify, position and structure the scientific developments, in line with the requirements derived from the scope of our

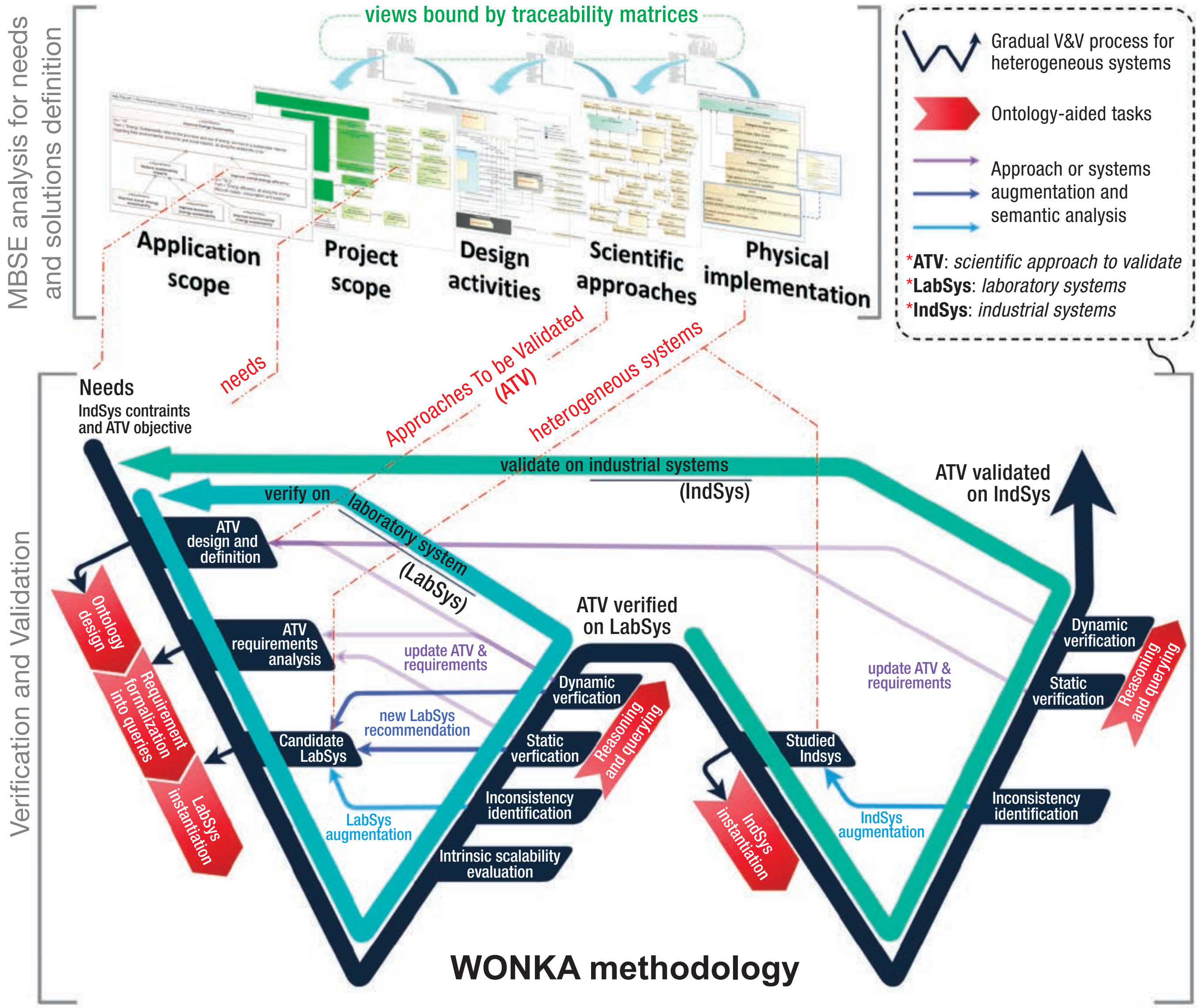

Figure 2. The WONKA framework coupled with the proposed MBSE analysis

research project, consistently with a holistic energy sustainability view. A complete methodology, consisting of an ontology, a querying mechanism and semantic reasoning, has been designed to study and support the applicability and scalability of the scientific approaches developed in this research project to industrial use cases. More importantly, the WONKA framework enables the early V&V of a system, thus limiting the number of physical/on-site experiments required on uses cases with high cost and low availability.

To make the WONKA methodology replicable and comparable to state-of-the-art approaches sharing the same goal, a benchmark on *Early Verification and Validation* has been proposed ("Benchmark 1. MBSE for Early Verification and Validation" [2021] 2023). The corresponding case study consists of one scientific approach to be designed (blind source separation technique), to be verified and validated on two industrial systems given three laboratory systems. Early V&V methodologies can thus be compared according to their features (from requirement elicitation and enrichment to V&V and traceability), as well as their quantified performances for which several measures of performance (MoP) are proposed. ■

REFERENCES

- "Benchmark 1. MBSE for Early Verification and Validation." (2021) 2023. HTML. S.mart–Systems.Manufacturing. Academics.Resources.Technologies. https://github.com/GIS-S-mart/Benchmark-1_MBSE_for_Early_Verification_and_Validation.
- Delabeye, Romain, Olivia Penas, Martin Ghienne, Arkadiusz Kosecki, and Jean-Luc Dion. 2021. "MBSE Analysis for Energy Sustainability Improvement in Manufacturing Industry." 2021 IEEE International Symposium on Systems Engineering (ISSE), 1–8. https://doi.org/10.1109/ISSE51541.2021.9582502.
- Delabeye, Romain, Olivia Penas, and Régis Plateaux. 2022. "Scalable Ontology-Based V&V Process for Heterogeneous Systems and Applications." ACM/IEEE 25th International Conference on Model Driven Engineering Languages and Systems. Montreal, CA.
- EnerMan H2020. 2021. "Energy Efficient Manufacturing System Management." EnerMan. January 1. https://enerman-h2020.eu/.

- Hehenberger, Peter, Dominik Leherbauer, Olivia Penas, Romain Delabeye, Stanislao Patalano, Ferdinando Vitolo, Andrea Rega, et al. 2023. “Holistic System Modelling and Analysis for Energy-Aware Production: An Integrated Framework.” *Systems* 11 (2): 100. https://doi.org/10.3390/systems11020100.
- International Energy Agency. 2022. “Industry–Analysis and Key Findings Report.” IEA. September. https://www.iea.org/reports/industry.
- ISO. 2023. “ISO 50001 — Energy Management.” ISO. June 5. https://www.iso.org/iso-50001-energy-management.html.
- Milis, Georgios M., Christos G. Panayiotou, and Marios M. Polycarpou. 2019. “SEMIoTICS: Semantically Enhanced IoT-Enabled Intelligent Control Systems.” *IEEE Internet of Things Journal* 6 (1): 1257–66. https://doi.org/10.1109/JIOT.2017.2773200.
- Roode, Mike de, Alba Fernández-Izquierdo, Laura Daniele, María Poveda-Villalón, and Raúl García-Castro. 2020. “SAREF4INMA: A SAREF Extension for the Industry and Manufacturing Domain.” *Semantic Web* 11 (6): 911–26. https://doi.org/10.3233/SW-200402.
- Roumili, Emir, Jean-François Bossu, Vincent Chapurlat, Nicolas Daclin, Robert Plana, and Jérôme Tixier. 2021. “Collaborative Safety Requirements Engineering: An Approach for Modelling and Assessment of Nuclear Safety Requirements in MBSE Context.” In *Smart and Sustainable Collaborative Networks 4.0*, edited by Luis M. Camarinha-Matos, Xavier Boucher, and Hamideh Afsarmanesh, 227–36. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-85969-5_20.

ACKNOWLEDGEMENTS

This work was funded by the EnerMan project from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958478.

ABOUT THE AUTHORS

Romain Delabeye is a PhD candidate at Paris-Saclay University, France. He received an MSc in autonomous vehicle dynamics and control from Cranfield University, UK, as well as a master’s degree in mechanical engineering, mechatronics and complex systems from ISAE-Supméca in 2020. He specialises in signal processing, systems engineering, and machine learning, with research activities ranging from ontologies, verification and validation to multiphysics model synthesis and blind source separation.

Dr. Olivia Penas received in 1999 the MSc degree in material science engineering, in 2002 the PhD degree in physics of materials (smart space composites), from INSA Lyon (France), and in 2019 the HDR degree (French habilitation to supervise PhD). She was head of the research technical support teams of Supmeca in 2006, then deputy director of LISMMA Laboratory in 2013 and research deputy director of ISAE-Supmeca (Paris) since 2015. Her main research topics are systems engineering (MBSE), agility, design metrics, mechatronic design, and multi-physics conceptual design.

Dr Régis Plateaux received an automated production Master 2 degree (ENS Cachan, Paris, 2004), industrial engineering PhD degree (ECP, 2011). Lecturer, he is head of Mechatronic and Complex Systems department of ISAE-Supméca. His main research topics are algebraic topology, mechatronic design, design, systems engineering (MBSE), and ontology to define gates to generate and maintain the consistency between the different levels of design, from requirements to simulation.

Bacquet et al. continued from page 14

PhD theses related to these topics. He has been a vice-chair of the French chapter of INCOSE (from 2012 to 2017). He received the INCOSE outstanding service award in 2015.

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 modelled specifications (adequate combination of models with textual requirements), to support more mature and efficient contractual exchanges with suppliers, as well as supporting early verification and validation of systems support of processes for combined definition and refinement of requirements and system architectures.

Pascale Marangé is a lecturer with the faculty of science and technology at the University of Lorraine and has been attached to CRAN for research since 2010. Her research focuses on modelling using discrete event systems (timed automata, probabilistic) as part of formal verification using model-checking, model-based systems engineering (definition of requirements, verification). and industrial regeneration (circular economy, sustainable engineering).

Kozak et al. continued from page 17

chairwoman and currently member of the best thesis award of the French chapter AFIS of INCOSE. In 2015, and she received the INCOSE outstanding service award in 2015.

Eric Bonjour is a full professor specialized in systems engineering, at the University of Lorraine/Graduate School of Innovation and Systems Engineering (ENSGSI). His main research interests touch upon the fields of innovation (acceptability, adoption), model-based systems engineering (formalization of requirements, product architecture, safe systems engineering, adoption of MBSE frameworks), and knowledge management. He has supervised 15 PhD theses related to these topics. He has been a vice-chair of AFIS, the French chapter of INCOSE (from 2012 to 2017). He received the INCOSE outstanding service award in 2015.

Jean-Pierre Micaëlli is an associate professor at iaelyon–Jean Moulin University since 1996, specializing in industrial management, project management, logistic chain cost analysis, industrial cost control, financial analysis of industrial investment, innovation engineering, functional analysis, and cost estimation. Concurrently, he has taught at institutions such as INSA Lyon, the University of Technology of Belfort-Montbéliard, and the National School of Engineers of Belfort. As the pedagogical coordinator since 2017, he oversees programs on the Bourg-en-Bresse campus, reinforcing his commitment to education and knowledge transfer.

Project Engineering for the Depollution of Industrial Sites: a Model-Based and Systems-of-Systems Approach

Chebbi Mayssa, mayssa.chebbi@mines-ales.fr; **Vincent Chapurlat,** vincent.chapurlat@mines-ales.fr; **Jean-Samuel Wienin,** jean-samuel.wienin@mines-ales.fr; **Laurent Aprin,** laurent.aprin@mines-ales.fr; and **Philippe Girones,** philippe.girones@cea.fr
Laboratoire, Université: Le Laboratoire des Sciences des Risques (LSR), IMT Mines Alès

■ **ABSTRACT**
This work addresses the challenges associated with depolluting brownfields or industrial sites, emphasizing the significant societal, financial, and environmental implications. Current depollution projects are often treated in an ad-hoc manner, lacking a systematic and industrial perspective, despite the growing number of such projects. The proposed method advocates for a structured approach grounded in systems engineering principles, aiming to enhance collaboration among stakeholders, preserve knowledge, and facilitate the industrial transformation of depollution efforts. The method encompasses elements such as establishing a common vocabulary, employing modeling languages, implementing a double operational approach, providing supportive tools, and managing shared knowledge to improve project design, execution, and collaboration across multiple companies.

■ **KEYWORDS:** depollution, depollution system, system of systems, Model Based SoS Engineering (MBSoSE), risk management

INTRODUCTION

Today, the rehabilitation of industrial sites for new uses is considered necessary on environmental, societal, human, and financial levels (Gilbert 2022). Depending on the nature and duration of past industrial activities, a site may be impacted by different sources of pollution, with long-term characteristics and effects. Such depollution then requires the design and implementation of projects, hereinafter referred to as depollution projects, whose mission is precisely to clean up the site to a level deemed sufficient for the purpose of the depollution.

These projects are described as complex for several reasons. They seem to have to be seen as different each time, depending on the characteristics, nature, possible recombination factors or even the simple quantity of pollutant. These projects must also consider the type and architecture of the site, which is itself different each time, for example, in order to assess its accessibility, its extent, and above all, its precise state of pollution. The first observation in the field is that each project therefore seems unique, a special case, unrepeatable or even new. However, many of the numerous activities required are often of the same nature, and there are many points in common between them, for example through the possible sharing of experiences and concepts. The design and implementation of these projects is therefore seen as difficult to industrialize, in order to reduce costs, risks and the often very long lead-times involved. Secondly, these projects require the involvement of several trades with expertise in certain techniques and activities (for example, measurement, assessment, excavation, or waste management). They generally have the appropriate resources or can innovate and adapt when necessary. The second observation is that the real collaboration desired between these essential business players currently remains too limited and poorly managed and is more a matter of working in silos. Finally, the phenomena observed in studies of field feedback (emergence of unexpected behaviors, managerial dependence of operating

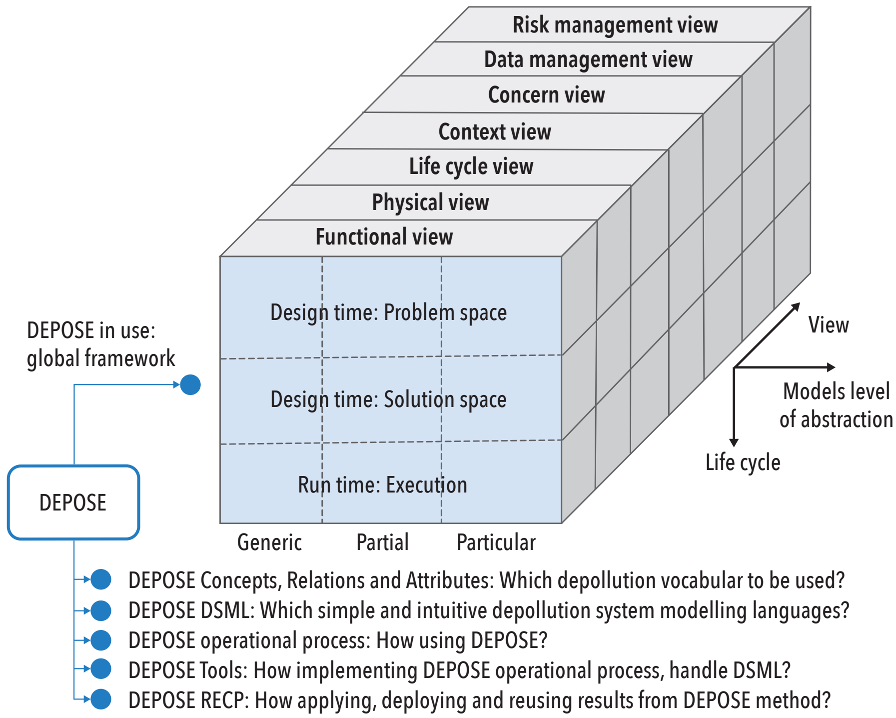

Figure 1. Overview of the DEPOSE method

companies, operational dependence, and interactions between the various elements of a decontamination project, etc.) further underline this complexity.

The aim of the work undertaken is to develop and implement a method called DEPOSE (DEPollution model based system engineering – Figure 1) for engineering and monitoring depollution projects. Our aim is to guide and support a group of professional players in the collaborative design, implementation and management of a depollution project perceived as a complex system. The aim is to enable the emergence of a form of industrialization expected of depollution, and a significant improvement in the indicators associated with these projects: shorter lead times, controlled risks, maximized safety and security of operations and players, as well as overall project performance and profitability.

DISCUSSION

Existing depollution methods (Laraia 2021) are essentially aimed at improving depollution techniques by balancing technical solutions, economic constraints, and environmental objectives. At the same time, several studies (Mukai et al. 2021) list the difficulties faced by industry players in: describing what their depollution project is, what it involves, and what it operates within (that is, the need to be able to model and exchange project-related models), communicating with each other before launching specific technical activities (that is, the need to be able to work together in a coherent, planned manner), assessing the effects a priori and then the actual effects in order to validate upstream, and then adapt each project according to its dynamics over time. We have made several observations here. First, the absence of shared and well-known systemic concepts, offering a global vision of the depollution, the site, the players and their roles, implications, and responsibilities, etc., makes it difficult to formalize and describe the depollution project. This is a systematic hindrance for business players, who often have different business knowledge and practices, as well as partial use of modeling. Secondly, reuse, or even the simple fact of being able to draw inspiration in confidence from descriptions of past projects, remains difficult or even irrelevant, despite its proven value in many fields. Finally, the work involves a succession of activities (for example, modeling, risk assessment, or process simulation) to guide and facilitate confident, consistent and, if possible, collegial decision-making. A more rigorous structuring is therefore needed to move towards better collaboration and progressive work, cultivating an environment of mutual trust).

RESEARCH METHODOLOGY

The research methodology that led to the development of DEPOSE is based on:

- A top-down, essentially bibliographical approach, from reference works on systems theory and model-based systems engineering (MBSE) / model-based systems of systems engineering (MBSoSE) principles to the field (how to make these principles understandable, useful, and usable) How can we then formalize them to plan how to implement them?
- A bottom-up approach that starts with use cases and targets specific sites to refine needs, uses and habits, and thus confirm or question the top-down approach (how is cleanup carried out on different sites when faced with different types and nature, extent, or complexity of pollutants)?

CONTRIBUTION: THE DESPOSE METHOD

The DEPOSE method is based on the one hand, on strong systemic principles to better perceive and master the inherent complexity of depollution projects. On the second hand, it is also based on two assumptions. First, we need to facilitate and equip modeling and model manipulation capabilities as early as possible, for example, to ensure verification or to simulate project behavior based on the content of these models. At the same time, this would make it possible to reuse all or part of, or even standardize, models from past depollution projects. The next step is to structure and organize the engineering work, that is, the activities that mark out the project. These include activities aimed at defining the requirements to be met, the stakeholders involved, or the activities to be implemented during the project and the way in which they are synchronized over time. Modeling these activities and then analyzing them for the purposes of decision-making and argumentation is therefore crucial. DEPOSE therefore borrows heavily from the principles and processes of MBSE (Henderson and Salado 2021), and more specifically MBSoSE(Shen et al. 2020; Maier 2009; and Baek et al. 2020). This article focuses more specifically on its conceptual aspects.

A strong concept

Any depollution project requires a range of skills, knowledge, and techniques that goes far beyond what a single company can offer acting in isolation. Pooling resources, skills and expertise is necessary to ensure the success of a project, from soil analysis and environmental engineering to community relations management and project financing. Collaboration between different, sometimes even competing, companies become imperative in this context. Emerging behaviors materialize, and the project's equilibrium requires, at the very least, considering the needs for managerial, organizational, and decision-making independence and the geographical location of each of the companies. The DEPOSE method is based on the concept that a depollution project can be seen as a system of systems (the stakeholder companies) (Maier 2009) called a depollution system. The companies all work together to achieve a common depollution mission for a given purpose, for example, to enable new activities to be relocated to the site in the future.

A structured development process leading to the DEPOSE method

Once this conceptual hypothesis had been validated, the first stage of the research work consisted in identifying the points common to several projects and proposing a set of concepts applicable to depollution. These concepts, their attributes, and the relationships to be considered between them were formalized in a single meta-model. This defines the basis of a common vocabulary for all depollution projects. With the aim of promoting a system vision (multi-view and multi-paradigm) and a model-based method, this meta-model has been structured into the following modeling views:

- Contextual view: to model the depollution system's environment in a given situation. It answers the question: "Which actors and elements interact with the depollution system? "
- Lifecycle view: to model the description of the evolution of a depollution system over time.
- Operational requirements view: to model and validate all the requirements (functional and non-functional) of the depollution system, and to model the expected behavior of the depollution system in the form of operational scenarios. The latter specify how the depollution system evolves according to different configurations and situations, events, or risk opportunities. They also help to clarify requirements and make them comprehensible, since they can be manipulated by all project stakeholders, from site owners to contractors and regulatory bodies.
- Functional view: to model the overall depollution process, the activities that make it up, the resources that can then be allocated to it and the capacities required for the mission within the framework of the chosen purpose.
- Physical view: to model these resources, i.e. means, tools and techniques, as well as their interactions during depollution operations.
- Data view: to model the various data, information, and knowledge (El Alaoui et al. 2022) that can circulate and be exchanged in the depollution system.
- Risk management view: models the various events and hazards likely to occur and assesses their impact on the project, on the resources involved, and deduces any need to implement barriers (Hollnagel et al. 2007).

As each concept and relationship in the metamodel is associated with one or more of these views, domain-specific modeling languages (DSML) (France 2005) are then proposed. In this way, business stakeholders can model their own point of view on projects by manipulating the concepts of each view. Their models can then be shared and understood by other stakeholders throughout the project. These DSMLs therefore need to be understandable and usable by experts from different fields who are not necessarily modeling experts.

To implement the method, an operational approach has been developed to guide stakeholders and facilitate the various modeling, simulation, analysis and evaluation stages required to specify and manage depollution projects. This operational approach consists of two stages, which can be juxtaposed. "Design time" focuses on the actual design and validation of the project as defined. "Run time" aims to implement and manage the project during its execution, ensuring the traceability of all modifications, results, operations, etc.

Every method is ultimately supported, on the one hand, by tools (in this case, computer tools) and, on the other hand, by a repository of expertise, knowledge, and practices (REKP). It enables stakeholders to acquire and rigorously follow the operational approach, to reuse past experience, or draw inspiration, for example in the form of technical activity modeling patterns or depollution technique implementation models. It also allows for the implementation of DSMLs and the unambiguous manipulation of defined concepts in a collaborative and trustworthy manner.

OUTLOOK

The DEPOSE method is an initial proposal. Among other things, DEPOSE will have to propose and evaluate suitable key performance indicators (KPIs) for assessing the project throughout its lifecycle. These KPIs must enable objective measurement of the performance of activities, safety, and security of stakeholders and, where possible, verify that the project meets the specific requirements and challenges of the field concerned.

Finally, the computer tools supporting the method are currently being validated to test, complete, and validate all the elements (concepts, DSML and operating procedure, use and implementation of REKP) of the method. Several use cases are being used for this purpose. The DEPOSE REKP can then be fed with implementation guides, examples of models, or study REX considered reusable to move towards the desired real industrialization of depollution. The aim is also to assess the response of this method to the economic and human challenges identified at the start of our work. ■

REFERENCES

- Alaoui, M. El, S. Rabah, V. Chapurlat, V. Richet, and R. Plana. 2022. "An Original Data, Information and Knowledge Management Approach for Model-Based Engineering Projects." 10th IFAC Conference MIM2022 on Manufacturing Modelling Management and Control: New Challenges for Management and Control in the Industry 4.0 Area, Nantes, FR, 22-24 June.
- Y.-M. Baek, Y. M., Z. Mihret, Y.-J. Shin, and D.-H. Bae. 2020. "A Modeling Method for Model-based Analysis and Design of a System-of-Systems," 27th Asia-Pacific Software Engineering Conference.
- France, R., 2005. "Domain Specific Modeling." *Software and System Modeling. researchgate.net*, doi: 10.1007/s10270-005-0078-1.
- Gilbert, R. O. 1994. "27 An Overview of Statistical Issues Related to Environmental Cleanup." Elsevier, accessed October 14, 2022: October 14, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S016971610580029X.
- Henderson, K., and A. Salado. 2021. "Value and Benefits of Model-Based Systems Engineering (MBSE): Evidence from the Literature." *Systems Engineering* 24 (1): 51-66, January. doi: 10.1002/SYS.21566.
- Hollnagel, E., D. D. Woods, and N. Leveson. 2007. *Resilience Engineering: Concepts and Precepts*. Ashgate Publishing, Ltd.
- Laraia, M. 2021. "Case studies and lessons learned from decontamination, demolition, and managing the produced wastes." *Sustain. Life Cycle Manag. Nucl. Cem. Technol.* pp. 591-627.
- Maier, M.W. 2009. "The Art of Systems Architecting." *Art Syst. Architect*, Jan. doi: 10.1201/9781420079142/art-systems-architecting-mark-maier.

- Mukai, T., Y. Nozawa, T. Ohta, R. Miyagawa and K. Nakagawa. 2021. "Determinants of support for the 'Recycling Demonstration Project for the Soil Generated from Decontamination Activities' in postdisaster Fukushima, Japan." *Asian J. Soc. Psychol.* vol. 24, no. 2, pp. 252-260, Jun. doi : 10.1111/AJSP.12427.
- L. Shen, L., W. Liu, X. Chen, Q. Gu, and X. Liu. 2020. "Improving Machine Learning-Based Code Smell Detection via Hyper-Parameter Optimization." in *27th Asia-Pacific Software Engineering Conference (APSEC)*, Dec. pp. 276-285.

ABOUT THE AUTHORS

Mayssa Chebbi holds a PhD in automatic systems and micro-electronics (SYAM) from IMT Mines Alès on depollution systems engineering crossing system engineering, model-based system engineering, and enterprise modeling.

Vincent Chapurlat is a full professor at IMT Mines Alès. His research aims to develop and formalize concepts, methods, and tools for building and formally verifying and validating complex systems models in the frame of model-based system engineering domain.

Jean-Samuel Wienin is an associate professor at IMT Mines Alès. His research interests include model-based system engineering, depollution issues and risks.

Laurent Aprin is a full professor at IMT Mines Alès. His research aims to study the physics of dangerous phenomena related to industrial risks and to characterize their consequences on the environment.

Philippe Girones is an expert senior at CEA, French Commissariat à l'Energie Atomique et aux Energies Alternatives. His expertise concerns both radiative material characterization and dismantling of nuclear facilities.

DECEMBER 2023
VOLUME 26/ ISSUE 4

Early Validation of Functional Requirements

Yasmine Assioua, yasmine.assious@renault.com; **Rabea Ameur-Boulifa,** rabea.ameur-boulifa@telecom-paris.fr;
Renaud Pacalet, renaud.pacalet@telecom-paris.fr; and **Patricia Guitton-Ouhamou,** patricia.guitton-ouhamou@renault.com

ABSTRACT
Technical specifications and intended functionalities are often gathered in documents that include requirements written in constrained natural language, that is, natural-like language with restricted syntax. In the automotive industry one challenge is the ability to produce safe vehicles, emphasizing the importance of safety by design. In the framework of case studies based on functions of autonomous vehicles, we introduce a systematic process for building formal models from automotive requirements written in constrained natural language, and for verifying them. By allowing formal verification at the earliest stages of the development cycle our aim is to avoid the costly discovery of errors at later stages.

KEYWORDS: requirement analysis, formal verification, rigorous design

INTRODUCTION

The automotive industry is changing, digital is gradually replacing mechanical systems. The advent of autonomous and connected cars increases the number and complexity of embedded electronic and computer systems, which poses new challenges and requires new development processes. Indeed, compared to conventional vehicles, these highly technological objects have an increased role in the safety of their passengers and their environment. Therefore, they require the highest level of confidence. Our research work aims to improve the current state of practice by reducing the risk of high-cost remedial measures at later development stages.

To effectively manage the design complexity, meet the growing demand for reliability of digital subsystems, and overcome some limitations of traditional approaches, we propose a method where validation is introduced as early as possible in the software development life cycle. The proposed method lays the foundations of an iterative approach for the validation and verification of requirements and other textual statements describing a system. The main goal is to detect errors, omissions, or inconsistencies before implementation. The process is semi-automated thanks to a custom analysis and transformation tool, and existing formal verification tools. Indeed, using formal methods in the development of systems can greatly strengthen confidence in them because these techniques

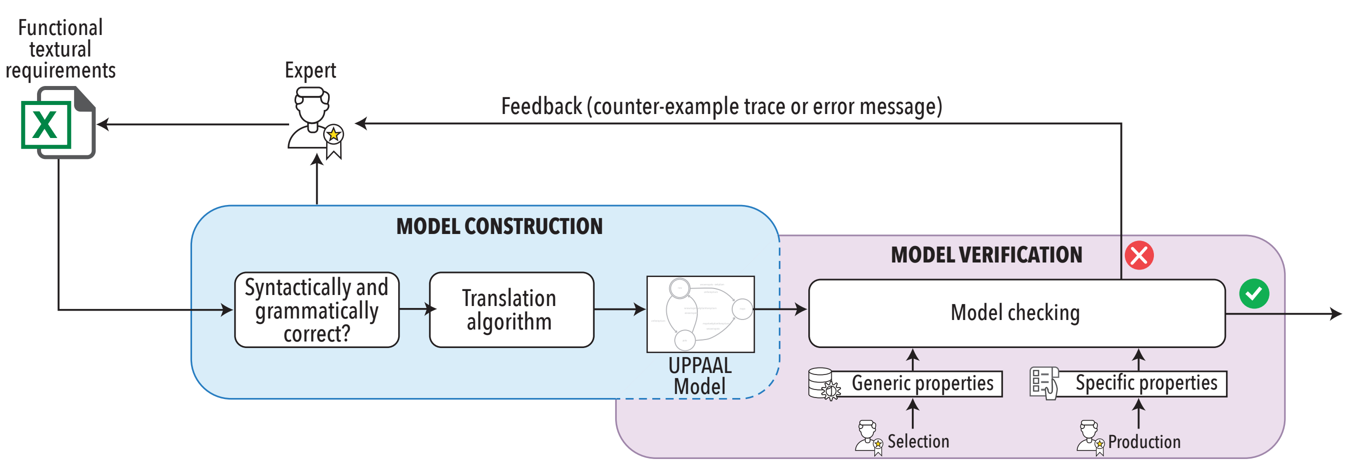

Figure 1. SARA framework for analysis and design of requirements

are based on mathematical approaches to specify and reason about their expected behaviors (Jean-Michel Bruel et al. 2021). Early validation of system requirements using formal methods allows not only to significantly improve productivity, but to enhance confidence in the quality of the systems and functionalities developed (Emmanouela Stachtiari et al. 2018).

Contributions: Figure 1 outlines the proposed framework, where our research objectives are achieved in two intertwined phases. In the **model building phase**, the system's functionality, which is formulated in pattern-based textual language called **SARA-L language**, is automatically transformed into a formal model–a network of communicating timed automaton–according to a set of well-defined translation rules from textual patterns to model elements. The modelling of requirements as automata occurs in a semi-automated way, based on a defined translation of textual patterns to concepts of the design model. In **the model verification** phase, we formally verify the obtained design model to check that the expected properties are fulfilled.

SARA FRAMEWORK: A PLATFORM FOR EARLY VALIDATION OF AUTOMOTIVE REQUIREMENTS

The SARA (safety analysis for requirements in automotive) platform starts from requirements written in textual form. After syntactical and grammatical analysis, these are transformed into models for performing formal analysis and verification.

LANGUAGE FOR REQUIREMENTS EXPRESSION

The analysis of multiple different sources of requirements writing at Renault has allowed us to identify recurring written patterns. To build a unified and automated process, we have defined a language for requirements expression called SARA-L based on these patterns. SARA-L is a controlled natural language with simplified grammar, a limited vocabulary, and precisely defined semantics to provide guidance to engineers and minimize ambiguity. The SARA-L format is similar to the EARS language (Mavin et al. 2009) in the sense that they are both based on structured patterns which consist of attributes and fixed syntax elements. But it is more precise in the statements and more constrained in schemas composition, allowing them to be combined with well-defined transformation rules. Rules that can be applied to transform textual requirements into automata.

while <state_name> | **if** <condition> **when** <trigger> | **component shall** <action>

CONTEXT | TRIGGER | SYSTEM RESPONSE

Figure 2a. SARA-L component-behavior template

REQ_SYS_01: **while** PWT_OFF, **if** brake pedal is pressed **when** push_start_button is received, **component shall** activate powertrain and switch to PWT_ON.

Figure 2b. component-behhavior requirement written in the SARA-L language

The studied requirements have enabled us to classify all the requirements defining a component into four categories based on their roles: state-definition, component-initialization, interface-definition, and component-behavior. Furthermore, the component-behavior category is itself subdivided into several subcategories that encompass all forms of expressing the behavior of a component.

An example of a component-behavior requirement written in the SARA-L language is presented in Figure 2b.

This requirement, which follows the rules of all the component-behavior requirement patterns, is identified as REQ_SYS_01. It expresses a behavior of the *powertrain*, the component responsible for propelling the vehicle forward. It explicitly specifies what the powertrain should do if it is in a state OFF and if the brake pedal is pressed.

MODEL CONSTRUCTION

From the textual requirements, we generate automata by establishing a connection between the patterns and automaton schemes. This connection, which we have defined as semantic rules, refers to an automatic translation algorithm. As part of our work (Assioua 2023) we have chosen to translate SARA-L specifications into UPPPAL semantics (Larsen et al. 1997). The latter is defined by a network of timed automata describing the behavior of a given system that can be verified using the model-checking tool. UPPAAL's model checker has proven to be successful and practical in various domains. Furthermore, it provides a user-friendly environment: it includes an editor, a symbolic simulator, and a verifier, for modelling and analysis (by covering exhaustive behavior).

The **proposed translation algorithm** processes all the requirements specifying a component by traversing them in a predefined order. It begins with the processing of requirements that define states (1–processing the state-definition category), followed by setting up initialization (2–processing the component-initialization category), then addressing the construction of the overall behavior (3–processing the component-behavior category), and finally dealing with the definition and setting of variables (4–processing the interface-definition category).

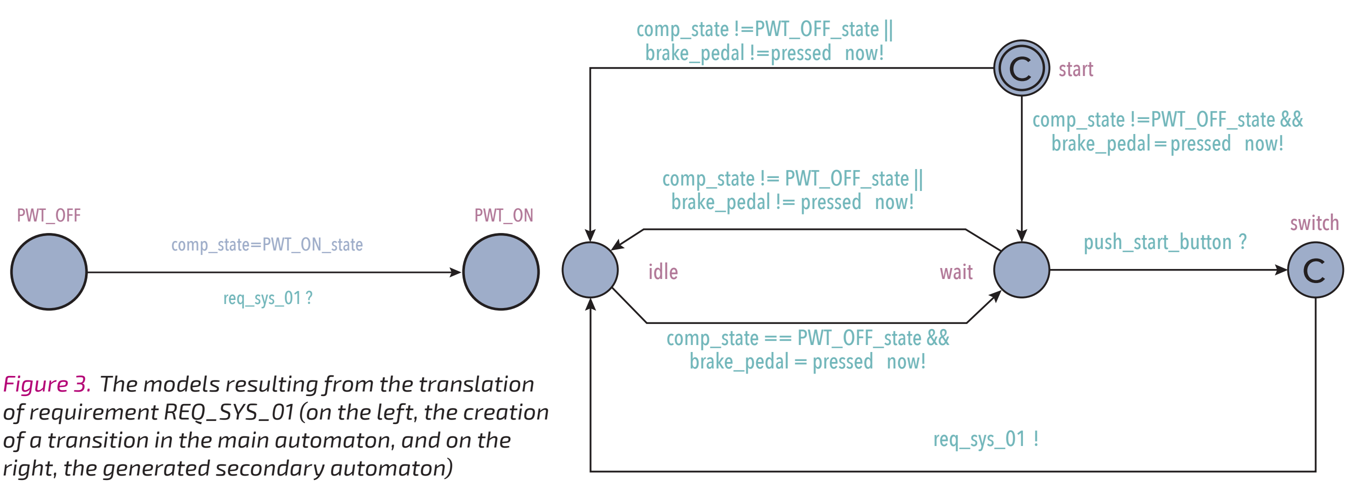

Figure 3. The models resulting from the translation of requirement REQ_SYS_01 (on the left, the creation of a transition in the main automaton, and on the right, the generated secondary automaton)

The novelty of our algorithm lies in the processing of requirements in the component-behavior category. We capitalize on the advantage offered by UPPAAL, which structures the model as a network of automata. Within a primary automaton, referred to as the main automaton, we depict the behavior of the entire system by integrating the actions of each requirement as events bearing the identifier of the requirement that is triggered. While the details of this requirement are described by a secondary automaton, which is generated by instantiating the schema automaton corresponding to the requirement pattern.

To illustrate how the construction algorithm works, let us consider the previously given requirement. The result of applying the algorithm will be, on one hand, the creation of a transition in the main automaton (see Figure 3 [right-side]) and on the other hand, the generation through instantiation of an automaton reflecting the behavior described by the requirement (see Figure 3 [left-side]).

MODEL VALIDATION AND VERIFICATION

Throughout the construction process, verification with model-checking is performed on the model under construction. The purpose of verification at this stage is to check its general and structural properties of the model, such as such as checking if states are reachable, or verifying the existence of initial states and the absence of blocking state. Once the translation procedure is completed, the ability to generate a valid model provides evidence that the set of requirements used in the construction is consistent, correct, and feasible. A posteriori verification with model checking, can then be used to verify specific properties of the model, such as safety properties.

CONCLUSION

This paper introduced our framework aimed at assisting engineers in the development of automotive systems by providing early validation of technical and functional requirements using formal methods. The SARA framework is designed for building models from automotive requirements written in a constraint natural language SARA-L with the aim to reduce the effort of testing and detects fixes late in software development lifecycle. The process is automated through a tool and existing verification tool. It is important to emphasize that our approach has been applied to real industrial systems: the APA (automatic park assist) function and the PAD (powertrain activation deactivation) system. Both consist of more than a hundred requirements. We conducted the verification of generic properties such as reachability properties on both case studies. More specifically, our work has contributed to the clarification of some phrasings in these case studies. ■

REFERENCES

- Mavin, A., P. Wilkinson, A. Harwood, and M. Novak. 2009. “Easy Approach to Requirements Syntax (EARS).” *17th IEEE International Requirements Engineering Conference*, Atlanta, US-GA: 317-322, 31 August – 4 September.
- Bruel, Jean-Michel, Sophie Ebersold, Florian Galinier, Manuel Mazzara, Alexandr Naumchev, and Bertrand Meyer. 2021. “The Role of Formalism in System Requirements”. ACM Computing Surveys, 54 (5) Article 93:1- 36.
- Stachtiari, Emmanouela ,Anastasia Mavridou, Panagiotis Katsaros, Simon Bliudze, and Joseph Sifakis. 2018. “Early Validation of System Requirements and Design Through Correctness-by-Construction.” *Journal of Systems and Software*, 145: 52-78, ISSN 0164-1212.
- Assioua, Yasmine. 2023. “Methodology for the Development of Safe Autonomous Vehicles Based on Functional and Non-Functional Requirements.” Thèse de doctorat en Réseaux, informations et communications, ED IP Paris (Paris, FR). https://www.theses.fr/2023IPPAT012.
- Larsen, Kim G., Paul Pettersson, and Wang Yi. 1997. “UPPAAL in a Nutshell.” *International Journal on Software Tools for Technology Transfer* 1(1-2):134–152.

ABOUT THE AUTHORS

Dr. Yasmine Assioua is software safety engineering at Renault Factory, a subsidiary of Renault Group. She received her graduated diploma in electronics, systems, and telecommunications at Université Cote d’Azur (UCA) and her PhD in networks, information, and communications at Ecole Doctorale de l’Institue Polytechnique de Paris (ED IP Paris) in 2023.

Dr. Rabea Ameur-Boulifa is an associate professor at Télécom Paris. Her research focuses on formal techniques for modeling and verifying systems, particularly in the context of distributed and embedded systems.

Pr. Renaud Pacalet is a director of studies at Télécom Paris and member of the LabSoc research team. His current research themes are: specification, design, and verification of integrated and embedded systems; software and hardware architecture for so-called software radio (Embb project); and integrity and confidentiality protection of external memories of integrated systems (SecBus project).

Dr. Patricia Guitton-Ouhamou is software architect engineer at Renault Factory, of Renault Group. She received her PhD in electronics at Université Cote d’Azur in 2004.After her PhD, she has worked for main semiconductors companies as ST Microelectronics, Texas Instruments, Intel, and finally Renault Group. Her main interests concern the design and specification methodology, hardware/software architecture partitioning and scheduling, and low power architectures.

Interoperability Forum for Requirements Exchange

Christian Koumlah Mbey, christian.koumlah-mbey@afnet-services.fr; **Frédéric Darré,** frederic.f.darre@airbus.com; **El-Mehdi El Amrani,** el-mehdi.el-amrani@mbda-systems.com; **Albert Lévy,** albert.levy@cimpa.com; and **Pascal Hubert,** pascal.hubert@afnet-services.fr

ABSTRACT

This article illustrates requirement exchanges based on the STEP AP242 application protocol. These results are the outcomes of the systems engineering interoperability forum (SE-IF) of the ATLAS program, a working group sponsored by the French industry and the French government. The SE-IF is composed of manufacturers, who define use cases and assign priorities and solution providers, who implement the standard, carry out interoperability tests and establish recommended practices. The objective of this forum is to enable exchange of requirements and their attributes in a fluid and tool-agnostic way, to facilitate collaborative work in the context of the extended enterprise. This work gives promising perspectives for standardized transfers of all other systems engineering data.

INTRODUCTION

Systems lifecycle activities (expression of needs, design, manufacturing, integration, verification & validation, etc.) are becoming more and more complex and involve multiple organizations with various corporate cultures, scales, and IT systems. This is why efficient requirements exchange requires effective communication channels, collaboration platforms, and standardized documentation formats. It also relies on active participation and engagement from all stakeholders involved. By leveraging the benefits of efficient requirements exchange, industries can overcome challenges, enhance system operation, and achieve successful certifications. Addressing these challenges requires a systematic approach, including effective planning, investment in technology and training, collaboration with industry partners and regulatory bodies, and a commitment to continuous improvement. Industries need to be adaptable, agile, and proactive in identifying and addressing potential issues to ensure smooth system operation and successful certification.

The use of a standard protocol, validated by industries and solution providers through interoperability tests, establishes a common ground for communication, integration, compliance, and collaboration in system operation and certification. It reduces ambiguity, promotes consistency, and facilitates efficient processes. By following a standard protocol, industries can overcome challenges, align their operations with industry best practices, and achieve better outcomes in terms of system reliability, compliance, and overall performance. It is then a solution to reduce development time and cost and to increase system quality.

STEP (STandard for the Exchange of Product model data) is an ISO standard (ISO 10303) for product data exchange, designed in the 1970s, and first released in 1994. It is an international standard for the computer representation of the description and exchange of product data.

The objective is to provide a neutral mechanism capable of describing a product throughout its life cycle, independently of an information system. This mechanism is not only suitable for file exchange, but also for structuring a database or a metamodel, for collaborative sharing, and for long-term archiving.

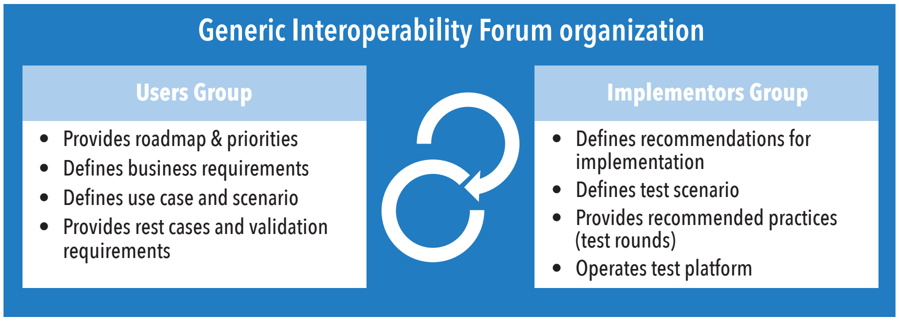

Figure 1. Generic interoperability forum organization

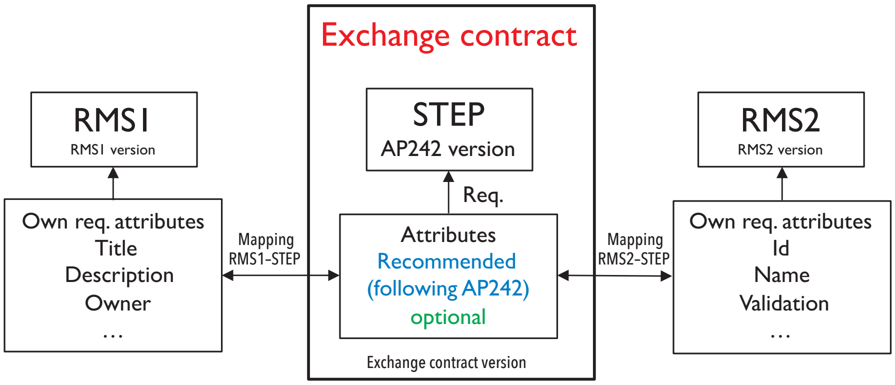

Figure 2. Exchange contract

STEP is a family of standards which describes industrial exchange needs through application protocols (AP). For instance:

- AP242 ("Managed Model-Based 3D Engineering") covers for example the design phase (3D, PMI, etc.) and the configuration management phase.
- AP239 ("Product Life Cycle Support") covers the operational product support phase; AP233 ("Systems Engineering") is specific to systems engineering (SE) but is not used because it is not up to date with SE standard developments or recent data exchange technologies.

Indeed, multiple formats (EXPRESS, XML, JSON, SysML, etc.) of specification and implementation are proposed to maximize the chances of dissemination of the standard. Moreover, the STEP community recently developed a STEP Core Model (ISO 10303-4000) that includes features a "requirement and V&V" core technical capability.

The SE-IF has been initiated by AFIS (Association Française d'Ingénierie Système), the French Chapter of INCOSE, and AFNeT (Accélérateur de la transformation numérique, écologique et énergétique des filières industrielles), the French Association of Net Users, at the end of 2019 as part of the ATLAS program with the aim of providing the first solutions based on the STEP standard format for sharing, exchanging, and archiving SE data within the extended enterprise. Initially focused on requirements and verification and validation (RV&V) data, the forum expanded in 2023 to all SE artifacts, including model and project governance data. However, this article focuses on the work done for the transfer of requirements.

Note that, ReqIF from OMG (Object Management Group) (OMG ReqIF 2016) is another (XML-based) standard, also XML-based, that covers the exchange of requirements only; therefore, it does not cover the required scope (also considering that the objective is to extend to the whole SE data perimeter).

The SE-IF is organized in two groups:

- The user group, composed of end-users, that define the industry priorities in terms of SE interoperability use cases, and representative test cases.
- The implementer group, composed of MBSE and PLM tools/service providers, is in charge of analyzing and challenging the use cases, elaborating interoperability solutions based on standards, validating these solutions through SE interoperability test rounds, and documenting these solutions in SE interoperability recommended practices.

REQUIREMENT FEATURES

A requirement is an expression that translates or expresses a need and the related constraints and conditions. When managing system specifications, stakeholders manipulate requirements attributes. These attributes provide the necessary information to build systems that meet industrial challenges in terms of cost, quality, and time, according to four categories: technical, configuration, organization, and requirements management.

Manufacturers use different methods for creating requirements and exchange them by several means depending on their needs. We can distinguish three different approaches: requirement-centric, document-centric, and model-centric.

The selected attributes previously described can support all these different approaches. However, for the document-centric approach, for example, the parts and sub-parts that form the structure of the document are all new information to be transferred, so new attributes will need to be identified.

The first use case considered within the SE-IF aims at implementing simple system requirements transfer scenario and basic quality control between two partners A and B, using a STEP file containing system specification with selected requirements from partner A.

To enable transfer of data without ambiguity, the STEP AP242 objects definitions are clarified from a systems engineering point of view within an exchange contract. To be executed, the use case has the following prerequisites:

- The mapping between the requirements data used by the partner A, the partner B, and the STEP format is defined through a correspondence matrix ("C-matrix") and agreed by both parties within an exchanged contract.
- The partner A can produce a versioned system requirements dataset from its requirement management system (RMS).

The scenario of the system specification transfer between two partners is described in Figure 3.

AP242 STEP EXCHANGE SOLUTION

The STEP format benefits from the advantages of XML coding. Indeed, the XML format supports Unicode, allowing almost any information in any written human language to be communicated. The hierarchical structure, suitable for most document types, allows representation of common computer science data structures: records, lists, and trees. Moreover, based on international standards, XML is heavily used as a format for document storage and processing. The standard allows validation using schema languages such as XSD and Schematron, which makes tests easier. Finally, it is platform-independent, thus relatively immune to changes in technology.

The main features of the AP242 have attributes classified into different categories. For the purposes of system engineering, the following categories are considered:

- Part properties: attributes specific to the entity.
- Reference properties and related relationships: attributes that carry reference to other entities.
- Related assignments: relating to entities with their own attributes.

For requirements, the main AP242 entities employed are *Requirement*, *RequirementVersion* and *RequirementView*. The *Requirement* entity is used to identify a requirement and to assign it to a classification. The *RequirementVersion* entity is employed to version a requirement and to attach metadata to it (creation date, writer ...). And finally, the *RequirementView* entity makes it possible to identify the context (application domain and life cycle) and to formalize the value of the requirement either in textual form (for exchange between humans) or in the form of a property (for automatic processing by software)

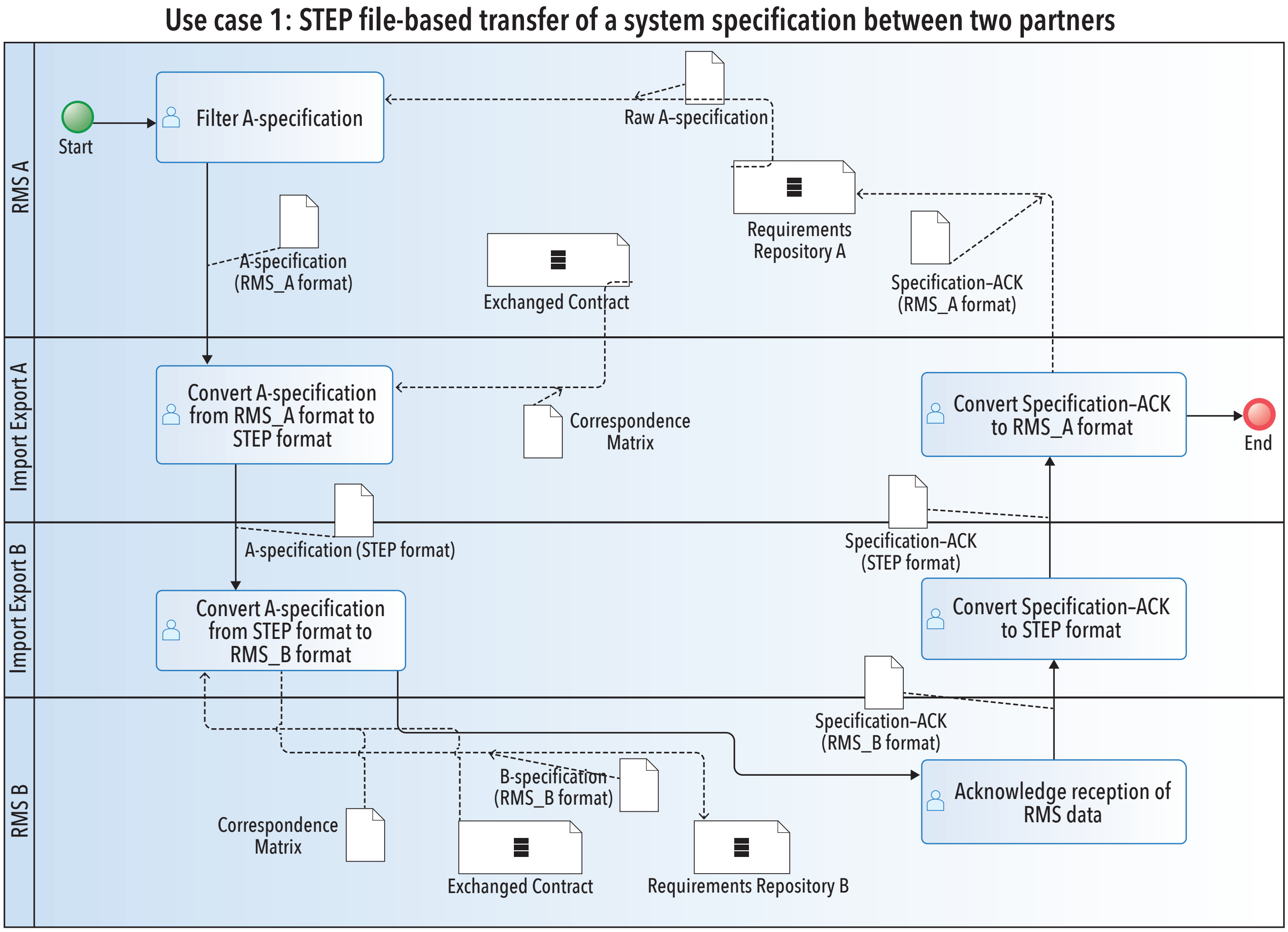

Figure 3: User case

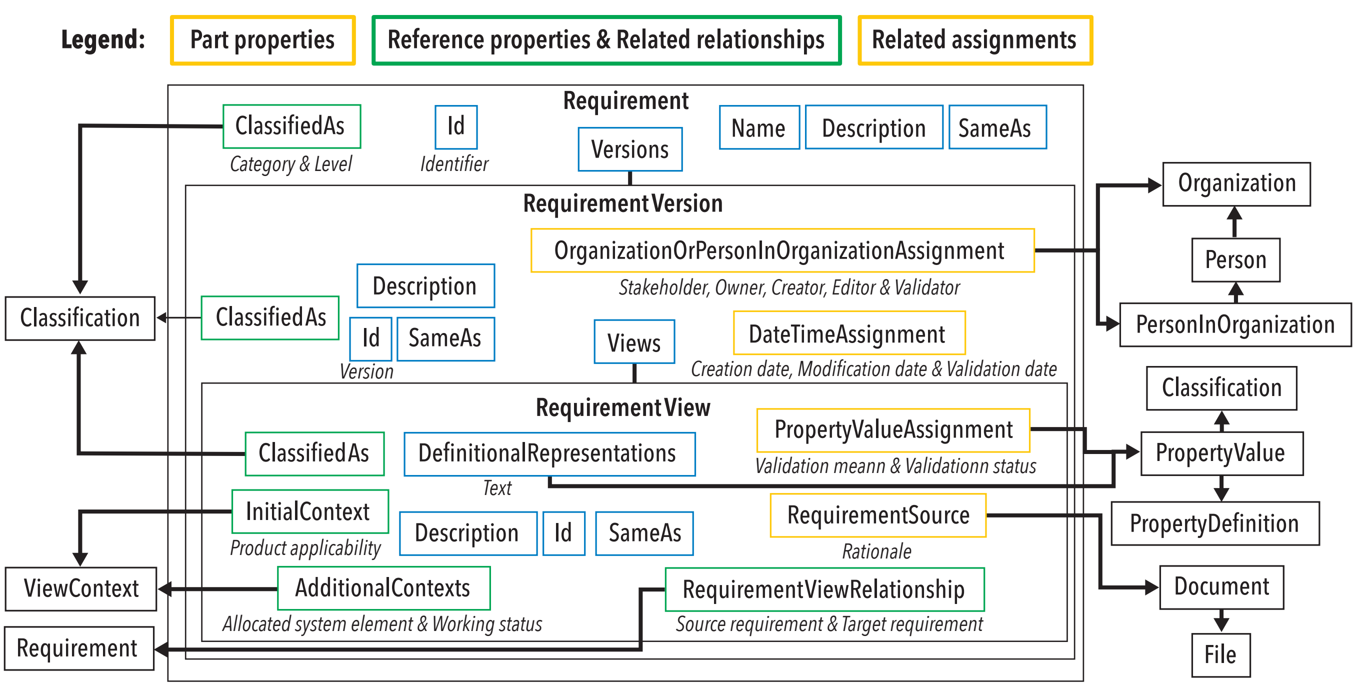

Figure 4. STEP AP242 elements for requirements data sharing

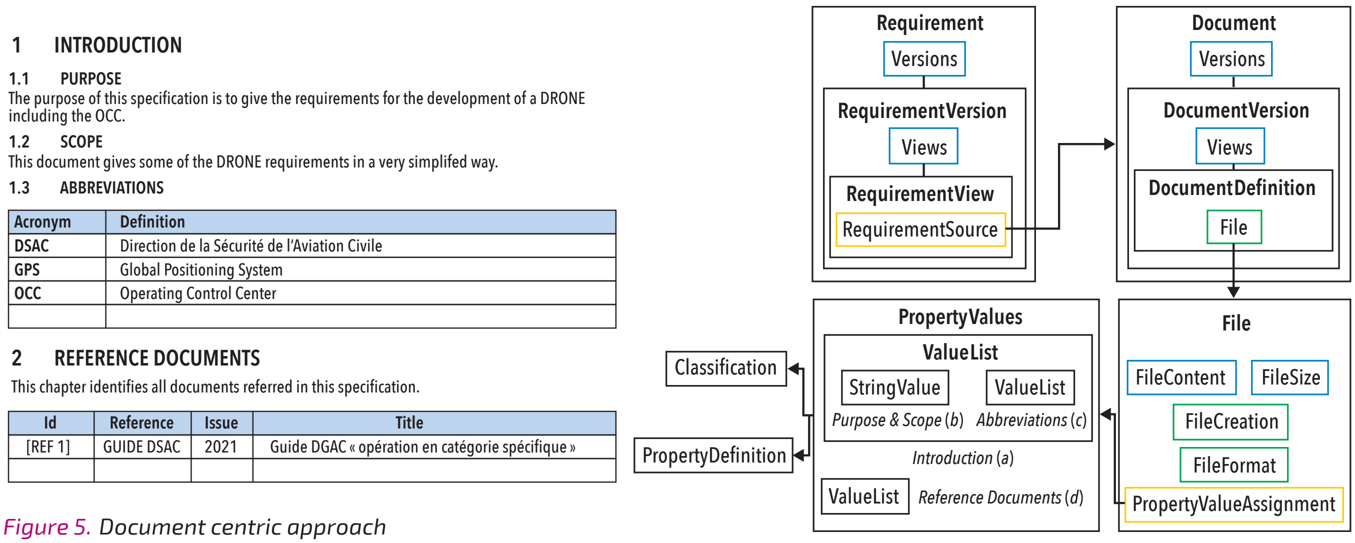

Figure 5. Document centric approach

In the case of the document-centric approach, the AP242 *Document and File* entities are used to store information about the document structure as shown in Figure 5.

In the specification example in Figure 5, all the information from the *Introduction part* can be contained in a *PropertyValue (a)* of type *ValueList*. Indeed, the *Purpose and Scope sub-parts* are simple texts and are stored in the STEP AP242 format in a *PropertyValue* of type *StringValue (b)*; *Abbreviations subpart* is a list of acronyms with their definition and is stored in a *PropertyValue* of type *ValueList (c)*.

The *Reference Documents part* is a list of documents; its content is therefore naturally stored in a *PropertyValue* of type *ValueList (d)*.

The scenario has been successfully tested with these choices:

- Partner A RMS is the Dassault System 3DExperience tool.
- Partner B RMS is the Thales Capella tool.

The description of all use cases, the recommendations for using the standard and the test procedures and their results are available within the SE-IF working group.

As an illustration, a demonstration video can be found at the following link: https://atlas.afnet.fr/systems-engineering-interoperability-forum/.

PERSPECTIVES

On primary focus, digital continuity has been tested with few amounts of data, and the requirements considered are purely textual. The next steps consist in running test rounds with requirements containing complex objects including images, tables, OLE objects, hypertext links, etc. Moreover, larger quantities of requirements need to be considered to test scalability and to evaluate performance, also to reflect a more realistic industrial exchange. Subsequently, the native STEP acknowledgement process and the collaborative modification of the requirements between partners will be tested.

On the other hand, use cases have already emerged which consider the development of a subsystem specification that includes traceability links to a system specification. This approach offers significant benefits from a process standpoint. By implementing this methodology, the team can effectively outline operational recommendations that facilitate the seamless integration of the system and subsystems structures. This entails addressing the requirements for exchanging, synchronizing, and controlling the configuration of systems engineering data among various stakeholders, including the client or customer, the system manufacturer, and the manufacturers of sub-systems or system components. Our ambition is to fully test these use cases and create recommendations for using the STEP AP242 XML format.

Furthermore, ongoing studies are being conducted to explore use cases involving the exchange of verification and validation data and models, particularly in the context of model-based systems engineering (MBSE). To facilitate this exchange, it is crucial to establish effective communication channels and sharing mechanisms for systems engineering (SE) data with other engineering disciplines.

When utilizing MBSE, the SE data must be seamlessly communicated and shared across different domains of engineering. For instance, a system requirement specified within the MBSE domain needs to be translated into a design specification within the detailed design domain, as well as a manufacturing specification within the manufacturing domain, and a support specification within the support domain. This interconnectedness ensures that the system design is appropriately justified, controlled, and aligned with the manufacturing and support processes.

Conversely, within the MBSE framework, the verification and validation (V&V) process interfaces with the design justification and the manufacturing/support control activities. This integration allows for a comprehensive evaluation and validation of the system design at different stages, ensuring its compliance with the established requirements and standards. By establishing clear interfaces and communication protocols between MBSE and the design, manufacturing, and support domains, the V&V process becomes an integral part of the overall system development lifecycle.

Through effective MBSE V&V interface with design justification and manufacturing/support control, engineering teams can achieve a more holistic and efficient approach to system development. This integrated approach ensures that the system design is rigorously tested and verified, considering the diverse requirements and considerations across different domains. It also enables the seamless flow of information and feedback between the various engineering disciplines, fostering collaboration and reducing the risk of misalignments or errors.

Finally, industries require the integration of different authoring tools, to go beyond file exchange. Indeed, data sharing architectures based on collaborative platforms need to be considered. This is why use cases and tests with the MoSSEC (Modeling and Simulation information in a collaborative System Engineering Context) standard could be interesting as it includes web services (machine-to-machine interaction over the network embedding SE data). MoSSEC enables traceability and re-use of modeling and simulation information throughout the product lifecycle and independently of the applications used in collaborative enterprises.

OVERVIEW OF THE ATLAS PROGRAM

Within the French government initiative called "*Accompagnement et transformation des Filières,*" the ATLAS consortium involving AFNeT, AFIS, MINnD (*Modélisation des Informations Interopérables pour les Infrastructures Durables*), and AIF (*Alliance Industrie du Futur*) responded in 2020 via AFNeT-Services (AFNeT spin-off dedicated to service provision) to a call for project named "*Mutualisation de moyens au service des filières et plateformes numériques de Filières.*"

The overall purpose of the ATLAS program is to sustain the French industry activities with development of enablers for digital continuity and interoperability throughout the entire industry value chain improved by standardization. The proposed ATLAS approaches to achieve the needed digital activities are cross-sectorial, from transport industries (air, sea, railway, or road) to health sector, including food, electronic, nuclear, fashion & luxury, wood, chemicals & materials, water, and waste industries. Multi-specialty development activities are also part of ATLAS, from product lifecycle management (PLM) and SE to support, including smart manufacturing, supply chain management, digital twins, building information management (BIM), and data & infrastructure.

The ATLAS program, through its ecosystem, gathers companies through the following axes:

- sustain industry efficiency, supporting companies in transforming their eco-systems through optimization of data exchange between actors of a project, on a production line, with provision of services.
- extend business models, encouraging innovation of new products and services as well as value creation for all company sizes.
- reinforce competencies, enriching the education ecosystem by upgrading the necessary environment for the transmission of knowledge, but also for the creation of new competencies.
- integrate sustainable development, enabling more responsible industry processes, and increased safety and traceability aspects, thanks to digital technology ■

REFERENCES

- ISO (International Organization for Standardization). 2012. ISO 10303-239:2012 - Industrial automation systems and integration — Product data representation and exchange — Part 239: Application Protocol: Product life cycle support. Geneva, CH.
- ISO. 2012. ISO 10303-233:2012 - Industrial automation systems and integration — Product data representation and exchange — Part 233: Application Protocol: Systems engineering. Geneva, CH.
- ISO. 2021. ISO 10303-1:2021 Industrial
- automation systems and integration — Product data representation and exchange — Part 1: Overview and fundamental principles. Geneva, CH.
- ISO. 2022. ISO 10303-242:2022- Industrial automation systems and integration — Product data representation and exchange — Part 242: Application protocol: Managed model-based 3D engineering. Geneva, CH.
- ISO. 2022. ISO/TS 10303-4000:2022 Industrial automation systems and integration — Product data representation and exchange — Part 4000: Core model. Geneva, CH.
- ISO. 2012. ISO/IEC TR 29149:2012 Information technology — Security techniques — Best practices for the provision and use of time-stamping services. ISO.
- OMG (Object Management Group) ReqIF. 2016. Requirements Interchange Format. Milford, US-MA.

ABOUT THE AUTHORS

Christian Koumlah Mbey worked for three years as a system engineer on aeronautics and space projects. He joined AFNeT Services in early 2023 as system engineering project manager. He is involved in various projects related to system engineering such as data interoperability between system engineering tools. Christian holds an engineering degree in missile and space systems engineering from the ELISA Aerospace engineering school.

Frédéric Darré started working for CIMPA in 2002. Since 2019, he works mainly on interoperability topics at AIRBUS, including data exchange and long-term archiving. He has developed ISO 10303 STEP interfaces for CAD and PDM tools such as Catia V5 and Windchill. He is involved in the development of the successive version of STEP AP242 and STEP AP239 standards and contributes to the development of the EN/NAS 9300 series of long-term archiving standards for PDM. He is also involved in the STEP adoption by vendors with the drafting of recommended practices and interoperability testing of tools in the PDM implementor forum.

El-Mehdi El Amrani, Methods and Tools engineer for more than 10 years, in different domains such as microelectronics industry, cars industry, aerospace and defense industry. El Mehdi Worked for multiple companies such as Texas Instruments, Valeo, Thales Alenia Space, Dassault Aviation, Airbus, and MBDA.

Albert Lévy has a 20-year career as engineer by CIMPA PLM Services, specialized in engineering analysis and numerical simulation. He is experienced in simulation interoperability and has co-led the LOTAR engineering analysis and simulation working group. He leads a research project on STEP standard based digital continuity of requirements.

Pascal Hubert, PhD, began his career as a Politecnico di Torino researcher. He held the position of research engineer at the Grenoble Planetology Laboratory before becoming an Assystem innovation consultant, and a manager within a digital transformation department of Safran. Then he joined AFNeT Services in 2021 as ATLAS program director, dedicated principally on systems engineering and digital twins.

Model-Based Systems Engineering Approach for an Indoor Multi-Usages System Development

Eric Razafimahazo, eric.razafimahazo@isae-supaero.fr; **Pierre de Saqui-Sannes,** pierre.de-saqui-sannes@isae-supaero.fr; **Rob Vingerhoeds,** rob.vingerhoeds@isae-supaero.fr; **Julien Soula,** julien.soula@cstb.fr; and **Romain Mège,** rmege@estp-paris.eu

ABSTRACT
This paper discusses the design of multi-usage systems able to perform various missions inside buildings, including inspection, digitization, monitoring of construction work, and evaluation of technical performances of the building. Designing such systems, carrying out various missions in different operational environments, is a complex task and requires adopting a well-defined engineering approach. A model-based systems engineering (MBSE) approach is proposed and applied to address the complexity of the indoor multi-usages system and to lead its development. The proposed method provides several complementary and comprehensive views of the system.

KEYWORDS: systems engineering; MBSE; method; unmanned vehicles; building operations; building inspection; construction; digitization

INTRODUCTION

The building industry is currently facing new challenges that motivate the authors of this paper to propose the use of multi-usage systems performing missions inside buildings. These multi-usage systems are expected to be adapted to different situations and operational environments for a large scale of use. This raises specific design challenges such as indoor navigation and localization issues. These design challenges increase the complexity of the system and its development, which motivates the authors of the current paper to adopt a well-defined model-based systems engineering (MBSE) approach. This paper extends the MBSE approach presented by Razafimahazo et al. (2021) and applied in Razafimahazo et al. (2022). The proposed approach is associated to a method providing a global perspective, including mission and operational analyses, and more specific perspectives including the definition of requirements, functional, logical, and physical architectures.

RELATED WORK

Designing multi-usage systems performing missions inside buildings is a complex task, which motivates the authors of the current paper to advocate for using an MBSE approach. The benefits of adopting an MBSE approach are clearly highlighted in the literature (Henderson et al. 2021), such as the ability to master the complexity of systems and their development. The use of MBSE models of the indoor multi-usages system is expected to allow reusing and customizing its architectures, enabling the adaptation of the system to specific situations during its utilization.

Applying an MBSE approach requires the adoption of a well-defined method to guide the systems engineer through the development of the system. A method applicable to the development of a broad variety of real-time systems is presented by Apvrille, de Saqui-Sannes, and Vingerhoeds (2020). This method includes the definitions of the assumptions and the requirements, and allow to address the analysis, design, simulation, and verification of a system. Fei et al. (2020) propose a six-step method covering modeling planning and organization, capture of the stakeholders' needs and definition of the requirements, synthesis of alternative system architectures, integration, and verification and validation (V&V) activities. Li et al. (2018) present an architecture design method incorporating the RFLP views: requirements, functional, logical, and physical. These systems engineering methods highlight complementary concepts needed to address the design of complex systems like drone systems. These concepts, such as needs and requirements,

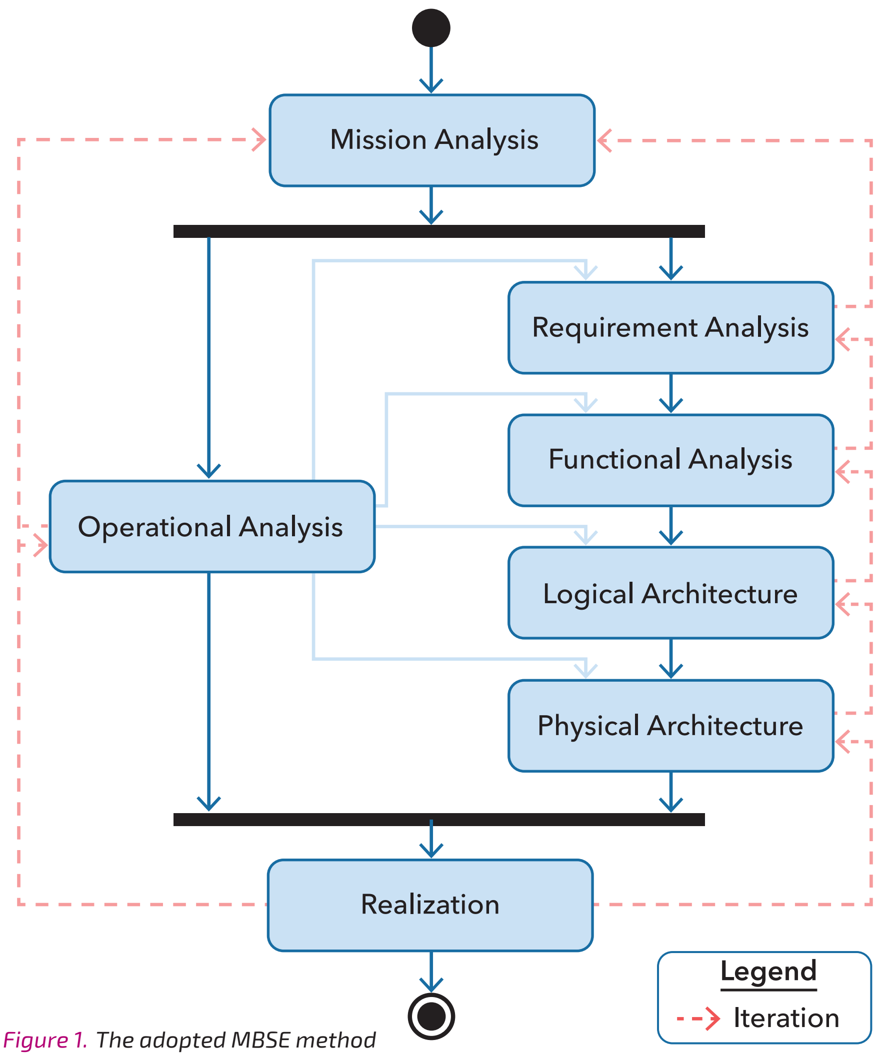

Figure 1. The adopted MBSE method

functions, behavior, and structure, allow one to consider the system throughout all the stages of its life cycle (Razafimahazo et al. 2021).

The MBSE method proposed in the current paper ensures that the needs and desires from the concerned stakeholders are considered while designing the system and provides complementary and comprehensive views of the system. These views include the operational analysis, which completes the mission definition and allows one to project how the system will be used in its intended operational environment.

THE ADOPTED SYSTEMS ENGINEERING METHOD

Extending on the iterative and recursive MBSE method presented by Razafimahazo et al. (2021), the method consists in seven main steps (see Figure 1). The mission analysis defines what the system should do. The requirement analysis includes the definition of the stakeholders needs and desires, which are further derived into requirements. The operational analysis studies the interaction of the system with its intended operational environment during its utilization, and provides some inputs to perform the other steps of the method. The functional analysis defines the services offered by the system. The logical architecture, which is a first decomposition of the system, studies the organization of the system by allocating the previously defined functions to logical components. The proposed method allows designing generic logical architectures of complex systems, without focus on technical solutions, to leave room for innovation and to ensure better exploration of the design space. The physical architecture studies how the system will be implemented by translating the functional and logical architectures into physical ones. The realization step combines the implementation and the integration substeps. The former consists in the realization of the system elements (subsystems and components), while the latter consists in synthesizing these implemented system elements into a realized system that satisfies the requirements. The verification and validation steps are transversal activities allowing to check if the solutions satisfy the requirements and the needs, respectively. They are performed after each step, but not displayed in Figure 1 for space reasons.

Compared to the methods proposed in the literature, especially with the usual RFLP method as presented by Li et al. (2018), the method adopted in the current paper starts with the mission analysis to define and explore the problem space. The operational analysis, which is concurrent with the RFLP steps, helps to consider the operational aspects, such as the interacting actors and operational scenarios, early in the design phases.

APPLICATION TO THE INDOOR MULTI-USAGES SYSTEM CASE STUDY

In this section, the system of interest (SoI) refers to the indoor multi-usages system considered at the system level, that is the overall system expected to explore the building of interest for data gathering, as well as to process the data and to provide the expected results.

Mission Analysis

The building industry is currently facing problems related to the complexity of indoor inspection activities which require the use of considerable number of resources with today's system. The same problem is encountered for the digitization and the evaluation of the technical performances of a building, which makes the operations time-consuming and costly. The purpose of the SoI is to provide a cost efficient and time saving solution for the inspection of a building, the creation of digital models of its interior, and for the evaluation of its technical performances. It is also expected to perform inspections of construction sites, in terms of monitoring of the executed work, as well as early detecting the design errors and disorders. The mission of the SoI is to explore the interior of a building, to gather the necessary amount of data and information that will be processed to achieve the expected objectives, and in the meantime to provide visual feedback to human operators.

Requirement Analysis

The needs and desires have been first defined through several interviews with the involved stakeholders of the SoI. Among them, professionals from the building industry, such as civil engineers and building inspection experts have been considered to understand the new trends arising from their perspectives; as well as the users, that can be individual humans or organizations, that are responsible of the use of the system to realize its intended mission. These needs

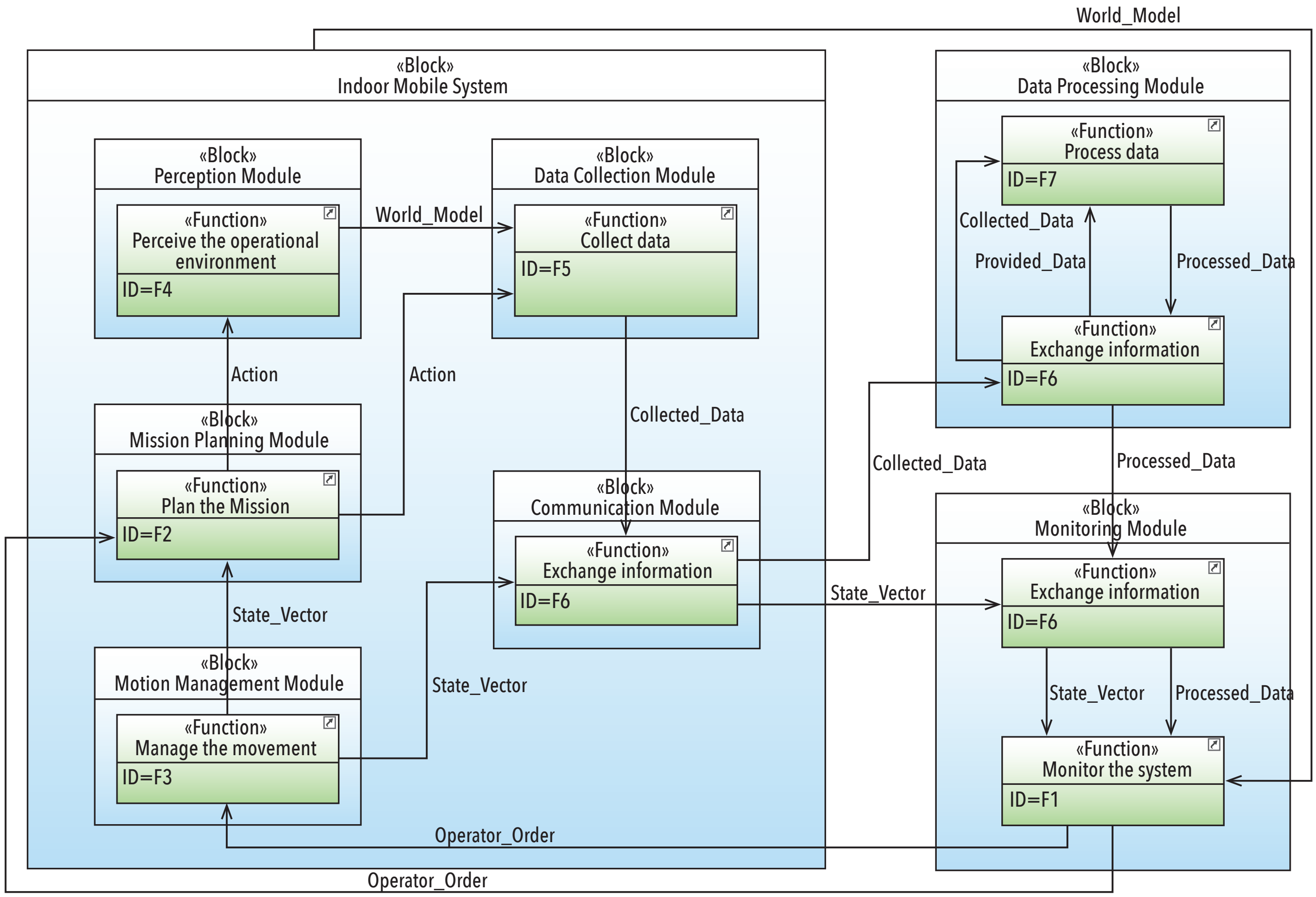

Figure 2. Logical architecture of the indoor multi-usages system

and desires have been formalized into requirements that will serve as a basis for the rest of the method. The requirements have been classified into functional, behavioral, structural, and experiential requirements according to the taxonomy proposed by Brazier et al. (2018). Functional requirements consist in the services offered by the system, for example: `*The system shall monitor the construction of the building.*' Behavioral requirements describe the way the system acts, for example: `*The system shall emit less than 80 dB noise.*' Structural requirements describe the constraints for the components of the system and their relationships, for example: `*The system shall move through windows of at least 0.80 m of overall width.*' Experiential requirements refer to more user-perception-related aspects, such as the look and feel of the user interfaces.

Operational Analysis

Since the SoI is intended to be multi-usages, it is expected to be adapted to at first four different operational environments which are referred to as scenarios. The first scenario corresponds to a building during its exploitation phase, where the SoI will be used to perform inspection, digitization, and evaluation of the technical performances of the building. In this scenario, the main actors with which the SoI is interacting include the users and the building experts, as well as the building of interest inside of which the mission will be carried out. The characteristics of the building of interest can be defined from the operational analysis, which can provide further information for the requirement analysis. For example, the structural requirement regarding the minimum windows width of the building can be refined according to the characteristics of the building of interest. The second scenario corresponds to a construction site, where the SoI will be mainly used to monitor the construction evolution and to update the digital model of the building. The third scenario corresponds to a building in danger, where the aim is to assess whether it is worth renovating or demolishing. The fourth scenario consists in performing post-incident inspection in which human intervention is strongly prohibited.

Functional Analysis and Logical Architecture

Seven main functions that need to be provided by the SoI have been derived from the functional requirements. Among these functions, the `collect data' function is responsible for collecting the required data to complete the expected mission. The functional architecture serves as a basis for the definition of the logical architecture candidates for the SoI.

Four options of logical architectures for the SoI have been discussed, comprising different variants ranging from having all the intelligence and data processing embedded on the same mobile platform, to having the mobile part moving inside the building and all analysis taking place `at a distance'. The logical architecture chosen in the current study is composed of three logical components, which allow to design the SoI step by step (see Figure 2). The indoor mobile subsystem (IMS) is used inside the building of interest to explore and collect data. The monitoring subsystem (MS) is responsible for monitoring the IMS while it is performing the mission. The data processing subsystem (DPS) is equipped with a computer to process the collected and provided data. The verification of the logical component consists in allocating the requirements to each logical component, which can launch new recursion of the application of the MBSE method to the subsystems.

The recursive MBSE method presented in Figure 1 was applied to the IMS subsystem to further define it until getting the physical architecture of its own subsystems. The physical architecture can be defined through performance evaluation, sizing, dynamic and structural simulations, which lead to the decision to reuse, to make, or to buy a system component.

CONCLUSION

The use of indoor multi-usages systems raises new design challenges which require the adoption of a well-defined method. The MBSE method applied in this paper offers complementary and comprehensive views of the system to make sure the needs from the concerned stakeholders are considered, leading to the definition of customizable architectures.

In the future work, the proposed method will be applied to each of the two other subsystems of the logical architecture (MS and DPS). Special attention will be brought to the operational analysis to study the automatic configuration of the system according to the building of interest characteristics thanks to the use of ontologies and reasoning. The MBSE models of the SoI could be converted into an ontology machine readable format to improve the configuration of the SoI from one specific operational scenario to another during its use. ■

REFERENCES

- Apvrille, L., P. de Saqui-Sannes, and R. Vingerhoeds. 2020. "An Educational Case Study of Using SysML and TTool for Unmanned Aerial Vehicles Design." *IEEE Journal on Miniaturization for Air and Space Systems* 1 (2): 117-129. doi: 10.1109/JMASS.2020.3013325.
- Brazier, Frances, Pieter Van Langen, Stephan Lukosch, and Rob Vingerhoeds. 2018. "Complex systems: design, engineering, governance." *Projects and People: Mastering Success*. NAP, ISBN: 978-90-812162-9-6.
- Fei, X., C. Bin, L. Rui, and H. Shunhua. 2020. "A Model-Based System Engineering Approach for Aviation System Design by Applying SysML Modeling." Chinese Control and Decision Conference (CCDC), Hefei, CN, 1361-1366. doi: 10.1109/CCDC49329.2020.9164443.
- Henderson, K., and A. Salado. 2021. "Value and Benefits of Model-Based Systems Engineering (MBSE): Evidence from the Literature." *Systems Engineering*, 24 (1): 51– 66. https://doi.org/10.1002/sys.21566.
- Li, R., W. Verhagen, and R. CurranR. 2018. "A Functional Architecture of Prognostics and Health Management using a Systems Engineering Approach." 4th European Conference of the Prognostics and Health Management Society, Utrecht, NL, 3-6 July.
- Razafimahazo, Eric, Pierre de Saqui-Sannes, Rob A Vingerhoeds, Claude Baron, Julien Soula, and Romain Mège. 2021. "Mastering Complexity for Indoor Inspection Drone Development." IEEE International Symposium on Systems Engineering (ISSE),. DOI:10.1109/ISSE51541.2021.9582483.
- Razafimahazo, Eric, Pierre de Saqui-Sannes, Rob A Vingerhoeds, Julien Soula, Romain Mège, and Claude Baron. 2022. "Towards a Customizable Architecture for Indoor Multi-Usages Drones." International Council of the Aeronautical Sciences (ICAS), Stockholm, SE, 4-9 September.

ABOUT THE AUTHORS

Eric Razafimahazo is a PhD student in the frame of a collaboration between ISAE-SUPAERO (Institut Supérieur de l'Aéronautique et de l'Espace) in Toulouse, France, and CSTB (Centre Scientifique et Technique du Bâtiment) in Sophia Antipolis, France. Eric's research interests include MBSE and ontology engineering. Eric is a member of INCOSE through the French chapter (AFIS).

Prof. Pierre de Saqui-Sannes is a full professor of model-based systems engineering at ISAE-SUPAERO, Université de Toulouse, France. Pierre's research interests include MBSE in terms of languages, tools, and methods. Pierre heads the Critical System Design and Analysis research group at ISAE-SUPAERO.

Prof. Rob Vingerhoeds is a full professor of systems engineering at ISAE-SUPAERO, Université de Toulouse, France. Rob's research interests include systems engineering and architecture, model-based systems engineering, concept design, and artificial intelligence techniques for engineering applications. Rob is deputy editor of the international scientific journal Systems Engineering.

Julien Soula is a research engineer at CSTB, in charge of research and development activities in the Information Technology Department. Julien leads a transverse research program on digital and data. Julien's research interests include responsible digital transition of buildings and cities, data science applied to construction and operation, digital building, and city models.

Dr. Romain Mège is a research director in charge at CSTB. Romain's research interests include structural engineering, structural dynamics, material sciences, building inspection, building renovation, and data analysis for building application. Romain is an associate professor at École Nationale des Ponts et Chaussées in Marne la Vallée, France.

2024
Annual INCOSE
international workshop

HYBRID EVENT

Torrance, CA, USA
January 27 - 30, 2024

WHAT IS #INCOSEIW?

The INCOSE International Workshop is the premier international event for engaging in working sessions, contributing your knowledge and experience to move the state of the discipline forward. Attendees build networks, perform activities, and produce outcomes beyond their typical network and focus area.

Whether you are already involved in a working group or simply curious to discover what is happening in INCOSE, it's an opportunity not to be missed for sharing and networking with friends and colleagues!

HYBRID EVENT

Accomplishing the event's goals is greatly enabled by in-person attendance. However, in accordance with our desire to include those who cannot attend in person, some sessions will be available virtually. See the Schedule at a Glance for those sessions that are offered virtually.

Dates
Saturday 27 January – Tuesday 30 January, 2024

The Venue
Torrance Marriott Redondo Beach
3635 Fashion Way
Torrance, California 90503 - USA

FLASHBACK TO 2023!

In 2023, there were 700+ attendees from a multitude of domains:

Academia
Aerospace
Automotive
Communications
Cyber Security
Defense
Energy Systems
Environmental
Infrastructure
Intelligence
Medical Systems
Tool Vendor
Transportation...

International Council on Systems Engineering
A better world through a systems approach / www.incose.org

Stay tuned for more! www.incose.org/IW2024
#INCOSEIW - Join the conversation

34th Annual INCOSE international symposium

hybrid event

Dublin, Ireland
July 2 - 6, 2024

Start planning your agenda for #INCOSEIS 2024

Dates
Tuesday 2 July –
Saturday 6 July, 2024

The Venue
The Convention Center Dublin
Spencer Dock, N Wall Quay
Dublin, Ireland

TOP REASONS TO ATTEND

- Enjoy a diversified program on different application domains
- Learn something new that you can use on the job
- Expand your network among the worldwide SE community
- Get inspired by forward-looking thought leaders
- Contribute and advance the discipline

SIGN UP AS A SPONSOR!

Take advantage of a golden opportunity to gain recognition for your organization among the worldwide community of Systems Engineering.

THANK YOU TO ALL SUBMITTERS

The 2024 Call for Submissions was a great success:

- XX Submissions
- XX Reviewers
- XX Countries represented

Notifications of acceptance will be sent out on 21 February 2024!
The program will be out in April 2024.

WHAT TO EXPECT IN DUBLIN?

A city brimming with history, culture, and friendly locals!
Nestled on the east coast of Ireland, it offers a unique blend of old-world charm and modern vitality.

BOOK YOUR HOTEL IN ADVANCE

Hurry to benefit from negotiated group rates at a selection of hotels, just a few minutes' walk from the venue!

INCOSE
International Council on Systems Engineering
A better world through a systems approach / www.incose.org

Stay tuned for more! www.incose.org/symp2024
#INCOSEIS - Join the conversation