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NII Shonan Meeting Report

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Using Multi-* Modelling to Manage Complexity in Systems Engineering

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March 10 – 14, 2025

National Institute of Informatics
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Using Multi-* Modelling to Manage Complexity in Systems Engineering

Organizers:
Prof. Fuyuki Ishikawa (National Institute of Informatics, Japan)
Dr. Stefan Klikovits (Johannes Kepler University Linz, Austria)
Prof. Hans Vangheluwe (University of Antwerp and Flanders Make, Belgium)

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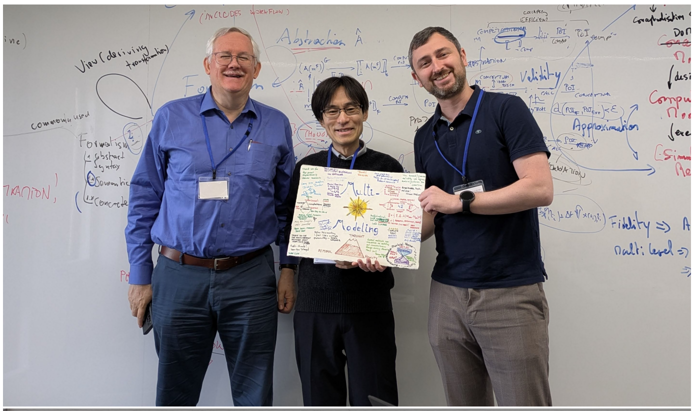
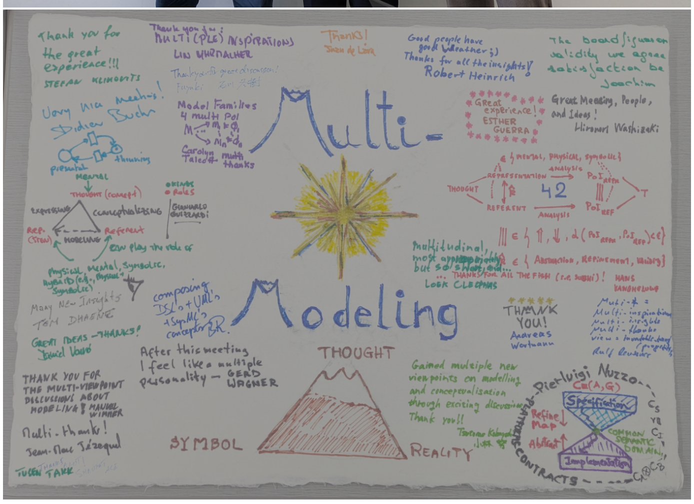




dates of the meeting;

Background and introduction

Recent decades saw the complexity of modern engineered systems raise to never-before-seen heights. Developments such as Smart Grids, the Internet-of-Things, Cyber-Physical Systems and Machine Learning open new opportunities, but also pose new challenges for systems engineers who have to integrate and navigate through a highly diverse network of application and computation nodes. Ranging from huge cloud services to powerful edge devices such as autonomous vehicles, systems creators simultaneously have to choose how to build, structure, maintain and certify their systems' functionality. After all, non-functioning cloud services might impact the lives of millions of users and involve enormous financial loss, while bringing highly autonomous agents (e.g. self-driving vehicles or delivery robots) and consumer health applications (e.g. pacemakers) have the potential to severely threaten human safety, health and life, if mismanaged.

The systems modelling and engineering community is at the forefront of developing solutions to manage this complexity. Models provide means to abstract over details, at different levels, and interact with specific "system views". Having created tools and formalisms to design and analyse such systems, the recent rise in complexity also affects this domain. Starting from the conceptualisation of Multi-paradigm Modelling (MPM), which proposes to "model every part and aspect of a system explicitly, using the most appropriate modelling formalism(s) at the most appropriate level(s) of abstraction", this multiplicity is nowadays expanded to various other parts of the modelling discipline.

Primary Topic

Modern systems typically require the management and synchronisation of many system views, where each stakeholder may require many different perspectives of a system. These views further impose different levels of abstraction using different modelling formalisms, to be effective. In addition to this complexity aspect, especially in large physical systems and systems-of-systems, the use of different abstraction levels introduces the need for dealing with different levels of fidelity as with growing abstraction levels the necessary lack of details can be modelled as uncertainty. In concert, these multiplicities (i.e. multi-* aspects such as multi-paradigm, multi-view, multi-abstraction, multi-fidelity, etc) require careful consideration, demanding sophisticated approaches, well-defined methodologies and the development of new modelling techniques and tools that support researchers and practitioners in the development of the next generation of large and complex systems. This requires the combination of various approaches ranging from classical formal methods and abstraction to the development of novel methods that include (but are not limited to) probabilistic fidelity and uncertainty modelling, surrogate modelling and substitutability, model adaptability and evolution, as well as the incorporation of AI to foster model understandability and explainability.

Meeting Objective

This meeting brought together systems modelling, engineering and formal methods experts from academia, featuring and taking a special focus on the complexity of modern systems engineering, to discuss how to design new engineering practices, especially for complex systems. Our goal is to deepen the understanding of the different kinds of multiplicities that modern systems engineering and systems modelling including multi-stakeholder, multi-domain, multi-formalism, multi-abstraction, multi-view and multi-fidelity modelling, learn from one another and develop a practical skill set to apply in the next generation of complex systems. Systems modelling covers a vast domain, ranging from model-based systems engineering to formal modelling and verification, to model-driven DevOps processes, where each sub-community discovers novel techniques for their domain problems. The objective is to think out of the box and come up with a coherent vision for research on systems engineering in the next decades.

The meeting was a great opportunity to gather world-leading researchers who pushed the forefront of the state-of-the-art and achieved new results over the past few years, so that we could further exchange novel ideas and techniques, learn from one another, and promote this truly important research direction and its industrial applications, together conquering the currently urgent demand of managing the multiplicities of modern systems.

Overview of the meeting

The NII Shonan Meeting "Using multi-* modelling to manage complexity in systems engineering" took place in Shonan, Japan from March 10th to March 14th, 2025. The seminar was organized by Fuyuki Ishikawa (National Institute of Informatics, Japan), Stefan Klikovits (Johannes Kepler University Linz, Austria), and Hans Vangheluwe (University of Antwerp and Flanders Make, Belgium). We hosted 24 participants from across the globe, bringing together a diverse range of expertise in systems modelling, engineering, and formal methods.

The meeting opened with six tutorial-style presentations that established a shared foundation for the subsequent discussions. Hans Vangheluwe introduced the principles of multi-paradigm modelling (MPM), Carolyn Talcott described the challenges of multi-abstraction, Adelinde Uhrmacher presented concepts on multi-level modelling, Pierluigi Nuzzo discussed contract-based design, Tom Dhaene provided insights into surrogate modelling, and Giancarlo Guizzardi examined the role of ontologies and conceptual modelling.

Building on these introductions, the meeting transitioned into intensive, structured group discussions divided into three phases. The first phase was exploratory, allowing participants to identify and map key challenges and themes; the second phase focused on bridging topics, fostering connections across different modelling perspectives and methodologies; and the third phase emphasized refinement and exploitation, with the goal of shaping concrete research directions and practical strategies for managing complexity in modern systems engineering.

The discussions throughout the seminar highlighted the importance of developing a coherent and integrated vision that embraces modelling multiplicities—such as multi-view, multi-abstraction, multi-formalism, and multi-fidelity—and emphasized the need for sophisticated methodologies, tool support, and interdisciplinary collaboration. A traditional Shonan seminar outing complemented the technical program, featuring visits to the Jomyoji and Hokokuji temples and a Japanese tea ceremony, offering participants both cultural immersion and opportunities for informal exchange.

Overview of talks

The seminar opened with six in-depth, tutorial-style presentations delivered by leading experts, each providing foundational insights into key modelling concepts and challenges central to managing complexity in modern systems engineering.

Multi-Paradigm Modelling (MPM)
Modelling Language/Tooling Engineering

Hans Vangheluwe, University of Antwerp and Flanders Make, Belgium

This talk first introduces general modelling concepts, in particular the notions of model validity and validity frame. Then, modelling formalisms with their syntax and semantics are introduced. This forms the starting point for an introduction to multi-formalism, multi-component, (multi-)abstraction, and (multi-)view modelling. Subsequently, the notion of (in-)consistency in collections of models is introduced. The notion of co-simulation is introduced and finally, the need for co-development of design-, trace-, input-, behaviour-, requirements-, ... languages, in particular when designing domain-specific languages, is explained.

Multi-Abstraction Modelling

Carolyn Talcott, SRI, USA

This talk will address the question: "What is abstraction?" It will discuss the many facets and roles of abstraction in modeling including: what is being abstracted, the properties of abstraction, the uses of abstraction. A sampling of cases will be illustrated by examples. The talk will conclude with some challenges in the context of multi-modeling.

Multi-level Modelling

Adelinde Uhrmacher, University of Rostock, Germany

In this talk, based on the definition of multi-level models and the role of upward and downward causation, I will move through the modeling and simulation life cycle and discuss some of the methodological challenges encountered. First I will shortly discuss two approaches for multi-level modeling. After that I will move to simulation experiments which rely on efficient simulation algorithms and suitable data, to finally look how to interpret possible simulation results.

Contracts for System Design

Pierluigi Nuzzo, University of California, Berkeley, USA

Designing complex systems by integrating components from various providers is a significant challenge. The frequent recalls and re-certifications in industries like automotive and aerospace underscore the inherent difficulties in system design. As a result, experts from government, industry, and academia have called for the development of both theoretical and practical tools to ensure the correctness of complex engineered systems. Assume-guarantee contracts offer a robust theoretical and methodological framework for compositional system design with rigorous correctness guarantees. Each component in a system is associated with a contract, which clearly defines the expected interactions between the component and its environment. These contracts specify the assumptions the environment must meet and the guarantees the component will uphold in response. The overarching goal of contract-based design is to enable modular reasoning, stepwise refinement, and principled reuse of components, and facilitate the analysis, verification, and even synthesis of complex systems integrating multiple components, views, and abstraction layers. In this talk, I will introduce contracts and their algebraic operations and illustrate their use with examples from requirement engineering and certification of avionics systems.

Surrogate Models

Tom Dhaene, Ghent University, Belgium

Surrogate models and digital twins are transformative methodologies in engineering that enhance the design, optimization, and predictive capabilities of complex systems. Surrogate models, often referred to as emulators, approximation models or response surface models, provide efficient mathematical representations that simplify the computationally intensive tasks associated with simulating real-world processes, enabling engineers and scientists to optimize designs and predict outcomes with significantly reduced computational costs and time. Meanwhile, digital twins serve as real-time digital replicas of physical objects or systems, allowing for monitoring, analysis, and performance optimization in various sectors, including manufacturing, healthcare, and urban infrastructure. The integration of surrogate models with digital twin technology amplifies their effectiveness, as surrogate models streamline the computation involved in the digital twin simulations, thereby facilitating rapid scenario analysis and performance evaluations without the need for exhaustive real-world experimentation.

Ontology-Driven Modeling: From Theory to Tools

Giancarlo Guizzardi, University of Twente, The Netherlands

In this talk, I will discuss the role of ontologies (as formal reference representations of domain conceptualisations) in the design of modeling languages. I demonstrate how an ontological theory can systematically guide the design of the syntax as well as semantics of modeling languages. Moreover, I discuss how languages that break with ontological neutrality become pattern languages, and the advantages of that. Finally, I illustrate this approach by demonstrating how the OntoUML language and its tool ecosystem has been designed according to the Unified Foundational Ontology (UFO).

List of Participants

- Dr. Shaukat Ali, Simula Research Laboratory, Norway
- Prof. Didier Buchs, University of Geneva, Switzerland
- Prof. Loek Cleophas, Eindhoven University of Technology, The Netherlands
- Prof. Tom Dhaene, Ghent University, Belgium
- Prof. Joachim Denil, University of Antwerp, Belgium
- Prof. Juan de Lara, Universidad Autonoma de Madrid, Spain
- Prof. Esther Guerra, Universidad Autonoma de Madrid, Spain
- Prof. Giancarlo Guizzardi, University of Twente, The Netherlands
- Dr. Robert Heinrich, Karlsruhe Institute of Technology, Germany
- Prof. Jean-Marc Jézéquel, University of Rennes, France
- Prof. Fuyuki Ishikawa, NII Tokyo, Japan
- Dr. Tsutomu Kobayashi, Japan Aerospace Exploration Agency, Japan
- Dr. Stefan Klikovits, Johannes Kepler University, Austria
- Prof. Pierluigi Nuzzo, University of California, Berkeley, USA
- Prof. Ralf Reussner, Karlsruhe Institute of Technology (KIT), Germany
- Prof. Bernhard Rumpe, RWTH Aachen, Germany
- Dr. Carolyn L. Talcott, SRI, USA
- Prof. Adelinde Uhrmacher, University of Rostock, Germany

- Prof. Daniel Varró, Linköping University, Sweden
- Prof. Hans Vangheluwe, University of Antwerp and Flanders Make, Belgium
- Prof. Gerd Wagner, Brandenburg University of Technology, Germany
- Prof. Hironori Washizaki, Waseda University, Japan
- Prof. Manuel Wimmer, Johannes Kepler University, Austria
- Prof. Andreas Wortmann, University of Stuttgart, Germany

Meeting Schedule

Check-in Day: March 9 (Sun)

- Welcome Banquet

Day 1: March 10 (Mon)

- Opening & Welcome from the Organizers
- 2-minute introductions by the participants
- Group Photo Shooting
- Tutorial-style opening presentations
- Selection of Discussion Topics & Formation of Groups

Day 2: March 11 (Tue)

- Discussions in Groups (Exploration Phase)
- Merging of Results

Day 3: March 12 (Wed)

- Discussions in Groups (Bridging Phase)
- Excursion and Main Banquet

Day 4: March 13 (Thu)

- Discussions in Groups (Exploitation Phase)
- Merging of Results

Day 5: March 14 (Fri)

- Planning on Follow-up Tasks
- Post-mortem & Wrap up

Summary of discussions

Initial Term Collection

Before the formal discussion phases began, participants collaboratively compiled a list of key terms and concepts central to modern systems modelling and engineering. This shared vocabulary served as a foundation and inspiration for forming the thematic focus of the initial discussion groups.

Phase 1 – Exploration and Definition of Core Concepts

In the first discussion phase, participants split into three thematic groups. Each group investigated a set of related terms, aiming to unpack definitions, identify overlaps, and surface ambiguities or tensions between concepts.

Group 1: Domain, View, Abstraction, Formalism

This group explored how different system domains influence the modelling views, levels of abstraction, and the formal languages or frameworks used to represent them. Particular focus was given to the interdependencies among these concepts and their implications for model consistency and transformation.

Group 2: Scale, Accuracy, Approximation, Fidelity

Group 2 investigated how system scale impacts modelling accuracy, and how approximation techniques and levels of fidelity play roles in abstracting real-world behaviours while maintaining trustworthiness and utility in simulation and analysis.

Group 3: Conceptualization, World View, Paradigm

The third group examined foundational modelling assumptions and how underlying paradigms and world views shape the way systems are conceptualized. This included discussion on epistemological implications and the alignment (or clash) of mental models across domains.

Merging and Alignment

Following the group sessions, findings were presented and compared in a plenary discussion. Participants aligned definitions, clarified conceptual overlaps, and began identifying connections between the thematic areas addressed in each group.

Phase 2 – Bridging and Merging

In the second phase, participants reorganized into new cross-functional groups, ensuring each group included representatives from the previous phase's discussions. The goal of this phase was to identify imprecisions, resolve terminological inconsistencies, and surface potential integration points across the previously discussed concepts.

Cross-group Refinement

The smaller groups engaged in critical reflection on the earlier findings, questioning assumptions and evaluating the clarity and applicability of each term. This phase emphasized mutual understanding and precision in language, with a focus on practical relevance and interoperability between modelling approaches.

Collective Synthesis

The groups reconvened to present refinements and conceptual bridges, setting the stage for more applied and forward-looking synthesis in the final phase.

Phase 3 – Exploitation and Refinement

The final phase of the seminar focused on applying the insights from earlier discussions into practical workflows and frameworks, while also synthesizing the core concepts into a unified understanding that could guide future research and practice.

Group A: Engineering Workflow

This group focused on developing workflows that integrate the various modelling concepts discussed in previous phases into the engineering process. They explored how to incorporate multi-view modelling, abstraction, fidelity, and formalism into a structured engineering workflow. The group aimed to identify key stages in system design, development, and verification where these concepts could be operationalized to support engineers in building more robust, adaptable, and verifiable systems.

Group B: Scientific Workflow

The second workflow group turned its attention to how these modelling concepts could be applied within scientific workflows. They considered how multi-abstraction, surrogate modelling, and contract-based design could facilitate scientific investigations into complex systems, particularly in fields like cyber-physical systems, AI, and materials science. The focus was on identifying steps in the scientific inquiry process where these methodologies could improve model understandability, accuracy, and reproducibility.

Group C: Unification of Concepts

The third group worked on synthesizing the findings from Phase 1 and Phase 2, aiming to unify the various terms and concepts into a comprehensive framework. This group worked closely to ensure that all previously discussed terminology (e.g., abstraction, fidelity, formalism, paradigm) was clearly defined and interconnected. The goal was to produce a glossary that not only captured the meaning of each term but also highlighted their relationships within a larger conceptual framework. This would serve as a reference for future research and collaboration, helping to ensure consistency in the application of modelling methodologies.

Group D: Glossary and World View

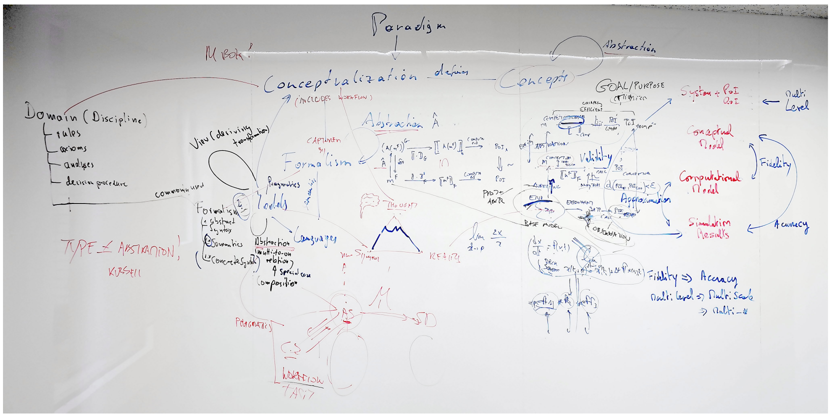
The final group consolidated the results of all previous discussions, focusing on creating a coherent "world view" of systems modelling. This group synthesized the diverse modelling approaches into a unified framework, making explicit the relationships between concepts such as domain, view, abstraction, formalism, fidelity, and paradigm. The outcome was a structured glossary that tied together the various perspectives explored during the seminar, with the goal of offering a conceptual map that could guide both future research and practical application in complex systems engineering.

Summary of new findings

Phase 1 – Exploration and Definition of Core Concepts

In the first phase, three groups collected definitions of and relations between various terms discovered in the preliminary phase.

Subsequently, the merging and alignment led to the following "unified view".



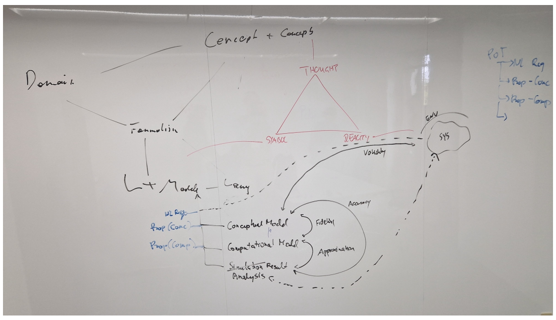
Phase 2 – Bridging and Merging

In the second phase, the reshuffled groups reviewed and corrected (parts of) the "unified worldview".

Group 1

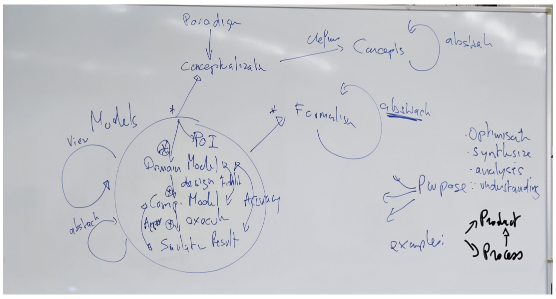
The first group integrated the semiotic triangle into the view of domains, concepts, formalisms, languages + models, and systems.

They also extended this view by defining validity, accuracy, fidelity and approximations to various levels of models.



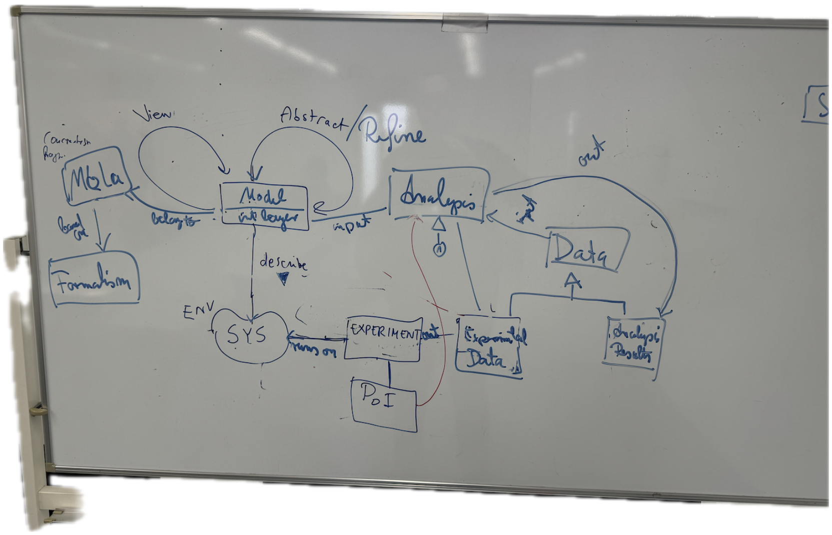
Group 2

Group two, similarly, looked at the same aspect, but came to a slightly different view of the same results. Their results are somewhat more operation-driven, placing specific tasks more prominently.



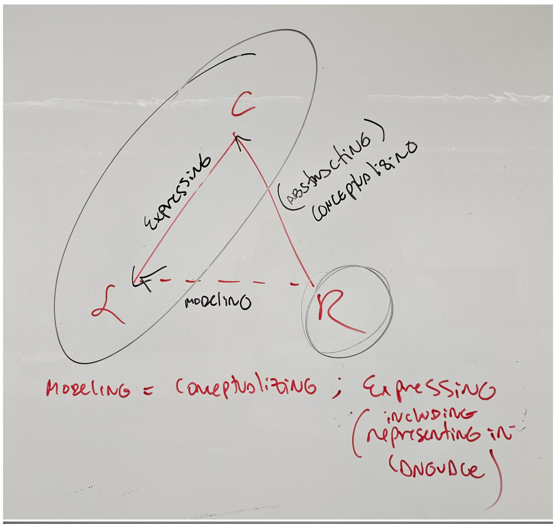
Group 3

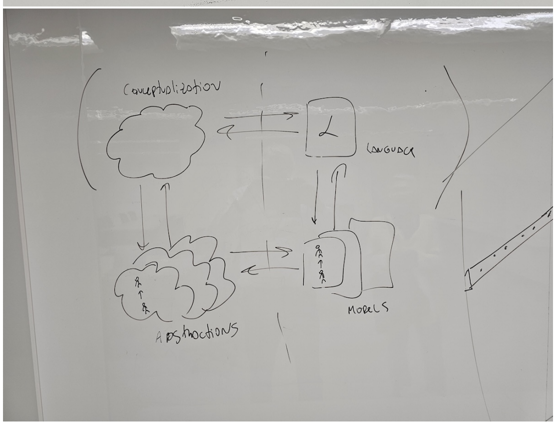
The third group chose a more UML-diagram(-like) approach to restructure the previous view:



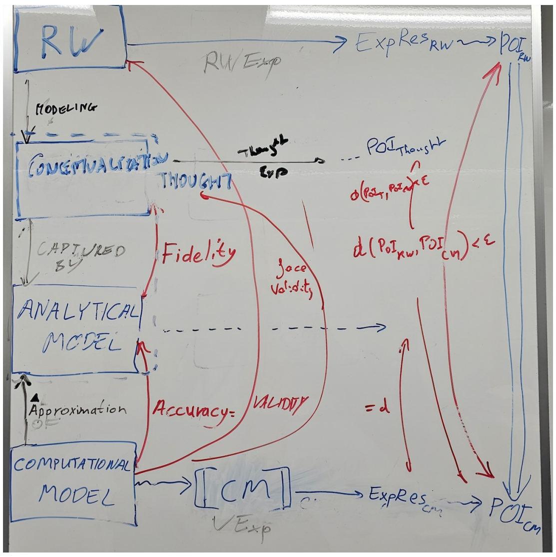
Group 4

The final group explored the unified view and its relation to the semiotic triangle, strengthening the roots of our approach.





After some iterations, the following relationships between modelling concepts were agreed on.



- RW is the Real-World artefact;
- Conceptualization is the conceptualization made of the RW artefact. This is arrived at from RW by modelling;
- An Analytical Model is a model which has an exact (in the mathematical) sense "solution". The model's fidelity captures how well this model's structure captures all parts of the Conceptualization;
- An Analytical model may be approximated in a Computational Model. The degree of this approximation is the accuracy.

The arrows to the right denote experiments. An experiment on RW is carried out in the real world. The experiment results are often traces of pertinent measured/observed quantities over time. An experiment on a Conceptualization is thought experiment. An experiment on an analytical model is often a hypothetical mathematical analysis of the model. This may or may not be feasible in practice, as with non-linear ODEs. An experiment on a Computational Model is carried out in a finite number of discrete computation steps. It often entails a (time or state-space) discretization and leads to approximate experiment results. When a model is expressed in a modelling language, the experiment operation corresponds to applying the semantic mapping function to the model. To reason about accuracy and validity, Properties of Interest are often computed based on the experiment results. A computational model is deemed valid if the distance between the properties of interest obtained from a RW experiment and from its "virtual" counterpart are sufficiently close. The distance between the Properties of Interest obtained from analytical and computational models leads the notion of accuracy.

Phase 3 – Exploitation and Refinement

In the final phase we worked on further expanding the knowledge and laying the groundwork for future exploitation and the integration of the *multiplicities* and *workflows*.

In this light, we worked on the *Science* workflow, i.e. research using an analytical/descriptive world view, the *Engineering* workflow, i.e. a world view with the goal to produce new artefacts, and the *Unification* group, which worked on strengthening the foundation of our discoveries on the semiotic triangle.

A fourth group worked on establishing a glossary of terms using the definitions we agreed upon.

The results of these processes will be disseminated in a whitepaper, manifest and/or journal article.

Identified issues and future directions

Possible outcomes from the workshop (identified in the Thursday afternoon and Friday morning sessions), as well as through a survey sent to all participants:

- Dissemination statement for our seminar: Fuyuki Ishikawa, Stefan Klikovits, Hans Vangheluwe. “Using Multi-* Modelling to Manage Complexity in Systems Engineering” (Shonan Seminar 219). Shonan Seminar Report 219, Shonan Village Center, NII National Institute of Informatics, (05/2025) https://shonan.nii.ac.jp/seminars/219/

- Another Shonan/Dagstuhl/... Seminar of similar format: It appears that despite interesting discussions, we only scratched the surface, so we are preparing a follow-up meeting to further discuss our findings

- Exploitation-meeting: We plan on capturing our findings in a whitepaper or manifest, such that they can be shared, discussed and referenced

- The findings should also be published in a common journal article / position articles.

- A set of papers for specific communities: Given the cross-discipline nature of our research, we plan on publishing papers that disseminate our results in the respective communities and make our findings accessible by a broad audience

- Most concretely, we will set up an online meeting series and working groups to further discuss exploitation options and concrete dissemination opportunities.