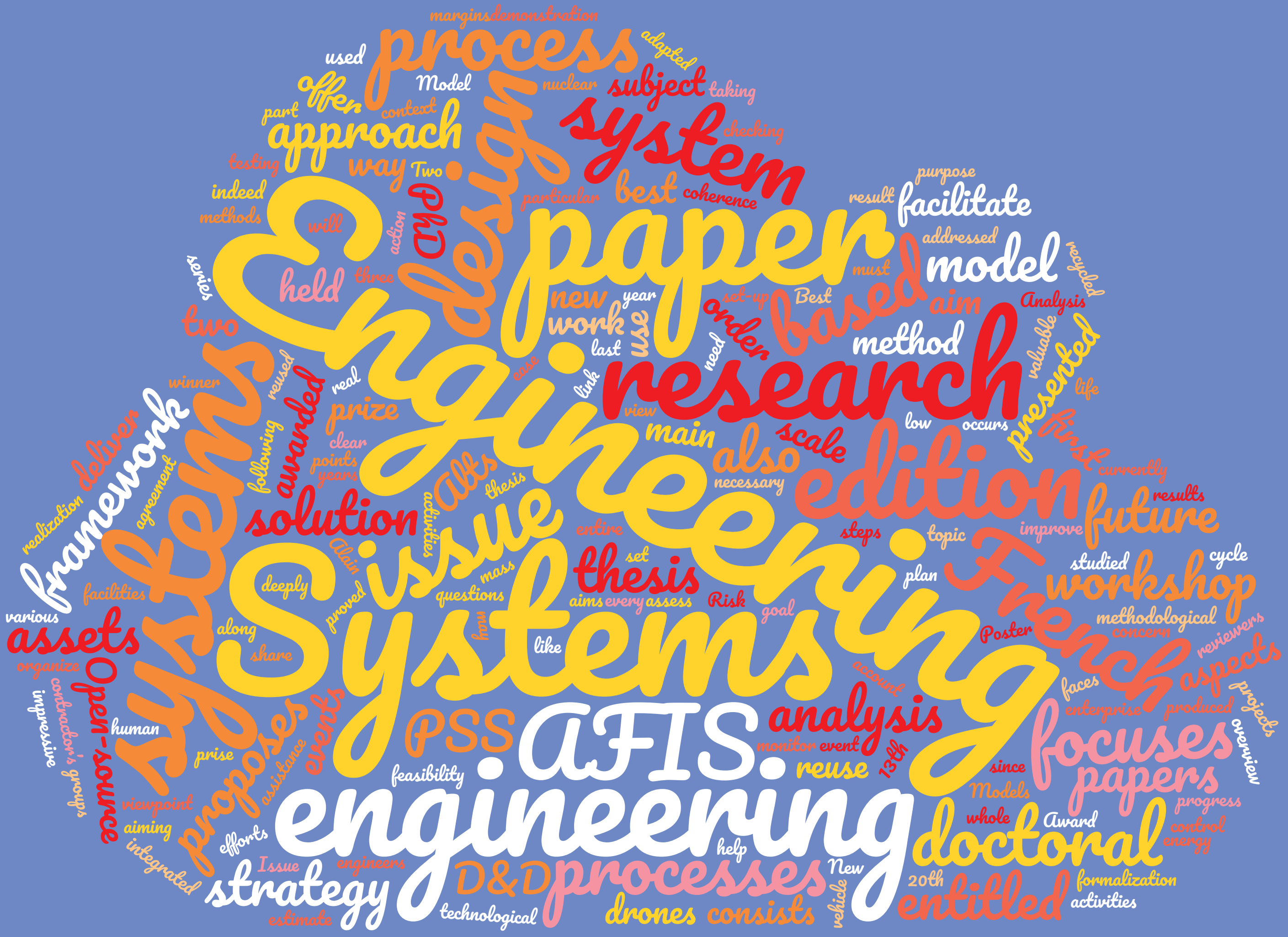
INSIGHT

This Issue's Feature:

New Challenges and Advances in Systems Engineering at French Universities



DECEMBER 2021
VOLUME 24 / ISSUE 4

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

2022

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international workshop

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INSIGHT

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

DECEMBER 2021 VOLUME 24 / ISSUE 4

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About This Publication

INFORMATION ABOUT INCOSE

INCOSE's membership extends to over 19,000 individual members 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
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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.

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to publish the December 2021 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 the 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. This is our seventh 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), and December 2019 (Volume 22, Issue 4). Articles were selected after peer reviews from a larger set of doctoral presentations in collaboration with French universities and industry. Articles from theme editors David Gouyon and Hervé Panetto, and authors address the following topics:

1. Theme Editorial
2. AFIS Academy-Industry Forum 2020 in Compiègne
3. Modelling Cyber-physical Systems using Data-driven Patterns
4. A Semantic Model Framework for Cyber-Physical Production System in System Engineering Perspective
5. Using Synthesis and Analysis for Design in Systems Engineering: an Integrated Approach
6. Qualimetry Essentials Applied to Embedded Software Development
7. Harmonica: A Framework for Semi-automated Design and Implementation of Blockchain Applications
8. Towards a Method to Operationalize Modelling, Verification, and Evaluation of Architectural Solutions in the Field of Nuclear Critical Infrastructure Engineering
9. Contribution to Nuclear Safety Demonstration through System Modelling and Artificial Intelligence
10. Model Based Commissioning, a New Methodological Approach for Commissioning of Nuclear Basic Facilities
11. Simulation System Design Methodology in Extended Enterprise Context
12. Intensive Data and Knowledge-based Approach for Sustainable and Circular Industrial Systems.

The editors of *INSIGHT* would be pleased to accept proposals from other INCOSE chapters, working groups, and affiliated bodies for themed issues centered on systems engineering practices beginning in the second quarter of 2023. The 2022 *INSIGHT* themes and articles are already committed: 1) Digital Engineering, 2) Systems Security in the Future of Systems Engineering (FuSE), 3) Unique Abilities of the Systems Engineer, and 4) Systems Engineering Grand Challenges. The first 2023 issue theme is Model-Based Test and Evaluation.

I thank assistant editor Lisa Hoverman and her team, Chuck Eng for layout and design, our theme editors in 2021, associate director for INCOSE publications Ken Zemrowski, Holly Witte in the 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. ■

Editorial of *INSIGHT* Special Issue

New Challenges and Advances in Systems Engineering at French Universities

David Gouyon, david.gouyon@incose.org and **Hervé Panetto,** herve.panetto@incose.org

ABSTRACT

This special issue of INSIGHT highlights the ninth edition 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. Due to the COVID-19 crisis, this edition occurred virtually in December 2020.

These meetings, which are composed of workshops and plenary lectures, provides 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.

SYNOPSIS OF ARTICLES

The first article of this special section, by Julien Le Duigou, Vincent Chapurlat and Jean-Luc Garnier, presents on the events that occurred during the meetings: a pre-forum, prospective workshops, plenary sessions, a doctoral seminar, and the AFIS PhD 2020 award. The other articles of this special issue relate to research works 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*, we invited doctoral students and their supervisors to submit an extended version of their presentations to emphasize the research aspects of Systems Engineering. We selected ten research papers for this edition to promote research on systems engineering approaches.

The first research paper, by Concetta Semeraro, Mario Lezoche, Hervé Panetto and Michele Dassisti is *Modelling Cyber-Physical Systems Using Data-driven Patterns*. In the context of the modelling of smart factories, characterized as large-scale distributed cyber-physical systems, the authors propose to define an approach using formal concept analysis to formalize data-driven patterns. The objective is to identify automatically, in the masses of data, invariant behaviours that can be modelled for the emulation of these cyber-physical systems and thus contribute to the digital transformation of industrial production companies.

The Cyber-Physical Systems are also the subject of the paper entitled *A Semantic Model Framework for Cyber-Physical Production Systems in a Systems Engineering Perspective*, by Puviyarasu. Sa. and Catherine da Cuhna. The authors identified the need for a generic semantic model framework to provide a unified description of all aspects and properties of the CPPS. The paper gives an overview and expected outcomes of such a semantic model framework.

In the third research paper, entitled *Using Synthesis and Analysis for Design in Systems Engineering*. An Integrated Approach, by Sephora Diampovesa, Pierre-Alain Yvars, and Arnaud Hubert, presents a general approach that relies on synthesis for the preliminary design of systems and on analysis for simulation. The approach deals in particular with mixed type design problems and includes non-functional requirements like eco-design in a single process. The approach constructs and solves synthesis models using constraint programming and object-oriented modeling with the DEPS problem modeling language and the DEPS Studio environment. The approach evaluates dynamic behavior of the solutions found with DEPS Studio with Modelica and OpenModelica.

Yann Argotti, Claude Baron and Philippe Esteban share *Qualimetry Essentials Applied to Embedded Software Development*. The authors conducted a three years research study with the initial objective to fill the gaps in quality definition, assessment, control, and prediction of embedded software in the automotive domain, including compliance constraints to standards and regulation. The numerous contributions to both theoretical and applied qualimetry defined a theoretical framework for quality control and monitoring of engineering and product development processes. The authors applied the study to embedded software, and hope these contributions have an impact on all industrial sectors.

Nicolas Six, Nicolas Herbaut, and Camille Salinesi introduce the Harmonica framework in the paper entitled *Harmonica: a Framework For Semi-Automated Design and Implementation of Blockchain Applications*. Despite the growing interest in blockchain technology from academia and industry, there are still major obstacles for blockchain mass adoption, as it is difficult to integrate the technology into existing or new architectures and systems. Blockchain differs from conventional technologies through its unique characteristics, such as decentralization, immutability, or resilience. Thus, software architects may struggle with the complexity of selecting an adequate blockchain or designing blockchain-based software. The paper proposes an end-to-end framework for the design and implementation of blockchain applications.

Nuclear power plants are complex critical systems, and are the industrial context of various papers of this special issue of *INSIGHT*. The first of them, by Bourdon Jérémy, Couturier Pierre, Chapurlat Vincent, Plana Robert, Richet Victor, and Baudouin Benjamin, is *Towards a Method to Operationalize Modelling, Verification and Evaluation of Architectural Solutions in the Field of Nuclear Critical Infrastructure Engineering*. It evaluates architecture alternatives using the EVA-CIME method, composed of five sets of elements: concepts, languages, operational approach, tools and repository of knowledge and expertise.

Nuclear safety is the main issue adressed in the paper entitled *Contribution to Nuclear Safety Demonstration Through System Modelling and Artificial Intelligence*, by Emir Roumili, Jean-François Bossu, Vincent Chapurlat, Nicolas Daclin, Jérôme Tixierand, and Robert Plana. It presents a methodology that mixes and takes advantages of Artificial Intelligence techniques and Model Based Systems Engineering. The aim is to guide and support engineers to improve their vision, their knowledge and vocabulary, and their capacities in terms of safety requirements elicitation and demonstration.

The commissioning of nuclear plants is the subject of the paper entitled *Model Based Commissioning, a new methodological approach for commissioning of Nuclear Basic Facilities*, by Alan Gaignebet, Vincent Chapurlat, Grégory Zacharewicz, Robert Plana and Victor Richet. The authors introduce a method called COGuiNF (Commissioning Guidelines of Nuclear Facilities) which aims at allowing to prepare in relation with MBSE processes then drive relevant activities for the commissioning of nuclear facilities.

The use of Model Based Systems Engineering and early verification and validation through simulations offers an effective way to manage the complexity of real-world industrial development projects. In this context, Renan Leroux-Beaudout, Jean-Michel Bruel, Ileana Ober, and Marc Pantel, provide the paper entitled *Simulation System Design Methodology in Extended Enterprise Context*. The authors consider that often modeling and simulation activities happen in parallel, based on a common core of requirements. This can lead to a product model that does not conform to the simulation model, and vice versa, due to potential misinterpretation of requirements. To fill this gap and meet the objective of the simulation conformed to the model, they propose a new approach that considers communication between stakeholders of the extended enterprise and, also between the simulation platforms.

The last research paper, by Nancy Prioux, Jean-Pierre Belaud, and Gilles Hetreux, is entitled *Intensive Data and Knowledge-based Approach for Sustainable and Circular Industrial Systems*. The paper focuses on the creation of a methodological framework centered on intensive data and knowledge for an economically viable and ecologically responsible design of industrial processes or systems. Composed of five steps, this approach is oriented towards offering decision support for the researcher or research and development (R&D) engineer during systems requirements and high-level design steps of the V-model. It is implemented within the domain of pre-treatment processes for a corn stover.

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. David Gouyon is an associate professor in Systems Engineering at the University of Lorraine, where he oversees work-linked training within a master's degree on Complex Systems Engineering. He is within the Nancy Research Centre for Automatic Control (CRAN), and his research interests are Systems and Automation Engineering, with models (MBSE). He is a member of the French chapter of the International Council of Systems Engineering, and Associated Systems Engineering Professional.

Dr. Hervé Panetto is a Professor of Enterprise Information Systems at University of Lorraine, TELECOM Nancy. He teaches Information Systems modelling and development, and conducts research at CRAN (Research Centre for Automatic Control), a Joint Research Unit within the National Centre for Scientific Research CNRS where he is managing a research project on the use of ontology for formalising models related to the interoperability of production systems, and mainly their enterprise information systems. He is a member of the Academia Europaea and 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, with applications in enterprise modelling, manufacturing processes modelling, furniture data modelling. He is working in ERP and MES integration from a business to manufacturing perspective. He is an 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 an editor or guest editor of books and special issues of international journals. He is author or co-author of more than 150 papers in the field of automation engineering, enterprise modelling and enterprise systems integration and interoperability. He is member of INCOSE and the AFIS French Chapter on systems engineering. He is Chair of the IFAC Coordinating Committee 5 on "Manufacturing and Logistics Systems" since 2014. He received the IFAC France Award 2013, the INCOSE 2015 Outstanding Service Award and the IFAC 2017 Outstanding Service Award. He is a co-organiser of the yearly OTM/IFAC/IFIP EI2N workshop on "Enterprise Integration, Interoperability and Networking" and General Co-chair of the OTM Federated conferences.

AFIS Academy-Industry Forum 2020 in Compiègne

Julien Le Duigou, julien.le-duigou@utc.fr; **Vincent Chapurlat,** vincent.chapurlat@mines-ales.fr; **Jean-Luc Garnier,** jean-luc.garnier@thalesgroup.com

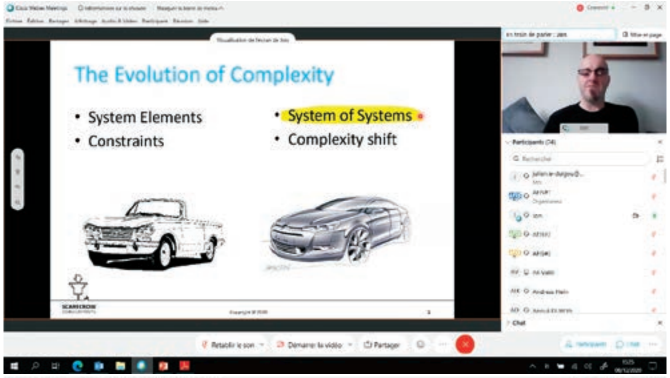
The AFIS Academy-Industry Forum, organised by the French INCOSE Chapter AFIS and Université de technologie de Compiègne (UTC), took place from the 7th to the 10th of December 2020. This ninth biannual edition was a real success, despite an exceptional situation with the global health crisis. The Forum was for the first time a 100% virtualized event as a result.

The AFIS Academy-Industry Forum 2020 focused on a "systems of systems" theme, preceded by a half day pre-Forum about industry 4.0 and cyber-physical production systems. Industrial presentations shed light on the academic concepts, particularly in the automotive, aeronautical, and railway sectors. The international scene included, with presentations by the president of INCOSE, an international expert from the English chapter, and the head of the Belgian chapter. Various exchanges and debates have been also possible despite the situation, particularly during a set of prospective workshops. Another novelty of this edition was the doctoral seminar, which took the form of PhD students' presentation in 180 seconds, a difficult exercise in synthesis and science popularisation.

Key figures about this 2020 Forum:

- More than 200 registrations and participants.
- Ten high-level plenary conferences, between 45 and 75 people connected per session.
- Six exciting foresight and prospective workshops, with 20 and 30 people connected per workshop.
- Fifteen presenters at the doctoral seminar and with so many candidates for the PhD 2020 Award, forty-five people connected during the doctoral seminar.

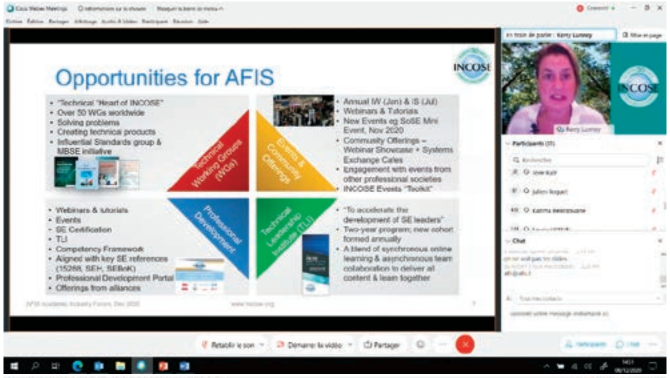
Information about the university that organized these meetings. UTC, a public scientific, cultural, and professional institution, a member of Sorbonne Universities, originated in 1972 as an experimental university of technology. It teaches systems engineering to its students, through the Master's Degree in Complex Systems Engineering, which is linked to the research unit Labex "Control of Technological Systems-of-Systems". Labex MS2T is a multi-disciplinary scientific team backed by the experience of three research laboratories in computer science, mechanical engineering, and biology (Heudiasyc, Roberval, and BMBI).



The Evolution of Complexity

- System Elements
- Constraints

- System of Systems
- Complexity shift



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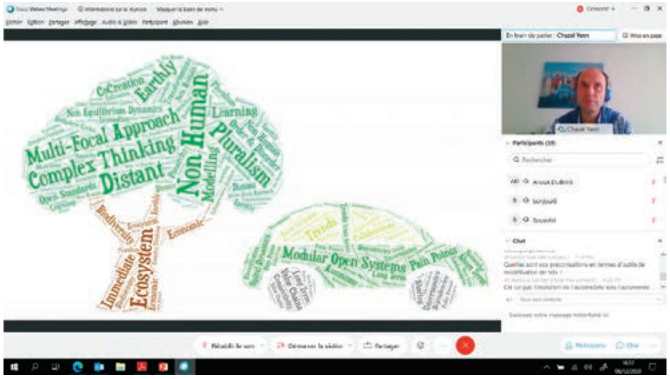
- New Events eg SoSE Mini Event, Nov 2020
- Community Offerings – Webinar Showcase + Systems Exchange Cafes
- Engagement with events from other professional societies
- INCOSE Events "Toolkit"

- Webinars & tutorials
- Events
- SE Certification
- TLI
- Competency Framework
- Aligned with key SE references (15288, SEH, SEBoK)
- Professional Development Portal
- Offerings from alliances

- "To accelerate the development of SE leaders"
- Two-year program; new cohort formed annually
- A blend of synchronous online learning & asynchronous team collaboration to deliver all content & learn together



PREFORUM

The PreForum is an event organized the day before the Forum, with the aim of promoting systems engineering in the region where the Forum occurs. The theme chosen in 2020 corresponds to a major concern for small to medium enterprises (SMEs): "Industry 4.0 and cyber-physical systems: what are the opportunities and challenges for SMEs?"

We were lucky to have specialists of the subject implanted locally, academic as well as industrial, on subjects such as:

- Cyber-Physical Production Systems – Benoit Eynard (UTC)
- A Man-Machine System: Cobotics – Sylvain Acoulon (CETIM)
- Industry 4.0: Automation in Smartphone Mode – Philippe Gerard (Bosch Rexroth)

And a round table on the subject: "Factory of the Future in SMEs: they have done it!"

The AFIS Pre-Forum took place within the innovation centre Daniel Thomas, which is a specific place in Haut-de-France, a melting pot of creativity, which hosts training, research, and valorisation activities in the service of innovation and enables multidisciplinary and multi-actor innovation skills to coalesce and collaborate. Supplying working rooms, technological platforms, and state-of-the-art equipment, the innovation centre is a space of "creative contamination" which plays a major role in transforming these new ideas into innovations.

PROSPECTIVE WORKSHOPS

The prospective workshops are an opportunity for AFIS members to discuss future topics related to systems engineering and to debate to create roadmaps for the next AFIS actions to be conducted on these subjects. Six workshops opened this year, including:

- Collaborative systems engineering and standards to facilitate the efficiency of a systems system. (Moderators: Anne Sigogne, Philippe Boeri, and Eric Gauthier)
- Systems engineering for obsolescence resilient management and (re)design. (Moderators: Marc Zolghadri, Joseph Aracic and Claude Baron)
- What new skills are needed to master systems engineering. (Moderators: Daniel Prun, Emily Aubry, Jean-Luc Garnier, Claude Pourcel, and Jean-Charles Chaudemar)
- Systems Engineering from a sustainable and responsible perspective. (Moderators: David Desjardin and Claude Pourcel)
- MBSE, MBSSE, MBSA and Trust. (Moderators: Lalitha Abhaya and Vincent Chapurlat)
- MBSE Agile or how MBSE secures an Agile approach. (Moderators: David Schumacher and Xavier Dorel)

These workshops led to further meetings, the launch of working groups and projects that will continue to progress until the next Forum.

PLENARY SESSIONS

The AFIS Academy-Industry Forum is also an opportunity to listen to and debate with specialists on the topics of the Forum. The speakers and their topics were as follows:

- Kerry Lunney – Welcome from the INCOSE President.
- Jon Holt – Systems of Systems: Modelling, Architecture,Integration, and Dynamics.
- Yann Chazal and Philippe Bouteyre – The System of Systems Approach in the Transformation of EcosystemsInvolving the Automobile.
- Christophe Laverge – INCOSE Belgium Chapter.
- Christophe Alix – Intelligent Distributed Air Systems
- Olivier Lecoq – Systems Engineering at Alstom

We thank all the speakers for the quality of their presentations and the discussions that followed.

DOCTORAL SEMINAR

The AFIS doctoral seminar, which takes place every two years as part of the AFIS Academy-Industry Forum, aims to supply an overview of PhD works in the Systems Engineering domain, either in progress or just defended, and to make them known to the AFIS community. This year, fifteen participants represented nine different teaching and research institutions from France.

Each student presented first an abstract reviewed by the AFIS scientific committee. The students presented their work following the "My PhD Thesis in 180 seconds" model, using a single slide without animation, and then answered questions for seven minutes.

The AFIS scientific committee established a ranking based on the presentations and the answers to the questions.

The winners are:

- First: Quentin Wu (Safran/University of Lorraine), "Capitalization and reuse of know-how in a model-based systems engineering approach: application to aircraft electrical distribution systems."
- Second: Julien Vidalie (IRT System X/ SupMeca), "Category theory for consistency between multi-level system modelling (MBSE) and safety (model-based system architecture (MBSA))."
- Third: Emir Roumili (Assystem/IMT Mines Alès), "Nuclear safety demonstration using model-based system engineering and artificial intelligence."

AFIS PHD 2020 AWARD

The AFIS PhD Award is a prize awarded by AFIS to young PhDs who have already obtained their PhD degree in the last two years, and who carried out work that adds value to the systems engineering discipline from a scientific and technical point of view.

In 2020, this is the 4th PhD Award. It is a mechanism appreciated and recognised by the academic and industrial communities for promoting this type of work. This year, fourteen doctors applied, coming from seven different teaching and research institutions.

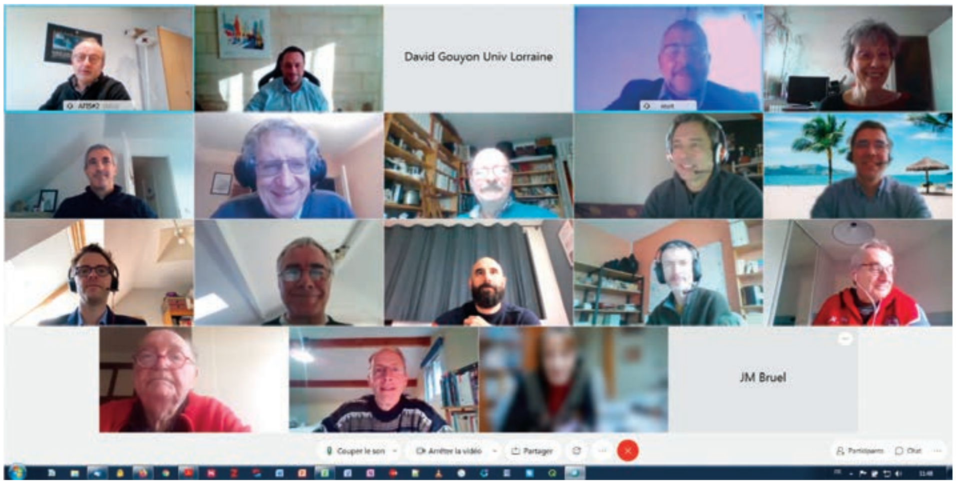
The AFIS scientific committee reviewed, evaluated and ranked their applications. Exceptionally, this year, two applications ranked first ex-aequo:

- First ex-aequo:
  - Maxence Lafon, "Méthode basée sur une approche systémique pour l'organisation et le suivi des chantiers d'Assainissement et de Démantèlement (A&D) des installations nucléaires" (Method based on a systemic approach for the organisation and monitoring of clean-up and dismantling (A&D) worksites in nuclear installations), IMT Mines Alès/ CEA Thesis, U. Montpellier.
  - Elaheh Maleki, «Un modèle sémantique basé sur l'ingénierie des systèmes pour supporter le cycle de vie des systèmes «Produit-Service»» (A semantic model based on systems engineering to support the life cycle of «Product-Service» systems), Thesis of the Ecole Centrale de Nantes, COMU U. Bretagne-Loire.
- Third: Franck Sicard, "Taking into account the risks of cyber-attacks in the field of cyber-physical systems security: proposal of detection mechanisms based on behavioural models", G-SCOP thesis, U. Grenoble-Alpes.

Congratulations to the winners and thanks to all the candidates for their work and participation.

ACKNOWLEDGEMENTS

Once again, we would like to thank all speakers, moderators, and members from both AFIS scientific committee and AFIS and UTC organising teams who made it possible to hold this event under these particular conditions. It was an exciting Forum to discuss systems engineering and to listen to the scientific and industrial debates raised by the various participants. Be sure these discussions will not remain without follow-up, and we look forward to seeing you at future AFIS events. ■



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Modelling Cyber-Physical Systems Using Data-driven Patterns

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ABSTRACT

Modelling Cyber-physical systems is quite complex and thus needs a big amount of data and modelling techniques representing the operational semantics of the modelled elements. Generally, the modelling action has a specific application type. For this reason, the paper proposes a series of modelling patterns aimed at automatically identifying invariant behaviors in the masses of data that can be modelled to emulate cyber-physical systems and thus contribute to the digital transformation of industrial production companies.

The Smart Factory paradigm represents the "fourth industrial revolution" in the field of manufacturing industry, through the implementation of "intelligent systems" consisting of physical systems and software to control and improve manufacturing processes (Zuehlke 2010). These intelligent systems typically include various components, such as sensors for signal acquisition, communication units for data transmission between components, control units for components, control and management units for decision making, and actuators to perform appropriate actions (Lezoche and Panetto 2018). In recent years, the emergence of cyber-physical systems (CPSs) has amplified the ability to sense the world through a network of connected devices using the existing network infrastructure. Cyber-physical system (CPS) aims at embedding computing, communication and controlling capabilities (3C) into physical assets to converge the physical space with the virtual space (Monostori et al. 2016). The combination of intelligent systems and sensing systems forming a large-scale distributed cyber-physical system is a key element in developing the distributed cyber-physical system. However, they lack modelling techniques that consider their technological parameters and their high degree of information and functional interrelationships. As the complexity of these systems continues to grow, the challenge of developing intelligent and sensing systems has exceeded the design complexity of their components (Lee, Bagheri, and Kao 2015). The main problem in developing intelligent systems is the complexity of integrating and managing these different components, technologies, and objectives across a broad spectrum. In this sense, the concepts defined in Systems Engineering are relevant to the challenge of shared knowledge formalization. It is necessary to define a modelling method that helps to analyse a new form of intelligent systems (smart) and detection in a sustainable perspective. The representation of shared knowledge is a branch of artificial intelligence that studies the way human reasoning occurs and defines symbols or languages. This representation allows the formalisation of knowledge to make it understandable to machines, aligned with reference models. An important prerequisite for the cyber–physical integration is a proper and highly-accurate digital model (Semeraro et al. 2021a). Considering the complexity of digital modelling, this work aims to identify and formalise elements that contribute to the construction of informational and functional models of systems to improve and simplify the modelling of manufacturing processes and products, based on networked components.

The idea is to propose a series of modelling patterns aimed at automatically identifying invariant behaviors in the masses of data that can be modelled to emulate these cyber-physical systems and thus contribute to the digital transformation of industrial production companies. This work aims to define an approach to formalize data-driven patterns for improving the smartness of manufacturing processes and products, involving networked components. Firstly, the use formal concept analysis (FCA) (Valtchev, Missaoui, and Godin 2004) allows the extraction of tacit knowledge included in the masses of data, as shown in Figures 1-3. Formal Concept Analysis (FCA) is a mathematical theory oriented toward knowledge representation and data analysis applications. It provides tools to group the data and discover formal patterns by representing it as a hierarchy of formal concepts organized in a semi-ordered set named lattice. The discovered patterns become concrete by modeling systems and procedures in system modelling language (SysML) (Figure 4). The idea behind data-driven patterns is to permit the re-use of predefined functional patterns for designing digital models based on the specific application. The approach makes the shared knowledge more easily reusable, and it is the basis of standardization efforts.

Figure 1. Data Table

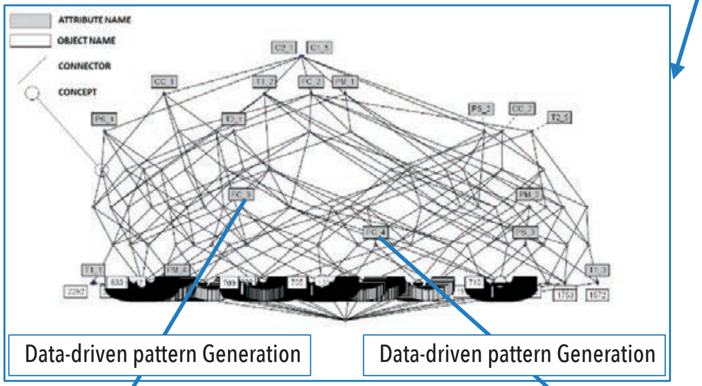

Figure 2. FCA Lattice

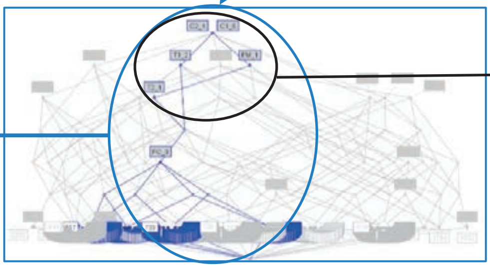

Figure 3a. Clamping Pattern

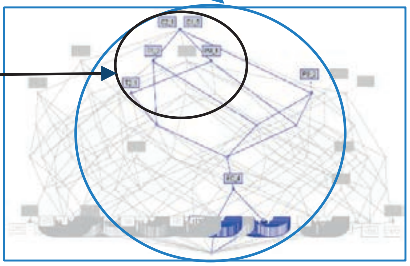

Figure 3b. Pression Control Pattern

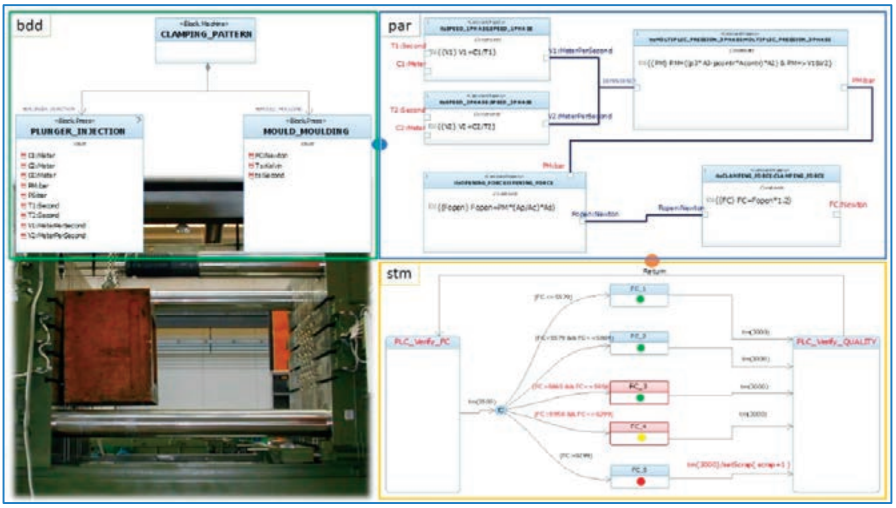

Figure 4. SysML Structuure and Behaviour Model of the Clamping Pattern

Figures 1-4. SysML Representation (Semeraro et al. 2019a)

In view of the above, a list of data-driven patterns has been presented in (Semeraro 2020) according to the methodology described in (Semeraro et al. 2019a). The detected data-driven patterns are as follow: Filling pattern (P1); Re-start machine pattern (P2); Clamping force pattern (P3); Pression control pattern (P4); State pattern (P5). The filling pattern (P1) is for use whenever it is necessary to model the behaviour of a plunger or an injection system. The re-start machine pattern (P2) applies for describing the machine restart after machine downtimes. The clamping force pattern (P3) describes the behaviour of a clamping system (the clamping of a mould) or for describing and preventing mechanical breakdowns. The pression control pattern (P4) has use in modelling hydraulic systems (the clamping of a mould) and related problems. The state pattern (P5) simulates different states of the machine based on the evaluation of a set of parameters (Semeraro et al. 2021b).

A real case study Master Italy s.r.l uses a set of patterns to create a digital twin model prototype to control and optimize a die casting aluminium process (Semeraro et al. 2019b). A Digital Twin (DT) is a "virtual" image of the reality constantly synchronized with the real operating scenario (Negri, Fumagalli, and Macchi 2017). The digital twin has received strong interest from researchers and industries since it allows the predictive manufacturing by integrating the cyber and the physical space. The digital twin requires the building and the applying digital models representing the set of resources and processes knowledge. A generic DT can consist of components organised into three main layers above recognized:

1. The physical layer, consisting of entities identified based on the stage of the product life cycle.
2. The network layer, connecting the physical domain to the virtual one. It shares data and information.
3. The computing layer, consisting of virtual entities emulating the corresponding real entities, including data-driven models and analytics, physics-based models, applications, and users.

The design criteria of a Digital Twin are not well-assessed or even standardised. In our approach, the digital twin prototype implementations occur as shown Figure 5, applying three data-driven patterns: filling pattern (P1), re-start machine pattern (P2) and the clamping force pattern (P3) to create the digital model of the die casting process. The resulting tool can exploit the existing knowledge and the information from the real process to emulate its behaviour and thus diagnose and even predict problems and propose potential improvements. The prototype can analyse the online data collected from the physical line to search for the optimal solution to the physical line. It can evaluate the production line real-time and optimize the resource allocation autonomously (Rosen et al. 2015). With our approach, the physical settings interact with the digital space, according to specific properties and rules, to understand the behaviour of the process and the correlations between technological parameters. The digital twin has been designed to support the employees in decision-making process to identify the several quality problems of the components autonomously, compared to the standards (dimensions, tolerances, finishes, quantity),

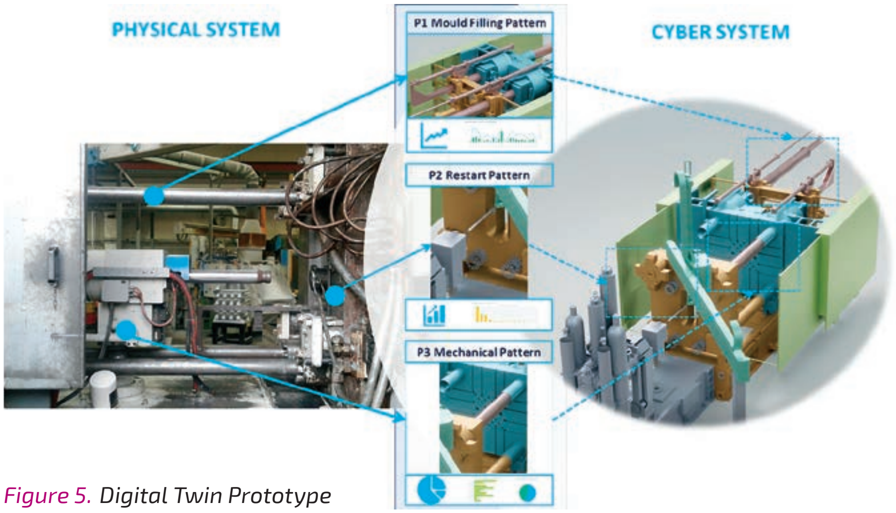

Figure 5. Digital Twin Prototype (Semeraro 2020)

alert operators through proper alarm systems about abnormal or out of tolerance situations and support the choice of corrective actions to eliminate the detected failures and defects. It is currently in use by the company, which now wants to extend it to other manufacturing systems in its plant. Compared with existing approaches with a barrier of high design complexity, this study proposes a modular solution for designing cyber-physical systems.

The present work's core idea is to automatically extract patterns from data and model these to design CPSs. The contribution has been tested through a real implementation on an industrial case study. A web platform and a digital twin prototype show how to instantiate and use a pattern. Future research aims to enrich the pattern's semantics to create a comprehensive library of formalized data-driven patterns. It means to select different production lines to apply the same patterns for designing digital models for different applications and scopes. Other data sets such as logistic data, product data, customers' data to extract new data-driven constructs and more will enhance the models. In this way, it is possible to create a consistent library of patterns. ■

ACKNOWLEDGEMENT

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Dr. Mario Lezoche is an associate professor at University of Lorraine, more specifically at IUT Hubert Curien of Epinal (Technological University Institut) where he teaches object-oriented software engineering, base knowledge systems and database development. He teaches, also, at the Computer Science Engineering School TELECOM Nancy ERP configuration, Enterprise 4.0, Blockchains and Semantic programming languages. He is researcher at CRAN (Research Centre for Automatic Control of Nancy) joint research unit with CNRS. In the CRAN laboratory he is attached to the ISET department (Department Ingénierie des Systèmes Eco-Techniques–Eco-Techniques Systems Engineering Department) and he is co-managing the research project Intelligent System and Objects in Interaction (SandO-2I) on the use of Knowledge formalisation (for example ontology, formal concept analysis, relational concept analysis) for optimising models interoperability of production systems. He graduated at Roma TRE University (Italy) in Computer Science Engineering. He received his PhD in Computer Science Engineering in 2009 and his Post-Doc in 2011 at the University of Lorraine. He has a strong experience in Semantic Web research and in models and semantics for systems interoperability. He works since long time 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, with applications in enterprise modelling. He is presently working on a conceptualisation approach and the use of Lattice theory through the Formal Concept Analysis (FCA) method for Enterprise Information Systems interoperability. The latest research works are on an improvement of the FCA method called Relational Concept Analysis (RCA) that focuses on the tacit knowledge extraction through a clusterization approach on multi contexts data structures. He is moreover a regular reviewer for international journals (EIS, FGCS, CII, IJPR). He is guest editor of special issues of international journals. He is author or co-author of more than 40 papers in the field of Automation Engineering, Enterprise Knowledge formalization and Enterprise systems interoperability. He is member of the IFAC Technical Committee 5.3 on “Enterprise Integration and Networking” since 2016 and he’s member of the IFIP Technical Committee 12 (WG12.1 and WG12.6) since 2020.

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A Semantic Model Framework for the Cyber-Physical Production System in the Systems Engineering Perspective

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ABSTRACT

A cyber-physical production system (CPPS) is a system of digital and physical components with networked connections. These components are deeply intertwined and operate in situation-dependent ways across all production levels. The system behavior is complex due to its dependencies and the relationship between its parts and their environment. The diversified components and their relationship lead to challenges for the involved actors in system development, operation, and end of life phases. There is a need for a generic semantic model framework to provide a unified description of all aspects and properties of the CPPS. In this paper, an overview and expected outcome of semantic model framework is presented. As a first step, the core elements, and boundaries of the CPPS are proposed. Based on a fundamental concept of systems engineering, the core elements are defined as a System of Interest (SOI) and Enabling Systems (ES).

Cyber-physical production system (CPPS) (Monostori, 2014) is defined as autonomous and cooperative elements connecting in situation-dependent ways, on and across all production levels. It enhances the communication between the machines, people, and products in the ecosystem. It is a new development which enhances the decision-making processes, and responds to unforeseen conditions in real-time. The basic capabilities of CPPS are connectedness, responsiveness, and intelligence (Cardin, 2019). The key characteristics of CPPS are modular, reconfigurable, and networked systems. A CPPS involves collaborative stakeholders in the system development phase, the operation phase, and the end of life phase (Lüder, et al 2017). The involved stakeholders require standardized semantics of all the heterogeneous and diverse components. Researchers discuss CPPS design, classification, and characteristics. However, there is a lack of studies on semantics involving all the decomposition facets of the system elements. There is a need for a generic semantic model framework to provide a unified description considering all the aspects and properties of the CPPS. Previous works used the systems engineering approach as a foundation to represent and construct the semantic models. Maleki, et al, 2018 constructed the semantic models for product-service systems. Meixner et al, 2019 used the approach to identify production system elements and relationships of the system. Following these backgrounds, we have adapted the systems engineering approach as a foundation to represent a unified CPPS model framework. The framework is organized in a facet-based systematic order (system, decomposition, life cycle, and business). The following categories of knowledge are at the heart of semantic model framework:

- **System and its decomposition models:** This category of models represents the system and its decomposition elements on a meta-level. It provides the common understanding of CPPS by defining the terminology, taxonomy, involved entities and the relation aspects. These models provide system-oriented knowledge by identifying the different concepts (which we refer to as information) and the relevant relationships between them. It includes:
  1. **System structure** – represents the components, entities, and properties of the system.
  2. **System behaviours** – represent how the system would work to ensure functions realization.
  3. **System functions** – describe of the functions that must be fulfilled by the system.

4. **Human– CPPS relations**– represent the human-machine agents, interactions, skills, roles, functionalities, cognitive workloads analysis and more.

- **System life cycle phase models:** This category of models describe the whole artefact CPPS life cycle phases which includes system development, operation, and end of life phase. It provides the life cycle-oriented knowledge by identifying relevant information on each hierarchy layer of life cycle in the production system. These unified information descriptions are applicable for the involved engineers to support their corresponding work on each phase.
- **System and its organizational task models:** This category of models represents the relationship between the CPPS and its parent organization. These integrated relation models support the repartition of tasks within the company. They specify the allocation of tasks to systems and describe the required systems' configurations.

The presented categories are at heart of semantic model framework. Each model involved in each category is at a unified meta level. The ambition is to provide the generic models to support CPPS life cycle. As a case example and first step of this framework- the core elements and boundaries in systems engineering perspective is proposed in this paper. SA Puviyarasu and da Cunha, 2021 described an integrated structural model for a cyber-physical production system. It is composed of different levels of abstraction, involved entities, and their relational aspects. Figure 1 shows the proposed main sub-systems, elements, and boundaries of CPPS structure with a systems engineering perspective. It is an integrated system composed of a system of interest and an enabling system. The CPPS's system of interest (SOI) is the set of elements of the system to produce a product. It is composed of:

Cyber Parts/Layer — It refers to intangible components. It encompasses the software that helps store data, analyze, process, collect, control, and actuate the information within the CPPS. The core elements of the cyber layer are "production network," "intelligent objects," and "everything as service (IaaS)."

Physical Parts/Layer — It refers to all tangible components that actively or passively participate in the production processes to add value. Its core elements are "physical machine" and "physical product." The physical machine forms an integral part to produce tangible asset of the product.

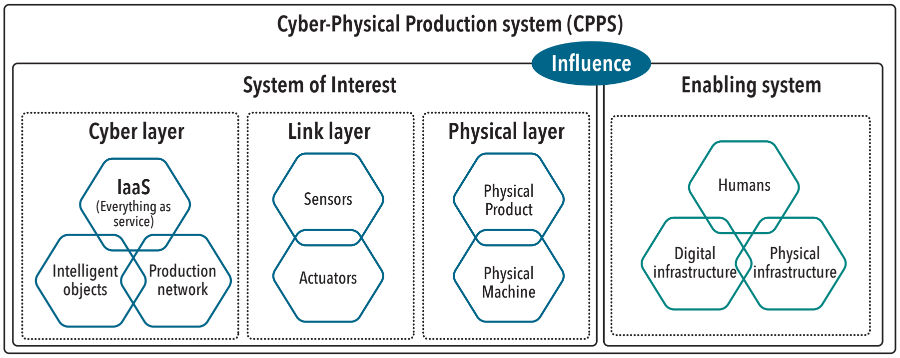

Figure 1. Proposed CPPS core elements and boundaries in a systems engineering perspective (figure enhanced from Maleki et al, 2018)

Linking Parts/Layer — It refers to intertwined components as sensors, actuators, and intelligent objects. These components serve as feedback back control loops between the cyber and physical world spaces.

The enabling system is a system that may support CPPS (SOI) throughout its life cycle. It is composed of:

- **Physical infrastructures** — It refers to the network of stakeholders, physical assets, and all other supporting physical systems.
- **Digital infrastructures** — It refers to information network, information systems and other infrastructure that influence or support digitally the system of interest.
- **Humans** — It refers to humans that interact with the CPPS machine to make decisions on their desired mode (centralized or decentralized scenarios) and manage the system of interest (SOI) via a computer-based user interface.

The framework supports multidisciplinary aspects as follows:

In a practical view,

- It serves as a foundation to clarify the complexity, terminology, and taxonomy of a CPPS paradigm.
- It serves as reference models which can integrate each layer of the V-cycle to support the system developments process. It will help to reduce cost and time to market.
- The framework allows any stakeholders of the CPPS to adopt required semantic models and use/reuse them in all phases: development, operations, and end of life. These models are modular and can be used as whole or independently adopted and integrated in various CPPS context.

In a global view,

- The framework contributes to the standardization effort in CPPS domain.
- The framework offers a first support to researchers, stakeholders, and managers in manufacturing companies by defining the semantics.
- The framework represents humans-CPPS relational aspects. It enables researchers to advance the theoretical foundation of systems engineering in the social sciences. ■

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Using Synthesis and Analysis for Design in Systems Engineering: an Integrated Approach

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■ ABSTRACT

This article presents a complete and general approach for the preliminary design of systems in the framework of systems engineering by relying mainly on synthesis. It is completed by a validation step through analysis to reduce furthermore the space of admissible solutions. This approach focuses on the modeling of design problems in electrical engineering and of their solving by including non-functional requirements right from the start through a single process. Starting from the specification of the requirements, the proposed approach develops the construction of synthesis models of design problems and their solving using the DEPS problem modeling language and the DEPS Studio environment based on Constraint Programming and Object-oriented modeling. Concepts related to this approach include in particular the issue of reusability of models, notions of subdefinite systems and of problem, knowledge and solutions spaces.

■ **KEYWORDS:** Subdefinite System, Design Problems Formalization, Synthesis, Constraint Programming, Problem-Space Oriented Approach

CONTEXT

In engineering, designing a system aims at defining a set of architectures said to be admissible, which satisfy all the design constraints specified in the specification of requirements (Jackson and Zave 1995). At the beginning of preliminary design, the system can be subdefinite (Telerman and Ushakov 1996): its architecture is at least partially unknown – the unknown is either its components, their numbers, their layout and/or the size of the system. This work addresses preliminary design, between requirements definition and detailed design. Preliminary design implies activities that are usually difficult and require a lot of expertise. Requirements may still evolve, and the system architecture is still at its "draft" stage. The problem of designing a physical system architecture is always complex from the structural, the mathematical as well as the algorithmic perspectives. Requirements may be ill-posed, leading to the absence of solutions. Upon the result of synthesis, decisions happen. Therefore, the most impacting decisions must happen as early as possible to find admissible architectures.

DESIGNING THROUGH AN ANALYSIS APPROACH

Analysis is still the major approach to design systems in physical systems in electrical engineering. Development models such as the V model or the IEEE 1220 standard (IEEE 1999) specifies design processes that rely on analysis as shown in Figure 1.

Analysis strongly relies on existing architectures as a starting point for design. It is based on simulation languages and tools (such as Matlab, Altarica, OpenModelica, PSPICE), and on iterative loops to improve the resulting architecture (Fontchastagner et al. 2007) – see Figure 1.

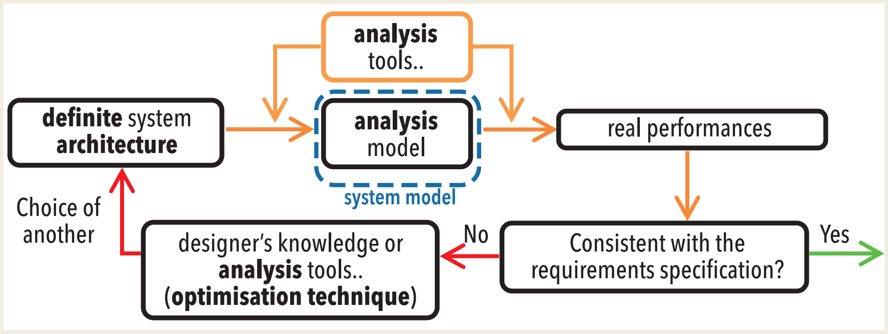

Figure 1. The analysis of the system architectures

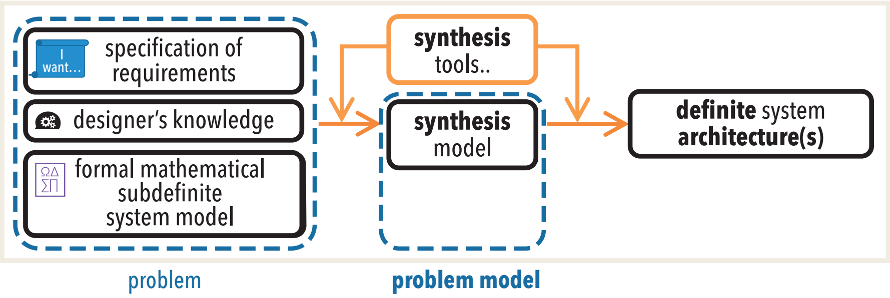

Figure 2. The synthesis of the system architectures

From analysis engineers build a behavior model of the system, which is definite (totally known, without variability). Engineers use black box models as well as any white box models (coarse or detailed).

However, analysis has shown its limits. This approach is iterative which implies higher development costs. The design consists in adapting only the dimensions but not the structures. Also, requirements identified as non-functional requirements, such as safety or eco-design, go unaddressed in one design step with analysis. Therewith, they increase the design efforts by requiring additional analysis processes at a later stage, such as Life-Cycle Analysis (LCA) for a design with environmental concerns. A designer must construct and analysis model for each aspect to evaluate (dynamic, LCA, safety, and so on). This means that designers do not have access to a high-level computational tool that allows them to assess the overall value of the designed system. Plus, as the problem is not explicitly stated, design usually occurs according to a single operating point, which means: a risk of over- or under-sizing and that structural constraints are not expressed (for example components cannot be chosen from a catalog). Modelling only the behavior usually means continuous design problems although real life ones are mixed type (continuous and discrete).

DESIGNING THROUGH A SYNTHESIS APPROACH

When designing a new system, it seems natural to think that the architectures would be the outputs of a process using the specification of requirements as inputs. But this perspective does not match the synthesis methodology presented in Figure 1. A synthesis approach allows them to complement it since it aims at finding correct-by-construction architectures, by modelling the design problem directly using synthesis tools and languages (Figure 2).

A synthesis approach allows the designer to directly describe the design problem as expressed by the requirements, which makes the approach more understandable by the different stakeholders. Admissible architectures then automatically and directly 'find' using *specific* design tools. Thus, the validity of a proposed architecture can be ensured as early as possible in the design process. Nevertheless, a synthesis methodology has certain limitations and is quite rarely used for the design of physical systems. Firstly, it relies on white box and coarse algebraic models and computational and mathematical techniques ensuring the admissibility of the architectures must be available and mastered. Secondly, there is a lack of adequate formalisms and tools to formalize a design problem explicitly for physical systems.

However, new tools and languages have been developed to help designers relying on synthesis such as the DEsign Specification Problem Language (DEPS) (www.depslink.com) (Yvars and Zimmer 2021) and its integrated modelling and solving environment DEPS Studio (Yvars and Zimmer 2019). Thus, designers should be able to build such synthesis models and use them to directly synthetize admissible architectures if an appropriate design approach is provided. DEPS and DEPS Studio are adapted to a Model Based System Synthesis (MBSS) approach: the MBSS way of thinking is based on two main concepts:

- Modelling the problem rather than the system.
- Using a solver based on constraint programming on mixed domains for computing one or several solutions that are correct by construction.

A PRELIMINARY DESIGN APPROACH FOR THE SYNTHESIS AND ANALYSIS OF ARCHITECTURES

Both synthesis and analysis approaches have their advantages and shortcomings and they are complementary. Thus, the authors propose to combine their strengths in a new approach for the preliminary design of physical systems. This both sequential and integrated approach is ready for use as soon as it is possible to formalize a subdefinite system and its requirements with DEPS during the conceptual and preliminary design phases. It is organized in processes, activities, results and resources (both manual and automated). The overall approach is in Figure 3. Through this approach, designers can perform complex and heterogeneous design right from the start, in a single process as non-functional requirements are to be modelled as any other requirements.

During synthesis, the formal modelling of the design problem is performed from the textual specification of requirements using DEPS in a reusable manner, by means of some modelling patterns dedicated to physical systems designers (step 1).

In the problem space, designers focus on defining and representing the design problem, which relies on the specification of requirements and on the support of experts from the relevant engineering disciplines. At this stage, the knowledge space helps in choosing a white box and coarse algebraic model of the subdefinite system. The authors propose the notion of knowledge space to complete that of problem and solutions spaces. During the problem modelling, this space helps in defining the design variables and their domains (because of technological constraints for example).

Designers construct models to ease the understanding of the problem. Low-level general-purpose formalisms are not adequate for most designers. DEPS incorporates some object-oriented structuring mechanisms to represent a subdefinite system organization and gives the opportunity to manipulate physical and technological quantities, to express a model in a vocabulary close to that of engineers. Finally, engineers require mathematical concepts to express constraints available in DEPS such as algebraic operators. DEPS also allows the designer to handle tuples of compatible values for variables using specialized constraints such as the catalog constraint.

The compiler of the DEPS Studio IDE generates generic computational model for solving using Constraint Programming (CP) (step 2). The solver synthesizes the set of all admissible and definite architectures with the built-in CP solver of DEPS Studio.

The synthesis process allows the designer to discard as early as possible the irrelevant design choices. Backward loops may be necessary in case the solver finds no solution. Possibilities include, in this order: verifying if the requirements have been correctly modelled, revising the modelling choices (for example a domain is too restricted) and relaxing some requirements.

Analysis follows synthesis and starts with a "boundary analysis" (step 3) where designers select architectures from the results of DEPS Studio among the set of admissible architectures. This step allows designers to filter architectures for selection from predesign, as one (or few ones) for detailed design. This step consists in the knowledge

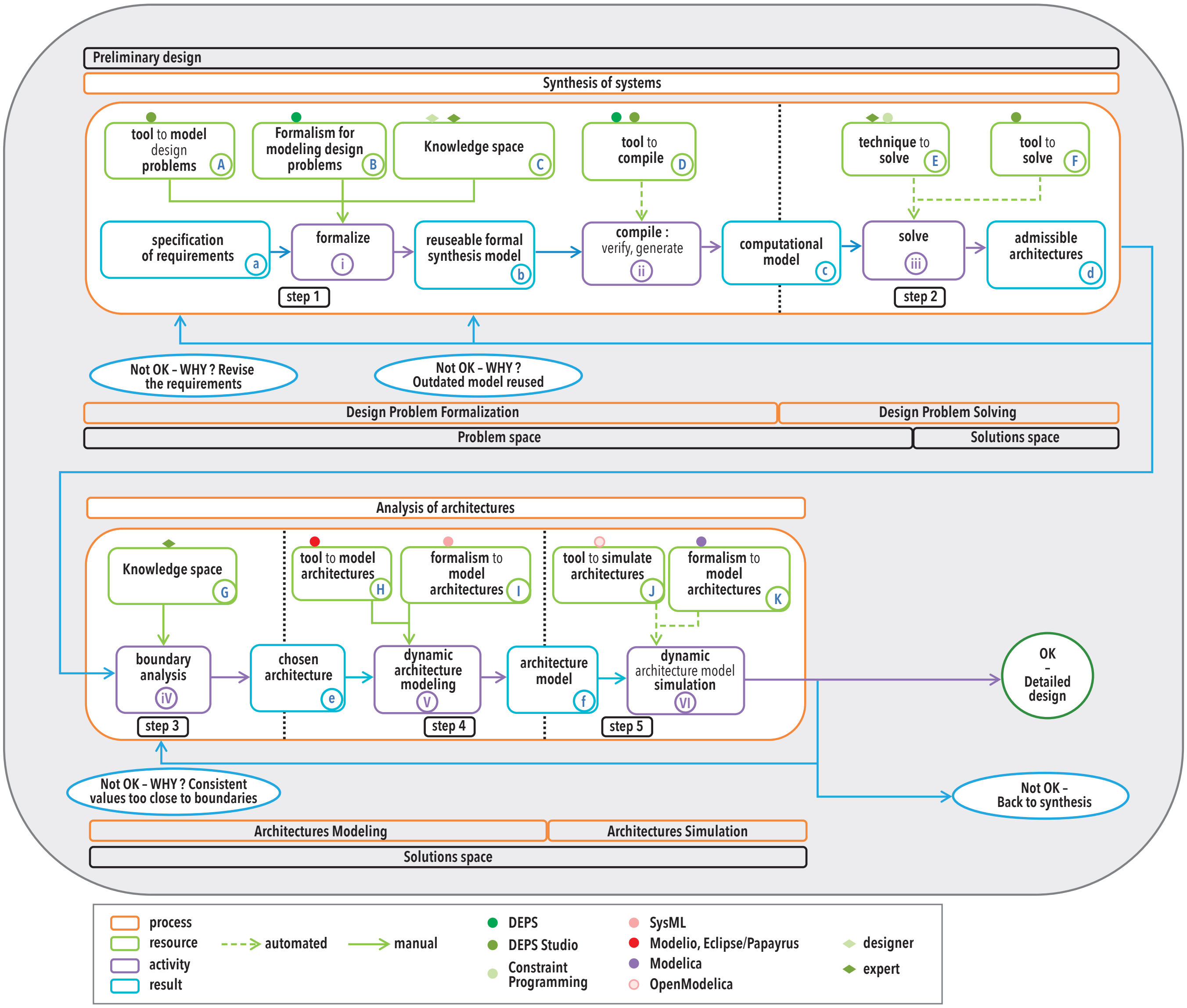

Figure 3. An approach for preliminary design combining the synthesis and the analysis of architectures

space selecting, for example, the architectures whose values are the furthest from the threshold values set in requirements modelled as inequalities constraints. The selected definite architectures undergo modelling (step 4) and simulation more precisely (step 5) with a dedicated tool depending on what the designer wants to evaluate (dynamic behavior, LCA, and so on). In case no architectures pass the analysis process, the designer must select another one in case of a black box model, a sensibility analysis can help choosing better architectures.

We applied the overall approach for the design (Diampovesa et al. 2021) and eco-design of a Li-ion battery for Electric Vehicles (both Battery Electric and Plug-in Hybrid Electric Vehicles). In particular, the analysis approach was successfully tested for the battery dynamic behavior (throughout algebro-differential relationships) with the use of the Modelica language and OMEdit/OpenModelica tools. Future works will focus on the application of this approach on the scalable case of the design of a whole electric/hybrid vehicle. ■

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Qualimetry Essentials Applied to Embedded Software Development

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■ **ABSTRACT**
With the initial goal of filling gaps in the definition, assessment, control, and prediction of automotive embedded software quality, including standards and regulatory compliance constraints, a three-year research study was conducted. The multiple contributions of the study to theoretical and applied qualimetry have helped to define a theoretical framework for quality control and monitoring of engineering and product development processes. Then, demonstrating the practicality of this solution, this study was applied on a real example from the automotive industry. This framework initially developed in the scope of embedded software is also applicable to systems and embedded systems, and makes these contributions have an impact on all industrial sectors.

■ **KEYWORDS:** Qualimetry, Quality Model, Embedded Software, Metric, Polymorphism, Genetic

1. INTRODUCTION

Research presented in this paper was a collaboration between the Laboratory for Analysis and Architecture of Systems, part of the French National Center for Scientific Research (LAAS-CNRS) and Renault Software Labs, a company developing automotive embedded software. The research aims at increasing competitiveness and reducing cost by improving quality. To reach this goal, the research focuses on the study of qualimetry, the science of quality quantification, applied to the development of embedded software. This work is part of the Renault group's strategy to further guide its processes through quality. This strategy particularly consists in designing and building more sustainable, eco-responsible connected electric vehicles, while increasing the residual value of the vehicle, through a permanent evolution of its life cycle.

The research work was carried out in the thesis of Yann Argotti (Argotti 2021). The research goal was to define a theoretical framework for the control and monitoring of engineering processes and product development through quality. The thesis made an exhaustive and thorough study of the existing quality models and led to three consolidated conceptual and methodological proposals: quality model classification, development and use of the polymorphism concept applied to quality modeling for built-in evolution and reuse, and construction of the genome of software quality models.

2. INDUSTRIAL SITUATION AND OBJECTIVES OF THE STUDY

Today, when a company designs, develops and manufactures goods or services, it must not only target a high level of quality for the products to satisfy customers, but also comply with many standards and regulations. This is particularly true with transportation systems where we can name few reference standards and guidelines: the ISO 26262 (ISO 26262-6:2011 2011) addresses the functional safety of road vehicles and covers the system, hardware, and software; the ARP4754 (ARP4754A 2010) provides guidelines for the development of civil aircrafts; and the DO-178C addresses software safety (DO-178C 2011) in aeronautics. Furthermore, these safety guidelines impose on the company the need to be at the state of the art for processes and methods, when designing and developing a new vehicle. Therefore, to ensure a high level of quality while complying with these standards and regulations, it is necessary that all quality requirements resulting from them are translated into a quality model. This model is the keystone for defining, evaluating, controlling, and even predicting the quality of the system.

Our research specifically addresses automotive systems (or software, depending on the choices made above), and in the context of its development, we therefore focus on the quality of embedded software in automotive vehicles.

Following an exploratory study of the literature in the field of quality models for embedded software, it appears clearly that there is an abundance of these models, but that there is no unified and operational solution that currently meets our needs. Our solution of applying Qualimetry essentials to the development of embedded software is therefore shifting towards the reinforcement and the unification of the activities to define, evaluate, control, and predict the quality of automotive embedded software.

We identified a set of four research questions:

- *Research Question 1:* Is Qualimetry, as the science of quality quantification, the right approach and what are quality and Qualimetry essentials?
- *Research Question 2:* Considering the set of software quality models, how

does one identify and decide which quality model is the most suitable for embedded software?

- *Research Question 3:* Considering a quality model for a software product, how does one operationalize it?
- *Research Question 4:* Can we have a unique reference quality model for software products?

Thus, through these research questions, not only do we aim to understand Qualimetry and quality modeling concepts from both theory and practice points of view, but we also aim to design a solution that fosters their practical aspects to answer to the company needs.

3. SYNTHESIS OF THE WORK DONE AND CONTRIBUTIONS

The research on quality models for embedded software conducted during Y. Argotti's thesis work (Argotti, Baron, and Esteban 2019; Argotti et al. 2020) resulted in several contributions, each addressing the research questions posed above, and even beyond.

To answer Research Question 1, it was found that Qualimetry (Azgaldov et al. 1968) is indeed the appropriate approach and the Qualimetry essentials were summarized into the "House of Qualimetry “ and its 6 pillars: three for quality models (that is analysis to identify quality characteristics, rules to control the depth of analysis and model structures, and characteristics weight factors) and three for measurements (that is the measurement theories with mathematical and statistical tools, aggregation of data, and measurement thresholds during evaluation, control, and prediction). They were complemented by polymorphism (that is overloading, coercion, inheritance, overriding, extension, and temporal change) for product variants and evolution in quality modeling during projects or the life cycle (Argotti, Baron, and Esteban 2019). We note that the inspiration for the concept of polymorphism can be found not only in genetics but also in some famous quality modeling contributions such as the studies of Boehm et al. (Boehm, Brown, and Lipow 1976), McCall et al. (McCall, Richards, and Walters 1977), FURPS (Grady and Caswell 1987) or Gordeiev and Kharchenko (2018). The corresponding contributions are shown in Figure 1.

To answer Research Question 2, a systematic collection and analysis of quality models in the literature first allowed the identification and characterization of the multiple models of software quality and retrieving, considering more specifically those related to embedded software, and finally those usable in the context of automotive (Argotti et al. 2020). The contributions answering this research question are summarized by Figure 2.

Then a method was defined for selecting and adapting a quality model, in parallel with the question of quantifying quality, in response to the third Research Question. This method considers the history and standards of the analyzed domain for the selection, and then integrates the constraints and consultation of stakeholders and experts with the use of Cohen and Fleiss Kappa to determine the optimum solution. Furthermore, compared to the corresponding standards (ISO/EIC 250nn series, and ISO/IEC/IEEE 15939 (ISO/IEC JTC 1/SC 7 Software and systems engineering 1999, 15939)), the added value of this method is that it guides, from a practical point of view, the development of tailored polymorphic quality models to real-world use cases. The results and their application to a complex automotive case, a subset of four high priority distinct and representative embedded software projects, are synthetized through Figure 3.

In parallel, it has been demonstrated that there is no unique reference quality model (Research Question 4) but a meta-model: the genome of software quality model (for comparison, see Figure 4).

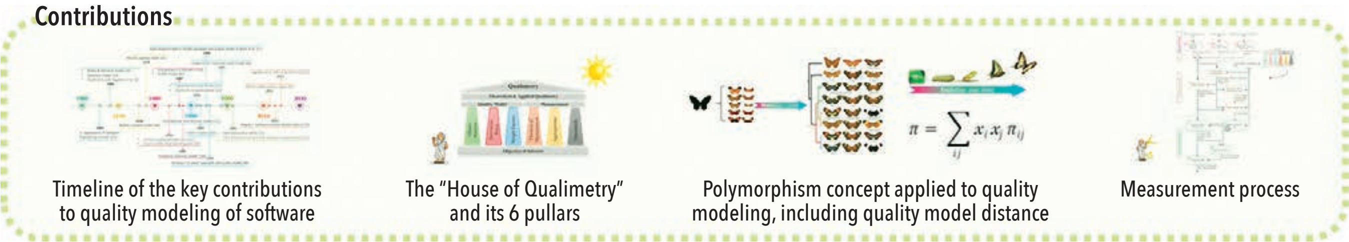

Figure 1. Contributions produced in answering Research Question 1

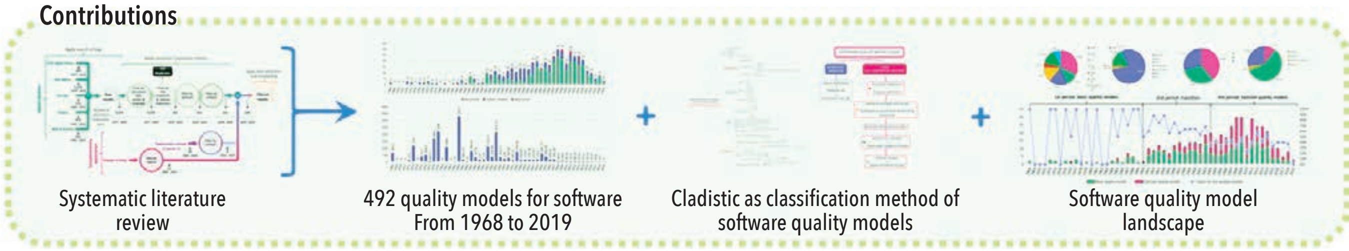

Figure 2. Contributions produced in answering Research Question 2

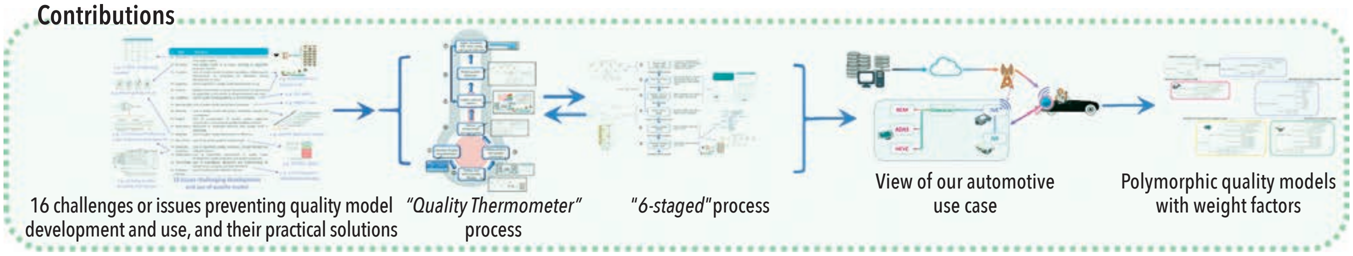

Figure 3. Contributions produced in answering Research Question 3

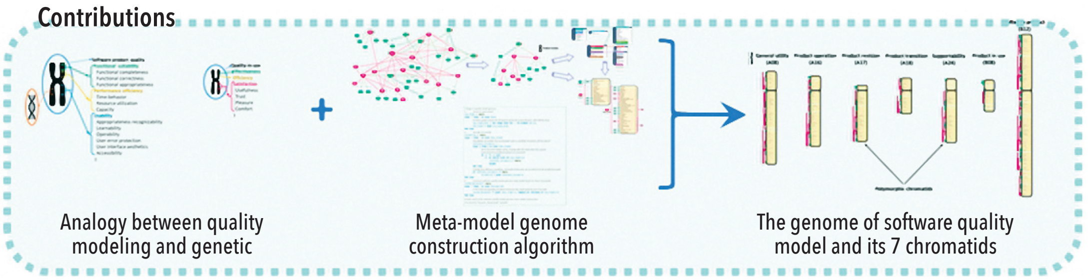

Figure 4. Contributions produced in answering Research Question 4

Finally, we defined a structured approach for the transfer and deployment of the results of this theoretical work, through a proposal for a digital portal for Qualimetry as well as prototype software tools. These contributions are key and completely aligned with ongoing work in the European Union's Horizon 2020 Quality-aware rapid software development (Martinez-Fernandez et al. 2019).

4. PERSPECTIVES

In the continuation of this work, we plan to analyze the attributes of the listed models related to sustainable development and eco-design, if they exist, or to define them otherwise.

Indeed, the Systems Engineering and Integration (ISI) team of LAAS-CNRS is conducting work on sustainable development, particularly related to the obsolescence of technical systems. In the context of a more global reflection on Industry 4.0, the team wishes to extend the problem of monitoring and predicting software quality to the study of software obsolescence. This subject, currently absent in the scientific literature, is usually treated in a purely reactive way in companies. Complementary to the work of LAAS-CNRS on the obsolescence of electronic systems and systems (Zolghadri *et al.* 2020; Salas Cordero *et al.* 2020), we therefore plan to focus on the characterization of software obsolescence.

Software obsolescence is a component of sustainability, which has a direct impact on the economic plan and on the digital footprint, we thus naturally consider extending the problem of monitoring and prediction of software quality to the study of software obsolescence, by defining new quality indicators related to eco-design.

5. CONCLUSION

This article synthesized the contributions made in Yann Argotti's thesis in response to the definition of a theoretical framework for quality control and monitoring of engineering and product development processes. Furthermore, the practical study conducted in it focused on embedded software, which is of paramount importance for all industrial sectors. Furthermore, this approach is generalizable to all embedded systems and complex systems.

In conclusion, this thesis, which has potential for a broad impact on the societal value, is applicable to all software and complex systems, and has laid the foundations that allow today to extend this work towards the characterization of software obsolescence in the context of sustainable development of software and its eco-design. ■

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Harmonica: A Framework for Semi-automated Design and Implementation of Blockchain Applications

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■ **ABSTRACT**

Designing blockchain-based applications is a tedious task. Compared to traditional software engineering, software architects cannot rely on previous experiences or proven practices, often formalized as software patterns. Also, the selection of an adequate blockchain technology is difficult without deep knowledge of the technology. This paper introduces Harmonica, a framework for the design and implementation of a blockchain-based application. This framework is divided in three parts: a decision-making engine to recommend a blockchain technology and blockchain-based software patterns relying on requirements, a configurator to generate code stubs and configuration files, and a knowledge base to support those tools.

INTRODUCTION

A blockchain is a ledger containing transactions embedded in linked blocks and shared by a network of nodes. In this network, an algorithm run by every node manages the inclusion of new transactions to the blockchain, namely the consensus algorithm. A transaction is an operation that changes the state of the blockchain. They are often used for two types of operation: exchanging cryptocurrencies between users and interacting with smart-contracts, which are programs stored on-chain that can also perform operations to change the state of the blockchain.

Through their special operating models, blockchain technologies have many unique characteristics. First, a blockchain network is disintermediated: no one is fully responsible for the management of the network. Second, using blockchain provides data security and immutability. The addition of blocks is ruled by a consensus algorithm and alteration of data is impossible, where traditional data storage technologies can be modified by authorized parties. Third, it is possible to retrace the complete history of state changes of a blockchain, enabling full traceability. However, the technology suffers from several drawbacks. Due to its design, blockchain often suffers from scalability and performance issues. Where traditional databases can meet hundreds of thousands of transactions per second, most of the public blockchains cannot reach even a fraction of it. Also, every data inside is publicly available, which can be an issue when data exchanges must be kept secret between users. The immutability of data is also a problem when using smart-contracts: upgrading an already deployed smart-contract is often impossible by design and specific techniques must be used.

In recent years, many new blockchain technologies have been designed to tackle those issues, but there is a constant balance between strengths and liabilities. For example, some blockchains (private blockchains) only allow a specific set of known nodes to join the network, add new blocks, and form a consortium, where others (public blockchains) let any user join the network and start creating blocks through slow albeit robust consensus algorithms, such as Proof-of-Work. Some blockchains also integrate data deletion features (automatic pruning), but this is in opposition with the immutability of blockchains. As the technology emerges and diverges from others, blockchain integration in new or existing software and systems is still a challenge. Most practitioners do not have enough expertise in the field to decide on which blockchain solution to use for a specific context. They must also be aware of blockchain technical specificities that differ from conventional technologies (high latency, data access rules, impossibility to query data from outside the blockchain, …). Where using architectural or design patterns to build software is a widespread practice in the software engineering field (Devedzic 2002), it is not in blockchain-based architectures, where only a few have been proposed and might lack extensive testing. Finally, it is also difficult to bootstrap a blockchain system from scratch if the practitioner chose to use a private blockchain. An adequate initial configuration is paramount to satisfy many system requirements (for example, performance) and is hard to update on a running blockchain network.

To address those issues, engineers designed models and tools to assist the practitioner in the choice of blockchain technology (Belotti et al. 2019). Engineers also created new patterns to support the design of parts of the application (Xu et al. 2018), and designed software to generate code stubs of smart contracts (Frantz and Nowostawski 2016). However, there is still no holistic framework yet to assist practitioners from the design to the development of blockchain applications. This paper proposes Harmonica, an end-to-end framework to fill the gap, through a suite of tools and a knowledge base. The next section introduces in detail the framework and its content, then a conclusion is given, and future work using Harmonica.

FRAMEWORK PRESENTATION

The proposed framework (Figure 1) is divided into two main parts, respectively the tooling suite and the knowledge base. The tooling suite is composed of two tools: (1) BLADE, a decision-making tool for the selection of a blockchain and blockchain-based patterns in a given context, and (2) BANCO, a configurator designed to assemble the major parts of a blockchain application using the software product line principles. Provided tools can be called independently from each other, an architect can obtain recommendations, code stubs and configuration files, or both. The framework's tools leverage a knowledge base, which contains information about a set of blockchain technologies and blockchain-based patterns, as well as core assets (for example, configurable code stubs) to build the software at the end.

KNOWLEDGE BASE

To perform, the tooling suite relies on a knowledge base, divided into three subsets:

- Blockchains: this subset contains organized knowledge about existing blockchain technologies. Each blockchain is described by attributes that allow practitioners to differentiate them from each other and gives detail on their capabilities.
- Software patterns: this subset contains the blockchain-based patterns (for decision-making). A template will be implemented from those patterns and stored with other core assets for code generation.
- Core assets: these are reusable elements to construct the blockchain application at the end. It contains smart-contracts, code features, blockchain configuration files, and implementation of patterns.

Building an efficient and useful knowledge base requires finding a suitable format to store collected data. Blockchain patterns are organized into an ontology that describes the different concepts (blockchain and patterns), and the relations between them. Such an approach helps to make recommendations, as powerful reasoning between concepts can be performed. Eventually, blockchain data will also be included in a dedicated ontology, allowing inferences between the two ontologies. To fill the knowledge base, there was consideration of multiple approaches. For the software pattern ontology, a systematic literature review identified existing blockchain-based patterns, and a taxonomy built from acquired patterns. Another envisioned approach is collaborative editing, to acquire knowledge from contributors that have an interest in the result. Where such methods are sufficient for the construction of a pattern knowledge base, they might not be efficient enough to build an accurate blockchain knowledge base, where blockchains are frequently updated, leading to changes in their attributes. Another considered approach to tackle this issue is the use of automatic methods such as scrapping or natural language processing (NLP) to collect knowledge of relevant documents (for example, whitepapers, academic literature, …). The build of this first version of this knowledge base supports the first iterations of BLADE and is published on GitHub.

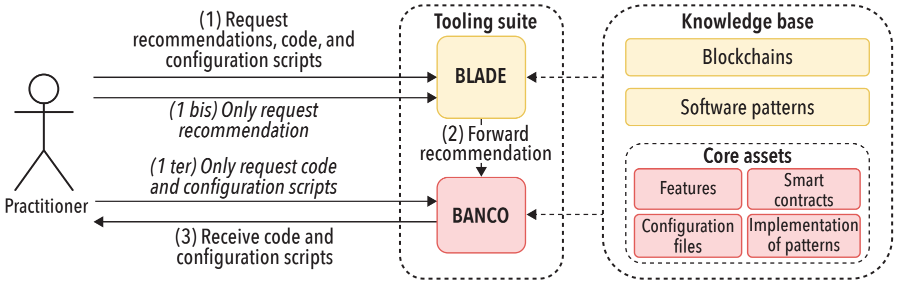

Figure 1. Framework overview (red artifacts are currently in development and yellow artifacts have already been implemented but further developments are planned to improve them)

BLADE

Relying on the knowledge base, BLADE is a tool capable of suggesting the most suitable blockchain and blockchain-based patterns to use for a given context. So-called context is an aggregation of different inputs: user requirements, models, and the company's assets (for example, infrastructure definition).

The process to generate recommendations is the following. First, the user must specify the blockchain attributes desired or required for the decision-making. The user can select a label (from *Indifferent* to *Extremely Desirable*) to express its level of preference towards an attribute. The user can also specify if an attribute is *Required*; if so, a blockchain that does not meet this requirement is automatically disqualified. BLADE dynamically generates a dependency model when a user selects requirements to prevent the user from selecting two requirements that conflict between each other. For example, it helps to balance the different strengths and liabilities of blockchain, such as immutability versus modifiability, or decentralization versus access control. We implemented the first version of BLADE for decision-making between five blockchain technologies (Six, Herbaut, and Salinesi 2020) described by 14 non-functional requirements as attributes, and a multi-criteria decision-making algorithm named TOPSIS (Lai and Hwang 1994).

BANCO

BANCO is the third artifact constituting this framework, to generate code and scripts from the recommendations, requirements, and user selection of features. BANCO leverages a variability model for the selection of many features that will compose the final product. A user can access further assistance for selection from the recommendations produced by BLADE, but also use both tools independently. Using the assistance, many features will be preselected such as the blockchain solution to use and recommended patterns. Following that, BANCO will use a library of core assets (code templates, configuration files, …) to generate parts of the new blockchain application such as smart-contracts or off-chain components for blockchain interaction. Each of those artifacts will contain off-the-shelf features, also generated from existing core assets. Using this approach also allows the generation of scripts to bootstrap a private blockchain with adequate configuration on multiple machines automatically. This work is still in its initial design and will be implemented in a later stage.

CONCLUSION

This framework aims at facilitating the work of software and systems engineers for the design and the implementation of blockchain applications, by proposing a collection of tools to obtain recommendations and artifacts to build the application over and set up the system with ease. Future works will consist in improving the existing artifacts and developing the others. First, by enhancing BLADE with the support of pattern decision-making. Using BLADE, architects will be able to get precise recommendations on the blockchain and related patterns to use, based on a knowledge base and a systematic process. Then, the plan is for the addition of more alternatives into the knowledge base, as well as the core assets and the architectural patterns to make more accurate decisions using BLADE and support the generation of code with BANCO. For example, an ongoing systematic literature study to collect patterns from existing solutions proposed by researchers will serve to add new patterns into the knowledge base. Finally, with the implementation of BANCO, Harmonica will take the recommendations of BLADE and the requirements of the user to generate code stubs that can be used off-the-shelf or customized to develop a blockchain application. We expect to trial the framework with blockchain experts and software or system architects to validate its correctness and utility when applied, notably through case studies on different domains. ■

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Towards a Method to Operationalize Modelling, Verification, and Evaluation of Architectural Solutions in the Field of Nuclear Critical Infrastructure Engineering

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ABSTRACT

Nuclear infrastructure development projects are increasing in complexity, involving numerous and various stakeholders. Highly constrained, they are often subject to many hazards. This has an impact on the number of desired design alternatives generated throughout the facility life cycle and their evolving assessment. In order to secure the delivery of such projects, the Évaluation for Critical Infrastructures Model-based system Engineering (EVA-CIME) method is proposed to implement and operate the architecture evaluation at the scales both of an organization and of projects. This article presents the elements justifying the formalization of such method and the obstacles to overcome. This method must be technically and organizationally usable by the different actors of a nuclear infrastructure development project. It is composed of 5 elements: concepts; languages; operational approach; tools and repository of knowledge and expertise. The good orchestration of these different components allows to set up an environment within the organization to carry out effective architecture evaluations with the aim of helping the architects to choose between the alternatives that they will imagine from the beginning of the project.

INTRODUCTION

In complex projects such as nuclear infrastructure (NI) development projects, several alternative architectural solutions require modelling, evaluation and comparison to characterize their relevance to all Stakeholder's expectations and values. For a better understanding of complex contexts and needs, exchanges with stakeholders of NIs are then mandatory, generating many reports and documents during the whole life cycle. These reports and documents generate design latency, losses, or misinterpretations of information. The goal of this research work is to establish the conditions to effectively assist and support design decisions in confidence during the project from the very first conceptualization step to the end of the development while considering stakeholders' concerns. This article presents a specification of the EVA-CIME method to meet this goal.

ISSUES

NI development projects take place in highly constrained contexts and are subject to setbacks (new needs, changing requirements, availability of modern technologies, new dimensioning assumptions). The multiplicity of stakeholders (Cameron 2013) leads to a variety of expectations which by nature may be STEEPLED: Social, Technical, Economic, Environmental, Political, Legal, Ethical and Demographic. To secure the development and delivery of NI, suppliers must be able to define, evaluate, and conduct different architectural choices applicable to NI at any time along the project and at the very first steps of the project. In fact, most of the costs of NI projects are incurred at a very early stage (Blanchard and Fabrycky 2000). It is therefore necessary to be able, at the time of these first decisions, to identify, understand, prioritize and, as far as possible, formalize the values, needs, expectations, and constraints of the stakeholders (both those carrying out the project and those for whom it is being carried out), to understand the full complexity of the project and the resources devoted to it.

An initial abstract vision of the system is drawn up, through capacities, services to be provided or used, missions, operational scenarios, and more, (Voirin 2017)with a focus on the collaborative definition, evaluation and exploitation of its architecture. This book describes the fundamentals of the method and its contribution to engineering issues such as requirements management, product line, system supervision, and integration, verification and validation (IVV or any other means deemed necessary is defined at this early project phase called the "architecting phase." An abstract "big picture" is used as a baseline for the engineering phases that follow and defines iteratively and with increasing concreteness potential solutions to be modeled, verified, validated, analyzed, and evaluated.

To compare and choose among alternative architectural solutions, the literature mentions two processes, the system analysis process as defined in the systems engineering standards (ISO, IEC, and IEEE 2015) and the architecture evaluation (AE) process as defined in the architecture standards (ISO, IEC, and IEEE 2019a)(ISO, IEC, and IEEE 2019b). System analysis is defined to be implemented in conjunction with other systems engineering processes. Architecture evaluation can, according to ISO 42020, be used in the upstream phases of the project as described above. The concepts and principles described in the previous standards can be used as a framework for conducting evaluations of proposed architecture alternatives in NI projects to help ensure that design choices meet the initial architecture vision and to correct any deviations. However, several issues need to be raised:

1. The systems engineering standards prescribe the processes to be conducted, but do not necessarily explain how to conduct processes such as architecture verification and validation (V&V) and analysis in both the exploration and definition phases.
2. There is a clear definition of the concepts and activities to be conducted for architecture evaluation, but there is a lack of methodology to implement these activities on a project.
3. It is important to be able to measure and quantify the performance of the implementation of the evaluation of a project.
4. A large project such as an NI will require multiple evaluation efforts, it is necessary to ensure that they are consistent and serve the same purpose.
5. Different evaluation techniques and approaches exist with their advantages and disadvantages, and project stakeholders need to be able to use the most efficient ones on a case-by-case basis.
6. The systematic implementation of architecture evaluation on a project can only be achieved by increasing the maturity of the organization in this area.
7. To implement architecture evaluation in a project implies the stakeholder must have access to the necessary means and resources or acquire them.

TOWARDS A NEW METHOD: EVA-CIME

Adopting model-based systems engineering (MBSE) principles conjointly with a process-based performance management approach, the method named EVA-CIME allows stakeholders to deploy and operate in confidence architecture evaluation at two levels: the company level and the projects level. This method aims to support both organization and project stakeholders in conceptualizing, defining and scheduling architecture evaluation effort during the whole system life cycle. This method is composed of five elements: concepts, languages, operational approach, tools, repository of knowledge, and expertise.

1. For EVA-CIME to be unambiguous and accepted among the organization, a Data Model should formalize without syntactic, semantic, and pragmatic ambiguities, the set of **concepts** and their relationships related to the fields of modelling and evaluating architecture, systems architecting, engineering and project management.
2. **Languages** handle concepts through different views which each frame some concerns regarding the architecture evaluation effort definition. They can be textual or graphical using existing languages like Business Process Modelling and Notation, SysML, Capella, Ecore, or Gantt diagrams or new languages definition to adapt to specific needs of the definition of architecture evaluation effort.
3. **Operational approach** must then guide users in using the method. This defines two parts each one for different user segment. One-part targets users who want to deploy and operate architecture evaluation effort on a specific project. The other part targets people who want to enable improvement within architecture evaluation through organization (training team, benchmarks, framework, evaluation team, person in charge of maturity gain).
4. **Tools** implement concepts, languages, and operational approaches to enhance the user experience and accelerate creation and manipulation of the different elements, models and more. Nevertheless, the method must stay as much as possible tools-agnostic. Therefore, the contribution to this part will be a functional specification of what it is expected from tooling for the method.
5. **Repository of knowledge and expertise (REK)** regroups best practices, examples, modelling and evaluation patterns, repository of tools and techniques. The REK will provide this set of information in a structured way to accelerate the modelling and improve and upgrade the method over time.

PROGRESS

The EVA-CIME method must allow project and company organizations to set up an environment appropriate to the evaluation of architectures. Such an environment shall improve design decision objectivity, traceability and reduce risks of rework. As depicted in Figure 1, this environment must consider the information coming from the architecting activities as well as from the engineering

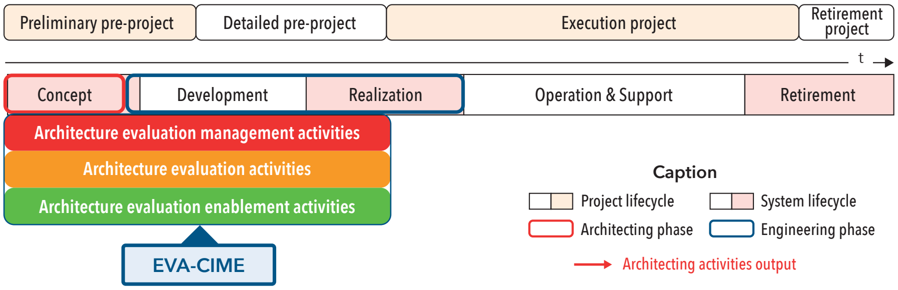

Figure 1. Temporality of use of the EVA-CIME method on a project

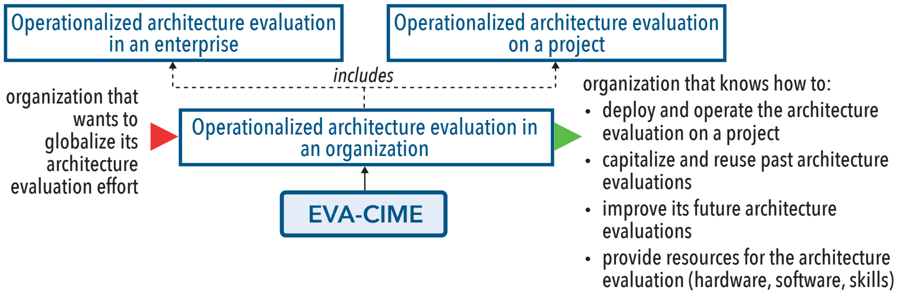

Figure 2. Main activities and results of the EVA-CIME method

activities. Indeed, the methods and uses of these activities are different due to their temporality and due to the actors performing them. It is therefore necessary to adapt to the different vocabularies to limit any loss or misinterpretation over time. This is why the EVA-CIME formalization focused firstly on linking the information from the value analysis for the exploration aspect with the framework from the ISO 42030 standard (Bourdon et al. 2020).

EVA-CIME shall be subject to a demonstration of consistence and usability in both technical and management aspects. Finally, the output of the method (at the scale of a project) shall be an architecture evaluation effort consistent over the duration of the project, from abstract to concrete NI's definition, from conceptual to technical phases and satisfying as much as possible the stakeholders. EVA-CIME shall provide the elements that will allow an organization to assess its maturity and determine its strategy for architecture evaluation efforts. This strategy will be the subject of operational declinations translating into acts of transition, change management, and continuous improvement. The purpose is not to provide generic framework and activities for architecture evaluation, that is already done through the ISO 42030 standard. It is rather to provide all the keys to the organizations to tailor architecture evaluation. The purpose of using EVA-CIME throughout an organization is to globalize the architecture evaluation efforts to obtain benefits as described in Figure 2.

Lastly, EVA-CIME must be as user friendly as possible and thus build a community of users within the company to retrieve as much information as possible to constantly improve it. After examining a set of standards and interviewing some engineers and architects among the organization, we built a conceptual model. It represents a federated and shared vocabulary compliant with usual standards 15288 for systems engineering and 42030 for architecture evaluation. Thanks to a model-based approach the method uses multiple languages and representations already applied in practice. This reinforces its intelligibility by the different parties. Each user will have at their disposal a set of representations that they can use to represent the information in an adapted and even customized way. These representations should reflect the different concerns of the stakeholders about the architecture evaluation effort, its scope, objectives, and purpose. ■

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Contribution to Nuclear Safety Demonstration Through System Modelling and Artificial Intelligence

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■ **ABSTRACT**

Nuclear Power Plant (NPP) engineering projects become increasingly complex. For instance, a nuclear reactor includes more than 50 buildings, 500 km of piping, 500,000 components and 100 million units of data (requirements, reports, schemes…). However, nuclear safety demonstration of any nuclear facility is at the heart of the nuclear industry, being the most important and limiting factor for all requested engineering activities. Ensuring all these activities are performed considering safety demonstration is mandatory to get permission to license, build, operate, dismantle, and more. This article synthetizes an innovative method that mixes and takes advantages of artificial intelligence techniques and systems engineering principles, processes, and model-based systems engineering (MBSE) principles and usages. This method aims to guide and support engineers to improve their vision, their knowledge and vocabulary, and their capacities in terms of, first, safety requirements elicitation, and second of safety requirements demonstration.

■ **KEYWORDS:** Nuclear Safety, Systems Engineering, Model-Based System Engineering, Requirements Engineering, Machine Learning, Natural Language Processing, NLP, Licensing

INTRODUCTION

Nuclear Power Plant (NPP) engineering projects are becoming increasingly complex. For instance, a nuclear reactor includes more than 50 buildings, 500 km of piping, 500,000 components and 100 million units of data (requirements, reports, schemes…). Safety demonstration of such NPP becomes then more difficult. The safety demonstration definition is the "*Assessment of all aspects of a practice that are relevant to protection and safety; for an authorized facility, this includes siting, design and operation of the facility* (IAEA 2010)." It is mandatory and a priority in projects that have different constraints of scope, schedule, budget, quality, resources (PMI 2013). Indeed, the research, analysis, organization, and links that need to be set up between reference documents and the installation or activities being demonstrated, can quickly become time-consuming and costly. The reduction of time and costs facing a competitive industrial world may lead to incomplete analysis, which will lead the safety authority to reject and this rejection leads to cost drifts. For this, among other expectations, engineers and architects must face safety requirements engineering and analysis activities all along the project.

Systems engineering (ISO 2015) (SEBOK 2020) has proven advantages in various industrial fields for conducting complex systems engineering projects. It promotes concepts, principles, and processes, but also the use of models as early as possible in the project. It is the purpose of Model Based System Engineering (MBSE) (Schindel 2018) that considers modelling and use of models all along engineering projects. The research question is then: How to integrate the use and manipulation of the expected safety concepts and safety demonstration approaches in line with an MBSE approach allowing teams to manage cost, quality, and duration considering that there must be safety demonstration mastery from a lean engineering perspective?

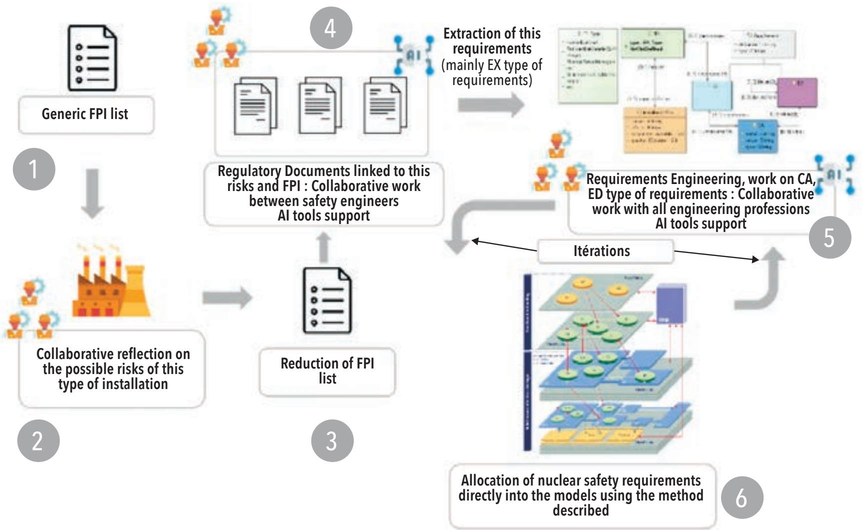

Figure 1. Big picture of proposed method

This article introduces a method aiming to guide and support engineers and architects deploying and conducting safety demonstration. By assumption, this method assumes crossing both model (MBSE context) and data-centric approach (AI tools and techniques), instead of the document-centric approach currently used. The goal is to describe method part that concerns and focuses on safety requirements engineering activities (Jacob, Chang, Lee, and Kristina 2019) illustrates approach to safety demonstration as practiced in the nuclear industry by using element presented lower. It is in points 4,5 and 6 that we find our addition of AI and MBSE approaches in relation to 3 pillars detailed in the next part. A more detailed explanation of this contribution can be found in Romuili et al., (2020, 2021).

The proposed method relies on the following three pillars:

- **Pillar 1: Set of nuclear safety requirements.** Demonstration of nuclear safety is a long, iterative process requiring a thorough analysis of regulatory texts (International Atomic Energy Agency (IAEA), French Nuclear Safety Authority (ASN), feedback…). This analysis will lead to a use of these texts with an industrial objective: "**Demonstrate that a particular activity or installation is safe in our country's nuclear safety authority's regulation,**" considering regulatory requirements and contractual aspects to move towards demonstrating the safety of nuclear critical installations and infrastructures. Statistical models from connectionist AI (inductive approach) require training on specific tasks and identified with quality datasets and validated by domain experts. It is worth considering this:
  - We created a corpus of qualitative requirements; based on the aggregation of various documents of the International Atomic Energy Agency (1141 requirements).
  - We train the BERT model (Natural Language Processing (NLP) algorithm from Google AI teams (Jacob, Chang, Lee, and Kristina 2019)) on the recognition of safety requirements. The dataset used for the training was the IAEA requirements corpus (explanation for the choice of BERT is in Roumili et al 2020). This makes various concepts and relations between these concepts emerge that address the Pillar 2. Indeed, this analysis allows us to set up parts of the safety demonstration that lend themselves to the use of a connectionist (inductive) approach of the AI. A second set of data of interest will allows us to train our algorithms on a Corpus of qualitative requirements based on the 'Codes of rules for design and construction" (RCC's *Legifrance* 2012a) . The deployment of trained algorithms on current datasets requires webapps, and APIs allowing engineers to use them.
- **Pillar 2: MBSE for nuclear safety.** The immersion in MBSE context (Schindel 2018) (Voirin 2017) deals with:
  - Engineering and management of safety requirements: This integrates work on the rewording of requirements and mass processing of textual data to find the requirements applicable to installation systems (semantic search, clustering…) by applying supervised and unsupervised algorithms adapted to nuclear safety processes.
  - Architectural design: multi-views and multi-paradigms modelling of installations, linking requirements and traceability of the latter by these models to ensure analysis and move towards the desired safety demonstration.

As a first approach, we analysed how nuclear safety demonstration happens in the industrial world, this led us to consider the following elements:

- **Interests Protection Functions** ("FPI" in French literature): functions that, if compromised, could result in radioactive releases or damage to the environment, the public or employees ("interests" in French regulation (*Legifrance* 2012a)). Considering the first design of the power plant, we analysed the types of risks that may affect the facility, which could compromise an FPI. From that, we set up a list of generic FPIs that must be preserved on the facility of interest.
- **Safety Requirements** ("EX" in French literature): for each type of risk, definition of the safety requirements for conducting the risks analysis and design: these are general design principles, "primary" safety requirements ("absence of radioactive material dissemination if an earthquake"), which serve as input data for the safety analyses.
- **Expected Characteristics** ("CA" in French literature): performance of design-based risk analysis (iterative process with the technical design engineers) and the safety requirements. CA are secondary requirements. They are the result of the risk analysis. We broke them down by technical batch and to be directly applicable for the technical design engineers. A "primary" safety requirement generates several CAs.
- **Defined Requirement** ("ED" in French literature): in an iterative way with the earlier point, the design is carried out by the technical trades based on the CAs. These are the technical measures proposed by the technical design engineers to meet the CAs. An ED applies to a system or sub-system. Thus, several EDs may have to meet a CA.

A FPI requirement will give rise to several EXs. An EX will give rise to several CAs and so on. The terms used in our description of the safety demonstration are related to the regulatory semantics of nuclear power (*Legifrance* 2012b). We made a parallel with the corresponding concepts in systems engineering in working groups comparing the semantics/concepts of nuclear safety engineering and systems engineering. We considered it more interesting to link the FPI to the concept of "function" in systems engineering and aligned all other elements to requirements.

The contribution to this Pillar 2 is formalized as a metamodel integrating more than 40 concepts, their inter-relationships as well as their attributes. This will allow the integration of the safety demonstration into general MBSE methodologies, thus helping collaboration between safety teams and project teams on shared models.

- **Pillar 3: Digital modelling tools.** This method will rely on an ecosystem of tools. Usually, safety guided engineering and analysis activities are manual with a written approach. This impedes a global vision of the safety demonstration and takes more time than the proposed approach. These tools will enable working faster, in agreement with time and completeness expectations from the regulation bodies and supply a better vision of the requirements demonstrated and their traceability throughout the project, over several years (the construction of a reactor takes about 6-10 years). The modelling tool will require an alignment of our metamodel with that of the software in which the integration will take place. It is necessary to find equivalent and missing concepts and to propose an extension of the metamodel that will include the elements that will allow safety engineers work.

APPLICATION

We are developing an application of the tools and concepts to a real case on a project with high "nuclear safety" stakes for the company in charge of the EPCm (Engineering, Procurement, Construction management) and for its nuclear operator. The goal is to measure the contribution of AI and MBSE to an operation that is complex enough to raise frequent questions and to feed the dialogue with the safety authorities, while being sufficiently comprehensive for all the issues to integrate into the developed approach.

VALIDATION

The question of the validation of the method naturally arises. In this context, it will be the use in the context of nuclear projects including safety demonstrations that will allow us to verify the interest of such a method based on the digitalisation of processes allowed by the field of MBSE and AI. It will be necessary to increase the competence of the teams in this type of modelling.

However, our method would benefit from partial validation if it could be applied to a concrete case because:

- The elements on which it is based, and our metamodel, are those recommended by the safety authorities for demonstration purposes. The contribution of the digital approaches does not contravene the typical safety's demonstration.
- Also, this work is based on elements that exist in the state of the art and have been proven (metamodels approach), so we gather valid elements between them to result in a new methodology applied to a new field but based on a solid approach.
- The supervision of this work is therefore conducted in the context of a company with expertise in the subject and, by people with expertise in the field of nuclear safety. The feedback on our work from these people is of interest in the context of this partial early validation.

Finally, in the nuclear industry, there are high risks that the license for projects construction and commissioning might experience delays or never issue due to lack of traceability or of reproducibility. To reduce these risks, the use of digital techniques is essential due to the number of costly non-conformities in most complex projects. In this context, we propose the combination of systems engineering and AI and its application through the demonstration of nuclear safety, an extraordinarily complex discipline only addressed in a document-oriented way.

This convergence between a data centric approach and MBSE will ensure the digital continuity throughout the project and minimize errors, bottlenecks propagating from licensing to design, construction, commissioning, and operations translating into major time and costs overrun observed for the majority of NPP projects. ■

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Model-based Commissioning, a New Methodological Approach for Commissioning of Nuclear Basic Facilities

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ABSTRACT

This article intents first to formalize commissioning that must be seen as a crucial need and an unavoidable obligation. Second, it aims to introduce a method called COGuiNF (Commissioning Guidelines of Nuclear Facilities) which would allow to prepare in relation with MBSE processes then drive relevant activities for the commissioning of Nuclear Facilities. COGuiNF must define, formalize and feed the inherent relations to be managed between engineering and commissioning. This article focuses on the five components of the COGuiNF method.

INTRODUCTION

The purpose of commissioning is to ensure that the system of interest operates safely and as intended, and that it meets the requirements of all stakeholders from various backgrounds: legal, environmental, social, safety, cost, performance, and more Indeed, Nuclear Facilities (NF) design and realization projects must meet both conceptually and technically, this crucial need, mandatory for their global activity. The goal is then to prepare, optimize, and deliver the necessary deliverables, proofs, and justifications that are requested by the stakeholders depending on their roles and interests: nuclear safety authorities, client, sub-contractor, or also maintainer in charge of operational maintenance of the NF. This article presents the COGuiNF (Commissioning Guidelines of Nuclear Facilities) method. This would allow stakeholders to prepare and then drive relevant activities, resources, and means focusing on NF commissioning objectives. This method must be developed by promoting the importance of the commissioning to be connected and in phase with systems engineering processes (for both NF design and realization). It must rely on and extend Model-based System Engineering (MBSE) principles for many recognized reasons in different industrial fields and be deployed considering company culture and knowledge. Different issues inherent to the commissioning in the nuclear field are presented in the following article. The COGuiNF method is then introduced as an enabler to any commissioning project in this field. Some perspectives will then conclude, aiming to complete and finalize the COGuiNF method.

NUCLEAR FACILITIES COMMISSIONING AIMS AND ISSUES.

Many issues are inherent to the commissioning in the nuclear field. Indeed, because of the complexity of the installations and the lack of a commissioning culture within the industry, commissioning does not benefit from a global vision. Furthermore, there is frequently no formal team assigned to commissioning, resulting in a lack of awareness, training, and operation methods. In addition, the progress of engineering over time has not considered commissioning, therefore MBSE and its principles do not include commissioning as a critical activity. The variability of the roles and duties of the stakeholders involved makes commissioning challenging, particularly because of the various way those stakeholders work. The volume, speed, and variability of data and models created and processed by both commissioning and engineering must be examined, demonstrating how complicated this process can be and how it must be viewed.

Further, costs and delays are crucial indicators for building any industrial complex system and in particular nuclear facilities. It needs methods to quantify and track the indicators during the commissioning process. In addition, safety and security aspects are specific to this domain and must be drivers in the process. All these indicators lead to the need of more formalized method to pave the way from the design time to the implementation of the solution. Nevertheless, this method has be well connected with enterprise culture about commissioning since it brings some rules to be integrated and followed.

Commissioning does not benefit from a global vision especially because of the complexity of the installations and the lack of commissioning culture within the global nuclear industry. Additionally, there is often no structured team allocated to the commissioning and this leads to a lack of method for awareness, training, and operation. Also, the evolution of engineering through time did not take into account the commissioning fully, therefore MBSE and its concepts does not enough consider the commissioning as a crucial activity.

CONTRIBUTION

Facing these issues, the proposed PhD research work consists in studying and developing a method, called COGuiNF, that must support and guide engineers, architects, and managers of complex systems engineering projects, hereafter NFs. The method must allow the team in charge of the commissioning to:

- First: to prepare and validate requested activities that must consider commissioning dimension, expectations, and needed engagements from all stakeholders involved, implied, or concerned by both engineering and realization activities; to adapt, optimize, and validate resources, means and techniques being considered during these activities. This allows us to define an idealized vision, even optimized, of the activities and operations that are requested during the NF realization phase.
- Second: drive, orient and adapt step by step these activities considering eventual problems and emergent phenomenon that relies during the commissioning of the NF.

So, the main objectives of COGuiNF method are:

- To improve the coordination and therefore the articulation of the various activities of all stakeholders involved both in design and realization phases of a NF by replacing the commissioning as the crucial activity of the project and creating the coordination around it.
- To bridge the gap between systems engineering processes, involving both MBSE practitioners and actors involved in commissioning, each that specialize in their own objectives (requirements engineering, architectural design, or integration, verification, or validation of the NF).
- To head and request these stakeholders to converge and particularly to support them in preparing, managing, and performing activities associated with reach commissioning objectives (in terms of resources, means, and more).
- To check the wholeness and therefore the relevance of these activities (trials, demonstration, report, and more) during a global and holistic way.
- To establish, formalize, and optimize planning of those activities in terms of costs, duration, and performance.
- Last, to arrange and complete the REX of the pointed-out commissioning, to facilitate its reuse by other projects.

Considering the complexity of the commissioning (finality, objectives, missions, number and heterogeneity of actors, skills and fields, duration, and more) and with regard to systemic approach and its advantages, the commissioning is here considered as a system of systems (Luzeaux and Ruault 2010). Indeed, (Konrad et al. 2019) shows how using MBSE to address the management of complex rocesses can be useful.

Therefore, composed of and highlighting various interactions between two abstract sub-systems presented below:

- The commissioning System of Interest (SoI), as classically defined in (ISO, IEC, and IEEE 2015) (ISO/IEC 2016) encapsulates the different activities and tasks that are needed to establish the evidence, provides justifications, and proofs allowing to transfer the responsibility to the future NF operator. It is by evidence closely linked to the NF itself and must interacts(raises awareness, irrigates and guides) with actors that are involved all along the systems engineering processes. It also exchanges flows with the commissioning System Used to Do (SUTD) in terms of management information (planning, milestones, resources availabilities, justifications needed for the regulatory body and the customer, and more).
- The commissioning SUTD helps the elaboration and the construction of the commissioning SOI. It ensures SOI's design, running and management, builds a program to follow ,and ensures the good coordination and exchanges (requirements repository, milestones, models, and more) between the commissioning SOI and other systems engineering processes. For this, it is mandatory to harmonize the vocabulary and to avoid any retroactive actions (requirements repository redaction) that are often encountered during commissioning.

In addition, the commissioning is characterized by two more or less overlaying steps linked to design and realization objectives of the NF:

- **Commissioning Design Time (CDT):** during this step, the commissioning systems (SOI and SUTD) are first defined and then validated. To do so, there is a crucial need to specify the activities and resources requested, the objectives to be achieved, the constraints and requirements to be considered by the NF. The CDT therefore begins at the stage of concept definition

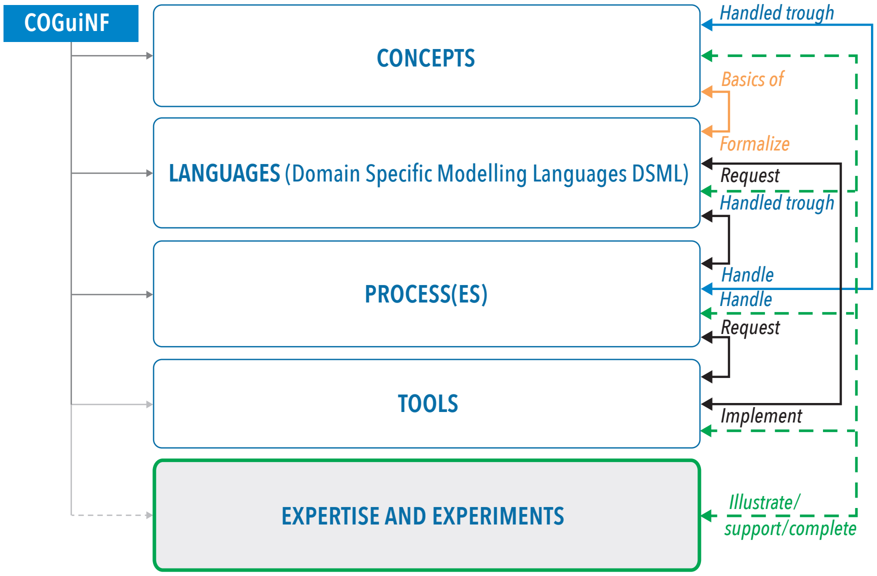

Figure 1. COGuiNF

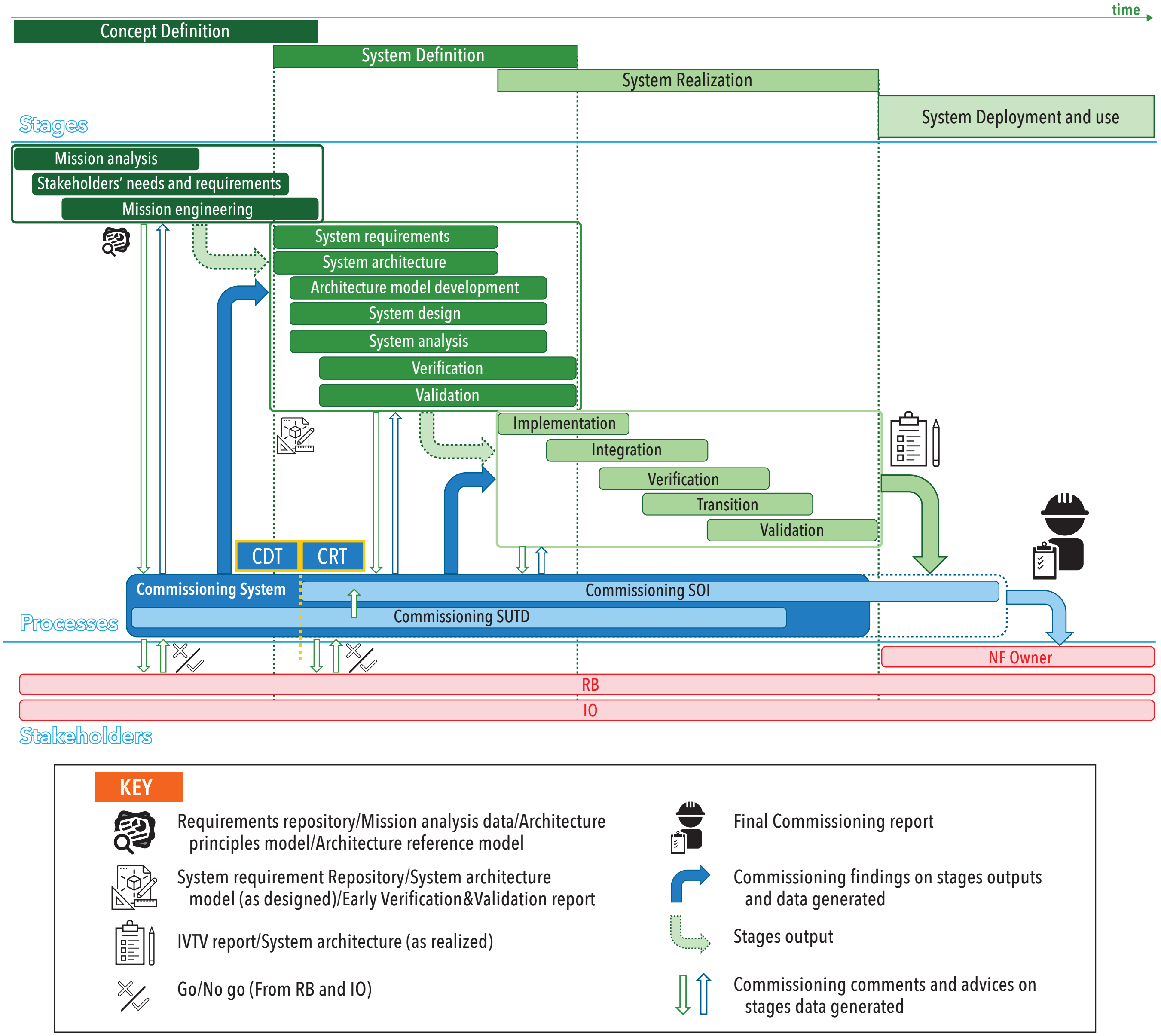

Figure 2. Commissioning Big Picture

of the NF, which allows to trace the data generated and to anticipate the constraints that derive from the construction and deployment of systems.

- **Commissioning Run Time (CRT):** the commissioning SoI performs the trials and other V&V activities that have been defined during the CDT, moreover the SUTD controls their evolution and improvement. Consequently, the SUTD must adapt the commissioning SoI as needed according to the various events or situations encountered during the realization of the targeted NF.

The CoGuiNF method is composed of five elements (Figure 1) that ensure the definition, the design, and the modeling of a commissioning system. It also encompasses the tools recommended and their potential interconnections as well as the commissioning framework and the best way to capitalize on projects by designing the knowledge repository.

Concepts: They express rules and standards of the domain (concepts and properties characterizing each concept), about the connection between these standards (relations and properties requested to characterize each connection when it is essential, but above all, about rules and imperatives linked to each connection) which are valuable to describe, formalize, and process a commissioning. These concepts and relations are vital for occurrence to depict and formalize the distinctive exercises and forms that are to be done all along commissioning. They are from now on formalized by utilizing a metamodeling approach (Bézivin 2005).

Languages: They talk about Domain Specific Modelling Languages (DSML) (Nastov 2016). They permit the modeler to demonstrate commissioning exercises, assets, trials, and more. This requires selecting and formalizing sets of concepts and relations which are asked to speak to a perspective of the commissioning framework. Classically, it is to address the functional, physical, and behavioral perspective as advanced in Framework Sciences field and, for occurrence, by SAGACE approach (Penalva 1997), or more absolutely as advanced in Framework Designing space, for occasion by ARCADIA approach (Roques 2016). Formalizing the DSML implies selecting an existing modeling language that matches with these concepts and relations (BPMN for functional and practical perspective) or characterizing theoretical and concrete syntaxes, semantic, and modeling and execution rules.

Processes: they depict how the strategy must be utilized for example how the partners must continue when considering commissioning tricky and how it is proposed to characterize and to set up a commissioning framework (outlined to conduct the commissioning) in stage with the building extend. Briefly, it waters and organizes the total set of systems engineering forms the venture demands. These forms are composed of different activities (to model, to check rightness, to assess, to optimize, to run tests, or to supply anticipated deliverable). Partners included in these exercises utilize at that point the proposed concepts and DSML of the strategy in a coherent way.

Tools: all along processes, they reinforce the proposed activities (modeling tools, simulation devices, optimization instruments). They execute the chosen DSML and must oversee all the information conducted and traded with other instruments which are for occasion committed to designing exercises.

Knowledge repository: usually a central component of the strategy that accumulates skill, encounters, design patterns (Pfister et al. 2012), and reference models. This permits clients to reuse different parts from past fruitful encounters at that point to reuse and design for occurrence existing models as of now utilized and approved, decreasing modeling terms, mistakes, or ambiguities. Without a doubt, it is essential to draw motivation from models considered as comparing to proven arrangements. On the opposite, it is additionally critical to require care and to draw motivation from models that compare accurately to arrangements that might not be connected or might not succeed. The objective is at that point to maintain a strategic distance from replicating certain past blunders and pick up time and execution.

Figure 2 presents the expected result of COGuiNF method when applied in various projects, showing the different interactions of the commissioning, the kind of interactions (refer to the caption), with systems engineering processes, Regulatory Body (RB), Inspection Organization (IO) and the NF owner and when they occur.

CONCLUSION AND PERSPECTIVES

This article has illustrated a formalization of commissioning which is a vital and unavoidable commitment. At this stage, the strategy called COGuiNF was presented to prepare and conduct important exercises for the commissioning of Nuclear Facilities. COGuiNF accepted the inalienable relations to be overseen between designing and commissioning goals. We believe that it will encourage, drive, and inundate framework designing System Engineering processes, taking into consideration model-based framework designing (MBSE) standards and practices. In addition, this article presented point by point the five components of the COGuiNF strategy. ■

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Simulation System Design Methodology in Extended Enterprise Context

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ABSTRACT

The use of Model-Based Systems Engineering and early Verification and Validation through simulations offers an effective way to manage the complexity of real-world industrial development projects. However, the modeling and simulation activities are often conducted in parallel, based on a common core of requirements. This can lead to a product model that does not conform to the simulation model, and vice versa, due to potential misinterpretation of requirements. To fill this gap and meet the objective of the simulation conformed to the model, we propose a new approach that considers communication between stakeholders of the Extended Enterprise and also between the simulations platforms.

CONTEXT AND PROPOSITION

An extended enterprise gathers partners with various competences to create an innovative product. The system architect of the product often needs simulations to ensure that the innovative product design meets the customer(s) requirements. However, the main difficulty is to realize simulation in the Extended Enterprise (ExE) context. So, the problems are multiple. It is necessary to consider the business specificities of each partner, and the architecture of the ExE simulation platform. To eliminate or at least minimize misinterpretation of requirements, one of the latest challenges is to organize and structure the dialogue between the partners.

In this work, we propose an approach to reduce these stated difficulties. The creation and modeling of the simulation platforms of each partner is a way to integrate their varieties, the scalability, and define the ExE's simulator architecture. For a clear and unambiguous dialogue between actor's roles, we propose to make the actors' activities independent of each other. For this independence to be effective, the exchanges between them are formalized. This formalized exchange integrates an end-to-end traceability of requirements: from the product's System Architect (SyA) to the creation of the simulator. This traceability should be able to remove doubts if the results of the simulation execution are not those expected. Finally, the intellectual property protection aspect is ensured by using the FMI (Functional

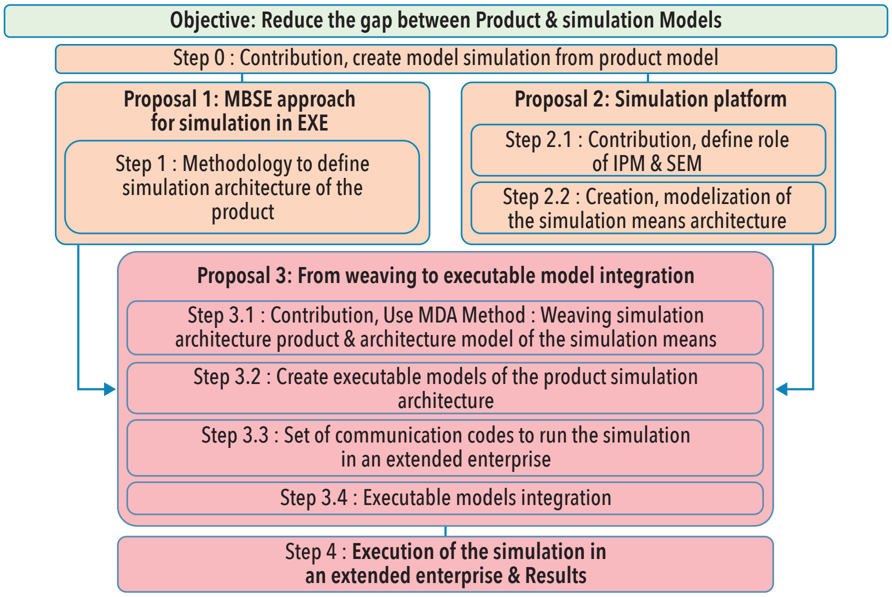

Figure 1: Overview of the contribution plan

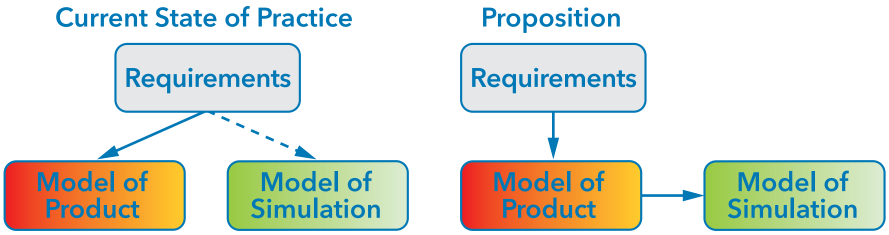

Figure 2: Reduce the gap between Product and Simulation Models

Mock-up Interface for Model Exchange and Co-Simulation, specification) 2.0 simulation standard (FMI 2014). This new approach to design a simulator in ExE is based on three axes (Figure 1) which represent our work plan:–the methodology in itself (Figure 1 and Figure 3: Proposal 1)–the creation of ExE simulation platform as a whole (Figure 1 and Figure 3: Proposal 2)–and from weaving to executable model integration (Figure 1 and Figure 3: Proposal 3).

II PROPOSAL OVERVIEW: GLOBAL METHODOLOGY

Often, simulation activities are performed in parallel with product modeling activities. However, this approach can lead to a product model that does not conform to the simulation model, and vice versa, due to potential misinterpretation of requirements (Figure 2).

This proposal (Figure 1: Step 0) (Leroux-Beaudout 2020) aims to bridge the gap between *Product* and *Simulation* Models (Figure 2: Right): from the set of requirements, the creation of the product model, followed by the creation of the simulation model. This approach has three advantages – the first should at least eliminate or minimize the gap between the product model and the simulation model; - the second creates a clear and seamless integration of simulation into the product development process, at system level; – the third is the continuous simulation aspect (in reference to the continuous integration term). The simulation model evolves with the product model.

Concretely, this proposal is based on a Model Driven Architecture (MDA) approach (MDA 2021) (Figure 3) and decomposed on three sub-proposals. The left part of the V (Figure 3: Platform Independent Model (PIM) and Figure 1: Proposal 1) represents the methodology: the communication between actors, the definition of a simulator, for a given set of simulation objectives. The right part (Figure 3: Platform Dependent Model (PDM) and Figure 1: Proposal 2) corresponds to the model of the ExE simulation platform, with the different execution units provided by each partner. The weaving of these two branches (Figure 3: Platform Specific Model (PSM) and Figure 1: Proposal 3) produces the ExE simulator model. This PSM includes all the information needed to run the simulator. The next section provides more details on the methodology by showing the three proposals broken down.

III PROPOSAL 1: MBSE APPROACH FOR SIMULATION IN EXTENDED ENTERPRISE

The objective of this proposal (Figure 1 and Figure 3: Proposal 1) is to create the conditions to give confidence in this approach, in order to remove the gap between the product and simulation models

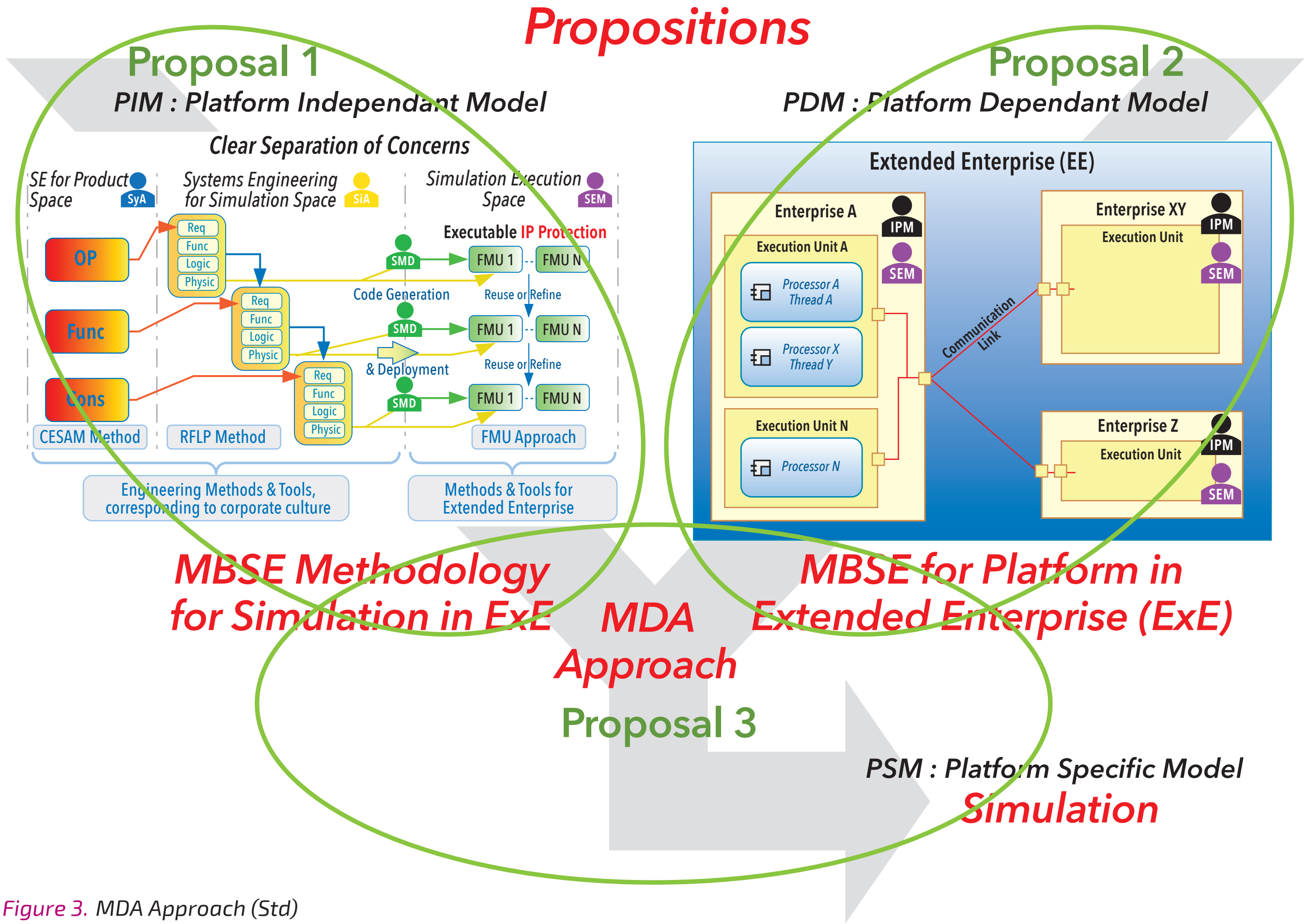

Figure 3. MDA Approach (Std)

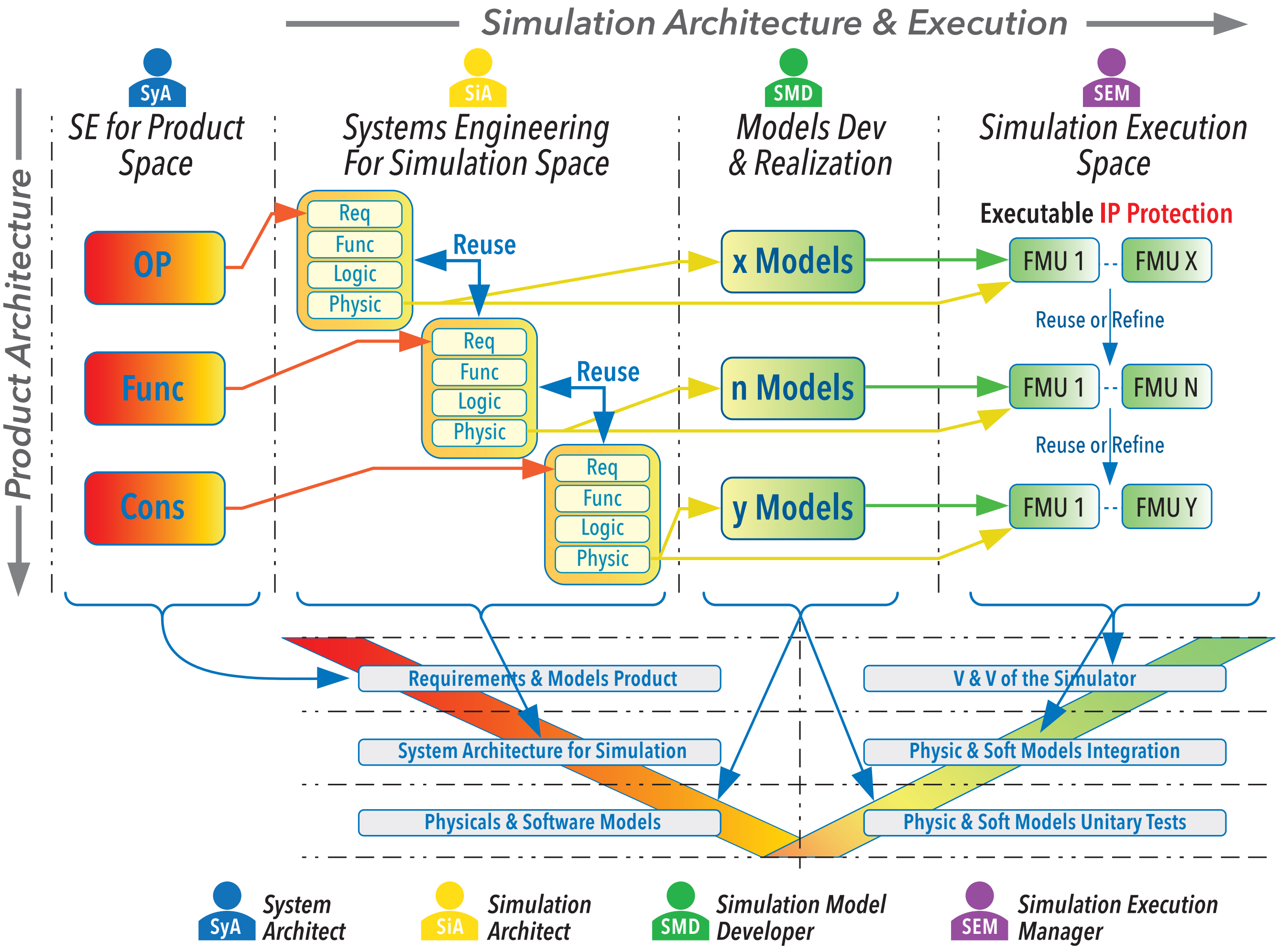

Figure 4. The simulation is a project in itself

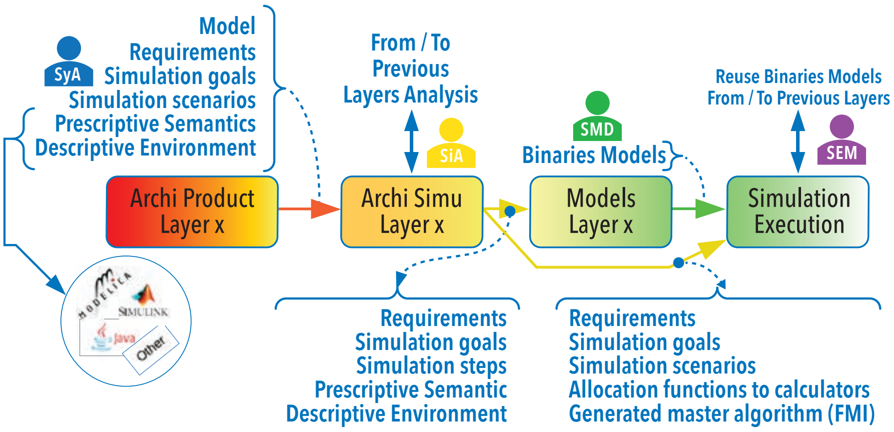

Figure 5. Formalized dialogue, continuity and traceability

The first condition is the independence of the actors among themselves (Figure 4 and Figure 5) (Leroux, Pantel, Ober and Bruel 2018a): the Product System Architect (SyA), the Simulation Architect (SiA), the Simulation Model Developers (SMD) and the persons in charge of the Simulation Execution Managers (SEM) in their own enterprise. In this way, no one can be the judge and jury, this means the one who does, does not test, and vice versa. The SyA create the product model, the SiA designs the simulation architecture, the SMDs create their executable models, and each SEM installs the executable models on its simulation platform. Only one of the designated SEMs runs the extended enterprise simulation. To ensure this independence, we formalize a clear and unambiguous dialogue between actors. This dialogue consists of data exchanges (Figure 5). At the beginning, the SyA receives customer requirements and is in charge of the product design and use the MBSE method of their company, for example CESAM (CESAM 2019) with Operational, Functional and Construction layers (Figure 4). The SyA, for each layer of its own method, can request a simulation from the SiA to ensure the accuracy of its architecture regarding the requirements. The SyA provides the necessary information (Figure 5): Model, Requirement (for traceability), Simulation goal, and more. This information becomes requirements for the subcontractor SiA. From the concept of independence, the SiA implements its own MBSE method, for example: Requirement, Functional, Logical and Physical (RFLP) layers (Figure 4) (Kleiner and Kramer 2013), so its role is multiple. The SiA defines the simulation architecture, and reduces, if possible, the simulation execution time. He adds the necessary adaptations to the simulation architecture when heterogeneous models are present (Leroux, Pantel, and Bruel

2017) (event-driven, sampled, continuous in time) in accordance with the SyA. The SiA assigns the simulation models to the execution units of each simulation platform, before generating all codes and information need by SMDs and SEMs. This assignment considers the knowledge of each partner. From the viewpoint of the SiA, the SiA designs a project: the end product of this project is a simulator. This approach is an advantage in the sense that this kind of project process of creating a product is well known in the industrial world (Figure 4: “V” cycle part): receive requirements from SyA, design and send requirements to equipment manufacturers SMDs and to SEMs, integration, and finally V&V. There is nothing new to learn, ergo, it is really an advantage in terms of time. This methodology can be implemented immediately. The SiA must consider the simulation platform of the ExE to assign simulation models to execution units of each partner. The following section, second proposal, highlights issues specific to the ExE simulation platform.

IV PROPOSAL 2: SIMULATION PLATFORM

The methodology allows us to define the simulation architecture and the simulation models in a formalized way. However, the execution of these models cannot be done without the presence of the simulation platform hardware and software resources. Depending on the hardware and software resources made available by the partners, this ExE simulation platform can be considered scalable. This is both an advantage and a disadvantage.

In both cases, this raises the question of synchronizing this scalability with the SiA. Another key point: sometime, the role of the person in providing a simulation platform is not clearly defined. The same applies to the manager to execute the simulation (SEM). These situations can lead to detrimental effects: –poor consideration of the costs associated with the creation/implementation of the simulation platform–or a misjudgment of the time required for the management and execution of the simulations with additional costs for the project. We propose to consider the creation of an ExE simulation platform infrastructure as an industrial project, with classical approach. To manage this platform creation, we define the role of a new actor: the Infrastructure Project Manager (IPM). The simulation execution in the ExE needs the collaboration and synchronization of each partner simulation platform. For this purpose, we define another new role actor: the SEM.

IMP Role (Leroux-Beaudout 2020). The IPM (one by company, Figure 6) oversees the definition up to the V&V of its own simulation platform. However, its role is much broader. He must ensure, directly or by delegation, for example the protection of people, the implementation of means against intrusions: viruses, hackers. The IPM must also coordinate with their counterparts the creation of communication links of the ExE. In our experience, and depending on the security policy of each company, setting up a communication link with the related access rights can really take a long time and therefore delay the availability of the ExE simulation platform. This is the reason, among the first actions to be carried out, IPMs must deal with non-disclosure agreements and the definition of communication means: VPN, IP address, and more.

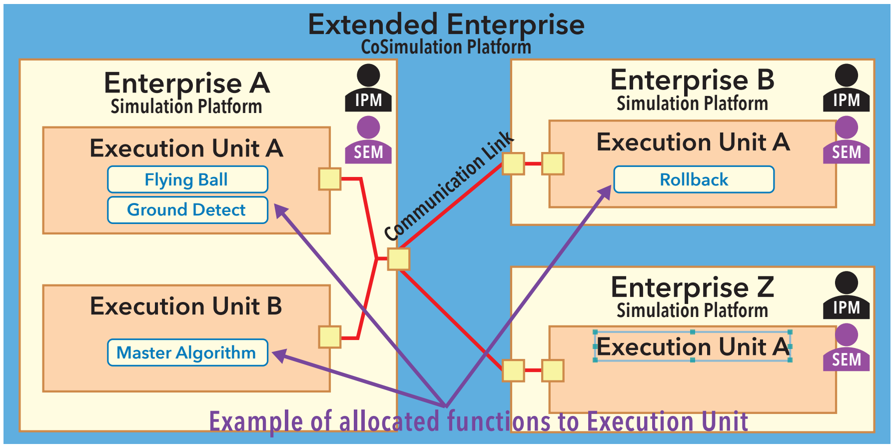

Figure 6. ExE simulation platform

SEM Role (Leroux-Beaudout 2020). The first activity of the SEM (one per company) is to integrate and V&V the set of hardware and software means of its own simulation platform. The second activity is to participate with their counterparts in the V&V of the ExE simulation platform, under the responsibility of IPMs. The next role of the SEM, by virtue of its duties, is responsible of the integration and execution of the simulation model on its own platform. The SEM receives integration scenarios from the SiA and coordinates also with its ExE’s counterparts for the successive integration of the global simulation model (Figure 4). The SEM also informs the developers (bug at runtime), provides the results of the simulation to the SiA. It is up to the SiA to inform the client: the SyA. Another important function of the SEM inside their company is to manage, organize models, their version, and associated documentation. The next section, the third proposal, weaves the first and second proposals.

V PROPOSAL 3: FROM WEAVING TO EXECUTABLE MODEL INTEGRATION

At this stage, SiA has defined its architecture, specified FMI APIs (FIM 2014) (Leroux, Pantel, Ober and Bruel 2018b) of each simulation functions, and assigned functions (Figure 6) on execution unit models of each partner. The ExE simulation platform model (Figure 6) come from the right branch of the MDA approach (Figure 3 and Figure 1: Step 2.2). The SiA can now weave its architecture and the ExE simulation platform model to produce code and information for the SMDs and SEMs. The SMD creates the simulation executable models (Figure 1, Step 3.2) with their own development method (the independence principle of the actors), do their unit test (Figure 4) and then transfers the executable models to their company SEM (Figure 5). In parallel, the SiA generates codes and requirements for the SEMs. The code consists of the master algorithm which translates the simulation scenarios provided by the SiA for the integration of the simulation models and by the SyA for the simulation of its product architecture. This code also contains all the “glues” to implement the communications between the simulation platforms (Figure 1: step 3.3). The SiA informs the SEMs on which execution units the models should be positioned (Figure 5, Figure 6). The SEMs is to integrate the executable simulation models with each other (Figure 4 and Figure 1: step 3.4). When the simulator (models + means, of the ExE) is V&V, the simulation scenario, provided by the SyA, can be executed (Figure 1: step 4).

VI EXECUTION AND RESULTS

The product System Architect wants to ensure that its architecture is relevant to the customer’s requirements. The SyA can trust the results obtained, on the fact that the simulation means are V&V as for any industrial project (Figure 3: Proposal 2). This confidence can be strengthened as the different parts of the simulation model have been subject to another project approach: from requirements to V&V (Figure 4). It is important to note: if the result of the simulation does not comply with the requirements, the problem comes from the architecture or parameters of the product model, and it is not from the simulator. Indeed, the means and models of simulation have already been verified and validated separately and together.

The method to create simulation models in the ExE is based on the product model. For this goal we have proposed three contribution axes, which are "*MBSE approach for simulation*," "*simulation platform*," "*weaving the MBSE for simulation and platform model*." This MBSE approach for simulation considers the different actors as independent between them. To ensure this independence, it was necessary to define a formalized dialogue between them. In addition, this dialogue allows a seamless integration of simulation models into the product design process. The extended simulation platform must specify the roles of two new actors: the infrastructure project manager, and the simulation execution manager. This precision is an important advantage because these two new profiles can be added to the human resources catalog and should allow more accurate project budget evaluations. Finally, this approach can be implemented immediately and does not require any changes in the classic project management process of a company. It improves the dialogue between the stakeholders of the simulation.

VII PERSPECTIVE

In the perspective term, it would be interesting to implement this methodology to do simulation at the physical layer, with Hardware in the Loop devices. With those conditions, what would be the modifications to be made to this methodology? In simulation context at the physical layer, performing qualimetry (Argotti, Baron, and Esteban 2019) on the structure of the simulation model should be able to improve the simulation time or the quality of the results. Another perspective would be to ensure the resilience of the simulation platform to disturbances that could affect the simulation performance (Moradi, Daclin, and Chapurlat 2018). ■

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Intensive Data and Knowledge-based Approach for Sustainable and Circular Industrial Systems

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ABSTRACT

The circular economy and its various recirculation loops have become a major study subject over recent years, particularly the transformation of the actual processes into sustainable processes. However, these environmental analyses require a huge quantity of data: foreground data and background data. The collection of these data can be long and tedious. Nevertheless, an increasing number of scientific articles describe the processes, which is a great source of data. This source of information is heterogeneous but big data tools can be used to compile, process and analyze them.

Following this perspective, this paper focus on the creation of methodological framework centered on intensive data and knowledge for an economically viable and ecologically responsible design of industrial processes or systems. Composed of five steps, this approach is oriented towards offering decision support for the researcher or R&D engineer during systems requirements and high-level design steps of V-model. It is implemented within the domain of pre-treatment processes for corn stover.

KEYWORDS: Data Sciences, Sustainability, Circular Economy, Biorefinery System, Life Cycle Thinking, Machine Learning

1. INTRODUCTION

In the industrial field, the circular economy has become a major subject over recent years. A lot of research is being done to transform the actual processes into sustainable processes: environmentally responsible, economically viable, and socially accepted (Santoyo-Castelazo et Azapagic 2014). The environmental and economic analyses require a lot of specific data, for which the collection can be long and tedious, or simply impossible in practice. On the other hand, increased data and knowledge (public or private) are available describing industrial processes, in particular through scientific articles or internal databases. However, the data from the web (public or private) does not constitute an easy-to-use database.

The goal of our approach is the development of a methodological framework centered on intensive data and knowledge for an economically viable and ecologically responsible design of industrial processes or systems (Belaud et al. 2019). This approach compliant with life cycle thinking is defined by five steps: (1) goal and scope, (2) data architecture, (3) life cycle inventory, (4) sustainability assessment and (5) visualization and analysis of results. It is a process systems engineering approach which is both model-oriented–through impact assessment models, foreground data/knowledge model (ontology), phenomenological model of process engineering and empirical model of production–and technology-oriented with the addition of Big Data tools. According to V-model, our approach is located on the left side of the "V" namely the "Systems Requirements" and "High-Level Design" parts (Blanchard and Fabrycky 2010). That is a part of "System Analysis" according to the ISO/IEC/IEEE 15288 technical processes *"The purpose of the System Analysis process is to provide a rigorous basis of data and information for technical understanding to aid decision-making across the life cycle* (ISO 2015)." The results of our approach provide added-value information in the frame of a decision management process. Our approach facilitates the integration of environmental issues as of high-level design, making use of concepts from industry 4.0 and sustainability management.

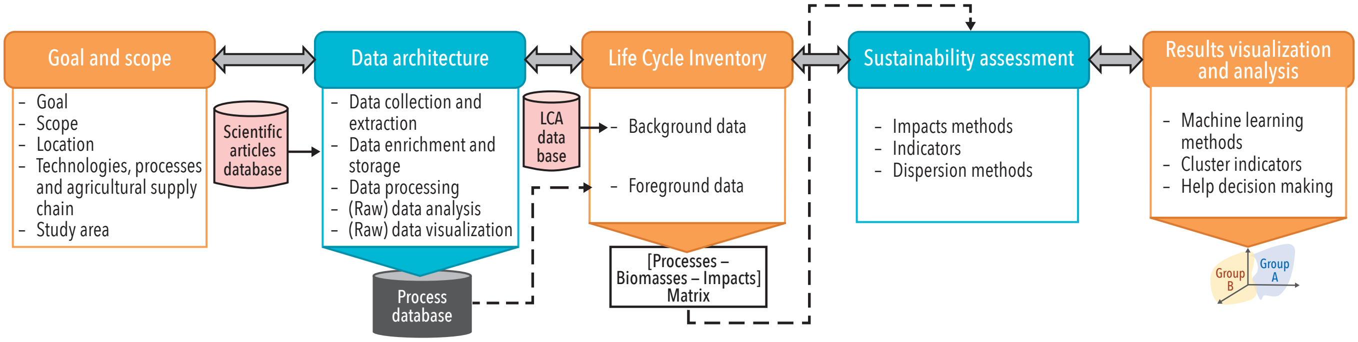

Figure 1: Five-steps approach schema

2. APPROACH DESCRIPTION

The first step of our approach defines the *goal* of the study and the boundaries of the system. A life cycle thinking is recommended for the system. It encourages a “from cradle to grave” or “from cradle to gate” approach. In the circular economy model, the part of the life cycle in which the product is used is a key element for progress towards ecological transition. “From cradle to gate” approaches are often preferred because the integration of downstream elements into sustainability analyses can be tedious and difficult. The second step consists of the treatment of the processing of data from scientific articles or private databases. The *data architecture* is directly inspired by the construction of big data architecture and consists of five sub-steps: (i) data collection and extraction, (ii) data enrichment and storage, (iii) data processing, (iv) (raw) data analysis, and (v) (raw) data visualization. The last two sub-steps (iv) and (v) take benefit from methods derived from machine learning (ML). The third step, *life cycle inventory*, lists and quantifies the various relevant inputs and outputs. It is possible to categorize the required data in two parts: the background data and the foreground data. The background data is available into specific databases like Ecoinvent, and the foreground data is the process data from the previous step. The fourth step, *sustainability assessment*, involves choosing the impact methods, the indicators, and the dispersion methods in accordance with each area of sustainability management. At the end of this stage, the main result is a structure [processes: biomasses: impacts] which is difficult to analyze. The last step, *results visualization, and analysis*, provides the methods derived from artificial intelligence (AI) and more precisely, from “machine learning” to help in the analysis of sustainability impacts. Starting from the statistical literature, traditional downsizing and unsupervised clustering techniques are combined to extract information of sustainability analysis. More precisely, this hybrid approach is based on the Multi-Dimensional Scaling using the Canberra distance and k-means (Lance et Williams 1966). The objective is to search for “hidden” structures in multidimensional data and to help interpret the area of clustered midpoints in the Life Cycle Impact Assessment (LCIA) evaluation matrix. The advantage of this approach is that database methods require little knowledge of processes to perform this task. At the end of this step, the analysis and the visualization of results can help group-based decision-making by experts.

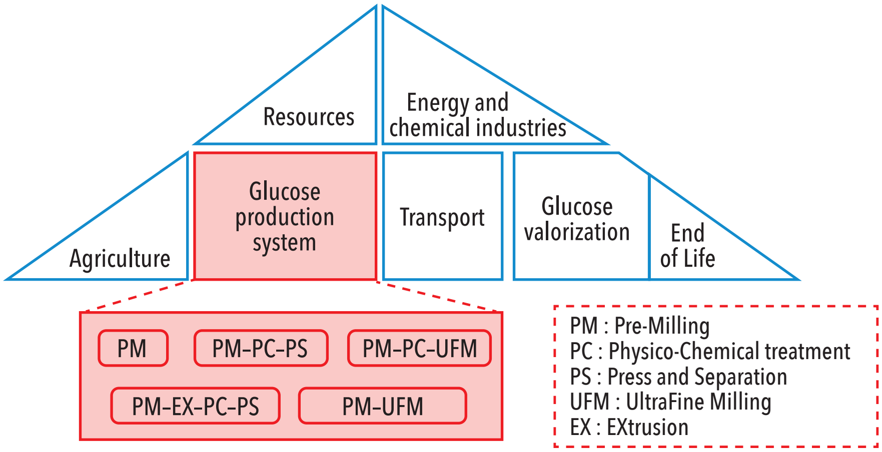

Figure 2. System life cycle

3. CASE STUDY

The case study is in the agro-industrial field: the valorization of the lignocellulosic biomass from agriculture. The goal of the study is to access different technological systems and biomass for the glucose production. In the Figure 1, we present the glucose production system and the different interacting systems in System Life Cycle. In our case study, five types of processes are studied in the glucose production system, and they are designed by their different succession of unit operations.

The system boundary is “from cradle to gate,” from the biomass–considered as waste – to the final product, the glucose (Figure 2). As biomass is here a waste (destined to become a co-product) of agriculture, it has a zero impact – the impacts of the agricultural phase are attributed to the end product of agriculture (corn). The biorefinery is close to the site, and therefore the transport stage is negligible.

Eighteen articles are initially selected and extracted from scientific databases such as Web of Science and Science Direct. Article data is extracted semi-automatically in an ontology. It is possible to do an assessment of document reliability thanks to the ontology. Each scientific article is entered in the ontology with its meta-information (source type, reputation, citation data). This meta-information allows data scientists to calculate a reliability score per article (Belaud et al. 2021). The ontology structures the process data and ensures an export in CSV files supplying internal software. This software developed on Microsoft Excel conducts a first “cleaning” of the data by simulating the processes to calculate and check the mass balance. This cleaning can consist of the deleting or changing of values. For example, the data from three articles were removed from our study because they contained inconsistencies or many missing data points that are not amenable to be verified by the simulation. The study therefore analyzes 15 processes of a biomass (corn stover). The

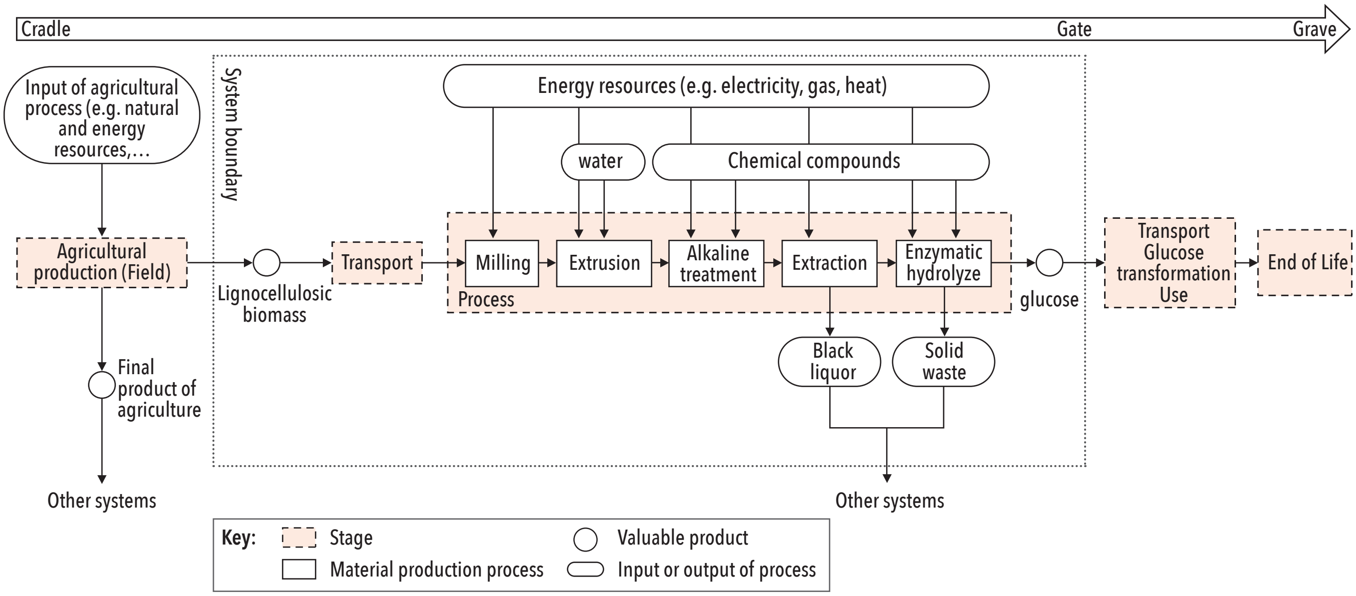

Figure 3. Biomass pre-treatment system

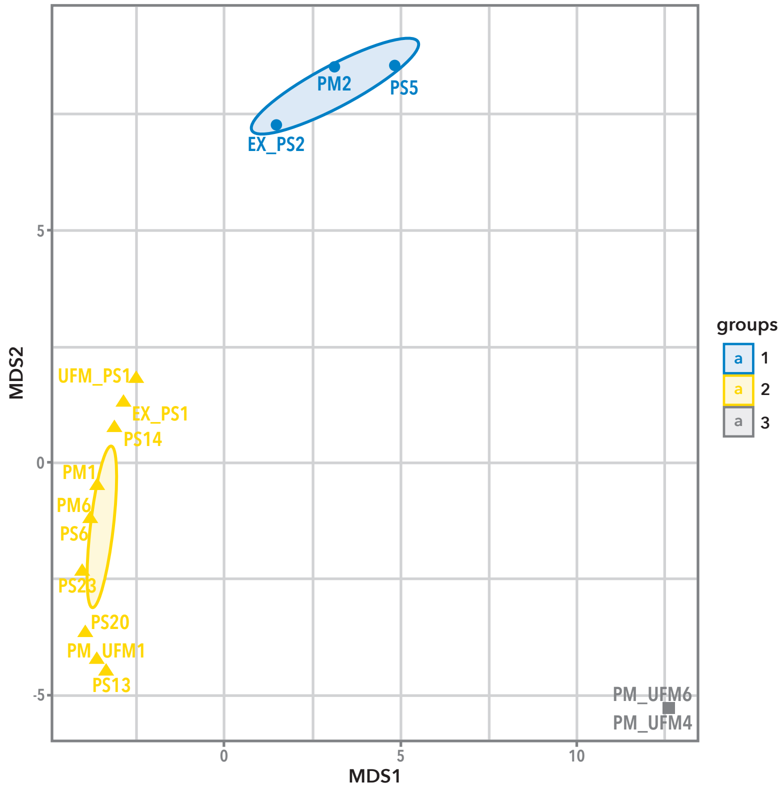

Figure 4. Projection Scatterplot (MDS) and k-mean clustering based on process distance matrix

(attributional) life cycle assessment method applied is ReCiPe 2016, the background database is EcoInvent v2.2 and the foreground data are "cleaned" process data. The environmental assessment leads to the calculation of 17 so-called "midpoint" impacts (Belaud et al. 2021).

The environmental assessment gives access to a "process-impact-biomass" matrix which is analyzed by multidimensional scaling using the Canberra distance and k-means thanks to R software. The two-dimensional of multidimensional scaling results of projected impacts is shown in Figure 4. We have represented the projection of the 17 impacts on the first two dimensions multidimensional scatterplot (MDS1 and MDS2) which represent a total variance of 45%. The acronyms captioning the dots represent each type of technological systems. In group 3, for example, there are two purely mechanical pre-treatments (PM-UFM for "pre-milling and ultra-fine milling"). Going back to the impacts, we find that these two pre-treatments have a significant impact on the depletion of fossils compared to the others. For Group 1, the three pre-treatments have similar impacts. For all impacts and for fossil depletion, the impact costs around $10, whereas group 2 pre-treatments have an impact costs around $1. Finally, through the case study, the approach provides an initial insight to sort by groups and to establish a way to pre-select technological systems by experts.

4. CONCLUSION

In conclusion, our approach allows for time savings, decreased expertise and no direct experimental implementation for the choice of a pre-treatment process design. Several limitations have been identified: (1) The data from the scientific literature are by nature data from a series of batch experiments in the laboratory. The life cycle analysis (LCA) is therefore performed for a low level of technology readiness level (TRL) or maturity (TRL 1/2) (2) the approach does not integrate the change of scale required to implement a semi-industrial pilot, especially if the process becomes semi-continuous and (3) the abundance and the quality of the data are not sufficient for these new technological processes. Other points for progress are to reconsider the functional unit, the global environmental assessment strategy by integrating the upstream agricultural phase (consequential LCA, system allocation and system extension policy) and considering the global supply chain according to a dynamic analysis, spatial, or even temporal. ■

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Venue – The conference will be organized in the university facilities on the Gløshaugen campus, south of the city center, and in walking distance of the city center. The campus is accessible to persons with disabilities, and the university hospital is across the street in case of a medical emergency. Our web site will contain more information and maps of Trondheim and the campus.

Accommodation & Travel

Trondheim is the third largest city in Norway with ample accommodations, restaurants, pubs, and cafés. There are many web pages in English that cater to visitors such as visittrondheim.no/en. The city of Trondheim offers a wide range of hotels. Special rates will be negotiated and listed on our website. Trondheim Værnes Airport (TRD) has many daily international connections, and most travelers are most likely to arrive from a major hub airport, such as Copenhagen or Amsterdam. The main operators are SAS, KLM, and Norwegian. The airport bus (Flybussen) brings you to the center of town in approx. 35 minutes. The city also has excellent public transportation and abundant taxi services.

Mark your calendar

March 24–26, 2022: Norwegian University of Science and Technology
Ttronheim, Norway
March 24: PhD colloquia Systems Engineering and Architecture Network (SEANET)
March 25–26: Conference on Systems Engineering Research

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