Application of Systems Engineering to Simulation

Notes on simulation needs and simulation validation

DR. HENRI SOHIER

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UNIVERSITY OF ANTWERP

IRT SystemX

SystemX INSTITUTE OF RESEARCH AND TECHNOLOGY

Institute of Research and Technology (IRT)
Non-profit Scientific Cooperation Foundation

Paris-Saclay • Lyon • Singapour

100
Economic partners
of which **1/3** are large groups
and **2/3** are SMEs

36
Academic
partners

Leads market-driven and applied research projects for the digital transformation of industry, services and territories:

1. Expertise: analysis, modeling, simulation and decision management
2. Own skills
3. Own assets: software, cyber-physical and tool-based platforms

4 main application domains

- Mobility and autonomous transport
- Industry of the future
- Defense and security
- Environment and sustainable development

8 scientific and technical fields

- Data science and AI
- Human-machine interaction
- Scientific computing
- Optimization
- System engineering and software design
- Safety of critical systems
- Digital security and blockchain
- IoT and future networks

Founding members

ALSTOM, Bull atos technologies, COSMOTECH, IDnomic, OVH.com, Renault Group, SAFRAN, SHERPA ENGINEERING, INSTITUT POLYTECHNIQUE DE PARIS, Inria, Institut Mines-Télécom, UNIVERSITÉ PARIS-SACLAY, Systematic Paris Region Deep Tech Ecosystem

Simulation at SystemX

- **Examples of projects in simulation**
  - **Decarbonized City**: Impact evaluation of city projects (e.g. installation of a district heating network) thanks to data management and digital twins
  - **JNI**: Development, instantiation and deployment of digital twins for complex industrial systems
  - **HSA**: Simulation and machine learning hybrid models and benchmarks
  - **openPISCO**: Open-source topological optimization platform driven by the level set method
  - **AMC**: Complex simulation architecture based on MBSE (needs, reuse, traceability)
  - **AFS**: Exchange of simulation models with sufficient fidelity

Simulation at SystemX

AFS project

- Develop a methodology to improve the **collaboration between a system manufacturer and a supplier** in terms of simulation
- Integrate this collaboration in new **simulation architecture tools** for better **agility**
- Develop a methodology to **manage simulation model fidelity** and guarantee simulation results credibility
- Develop new AI-based approaches to **improve physical models fidelity**
- **Standardize** information exchanges in simulation-based development processes

Industrial partners:

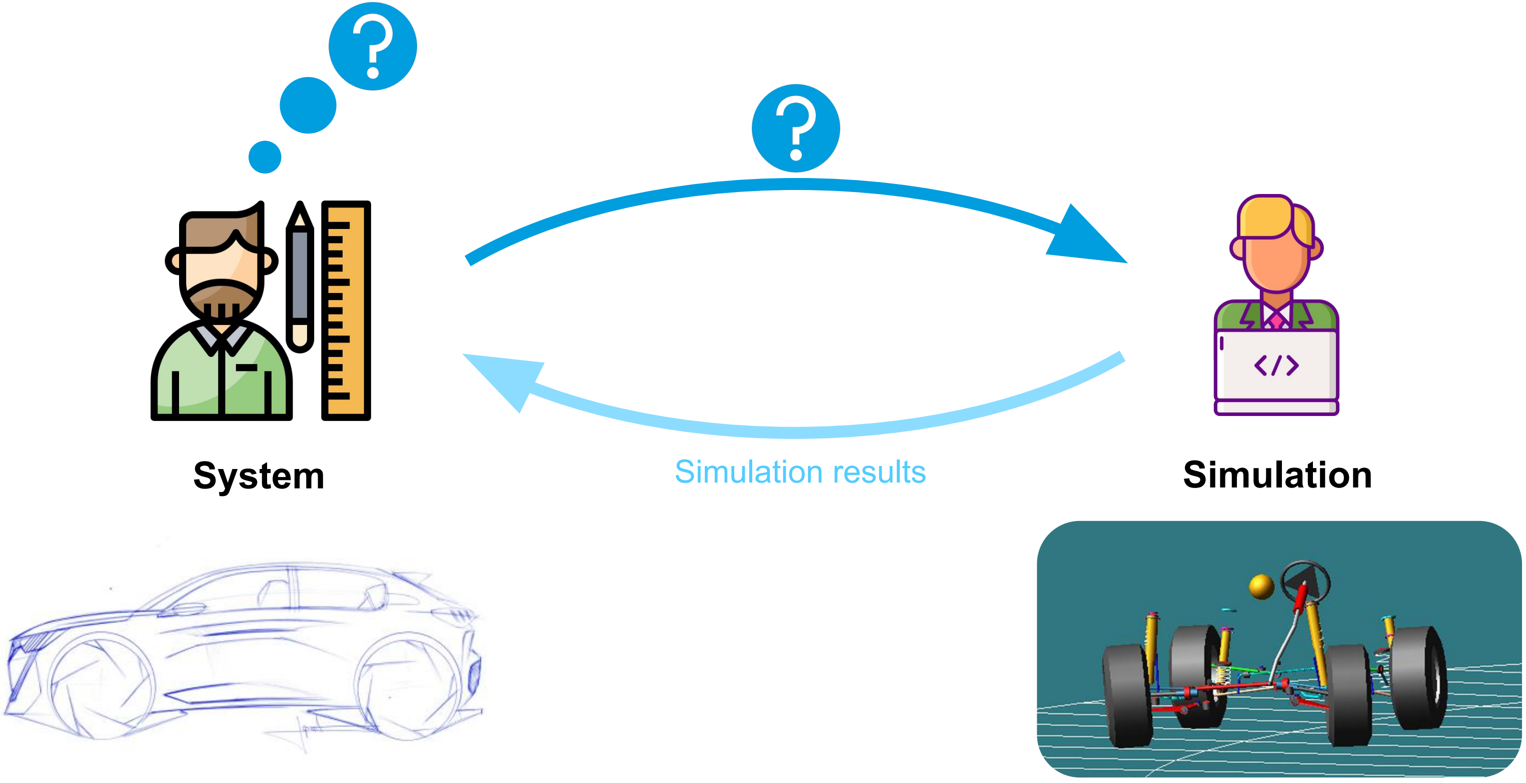
GROUPE RENAULT
STELLANTIS
esi get it right®
PLASTIC OMNIUM

Academic partners:

Arts et Métiers Sciences et Technologies
TBC

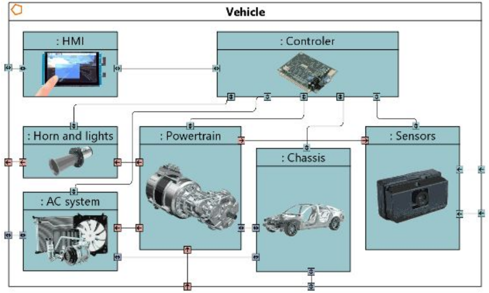
1. Who we are
2. Scope
3. Introduction to specification
4. Introduction to complex simulations
5. Simulation needs and validation
6. Applications
7. Conclusion

Simulation-based design

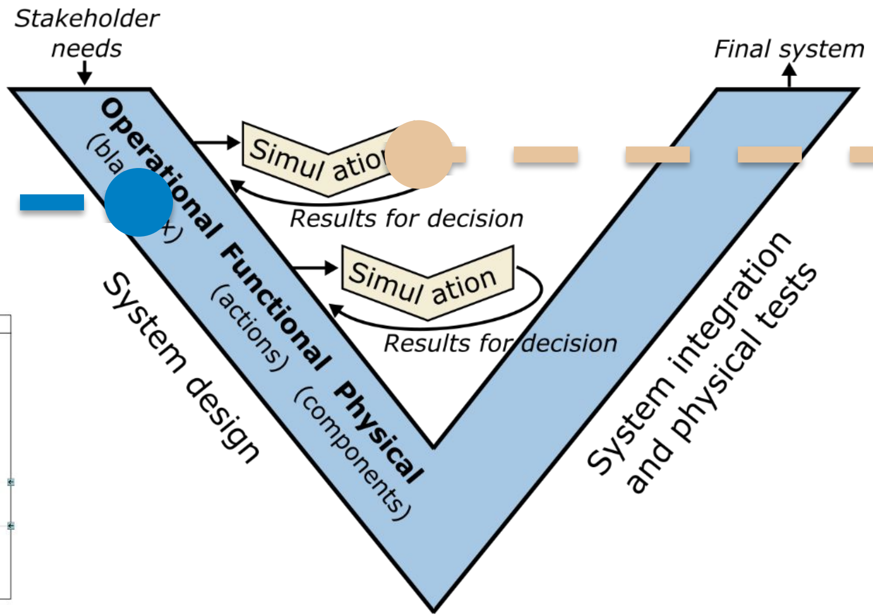


V-shaped processes

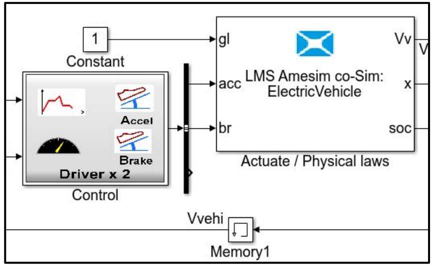
System architecture



How fast should the car be?
How much gas should it consume?
How much should it cost?
What are its components ?
…

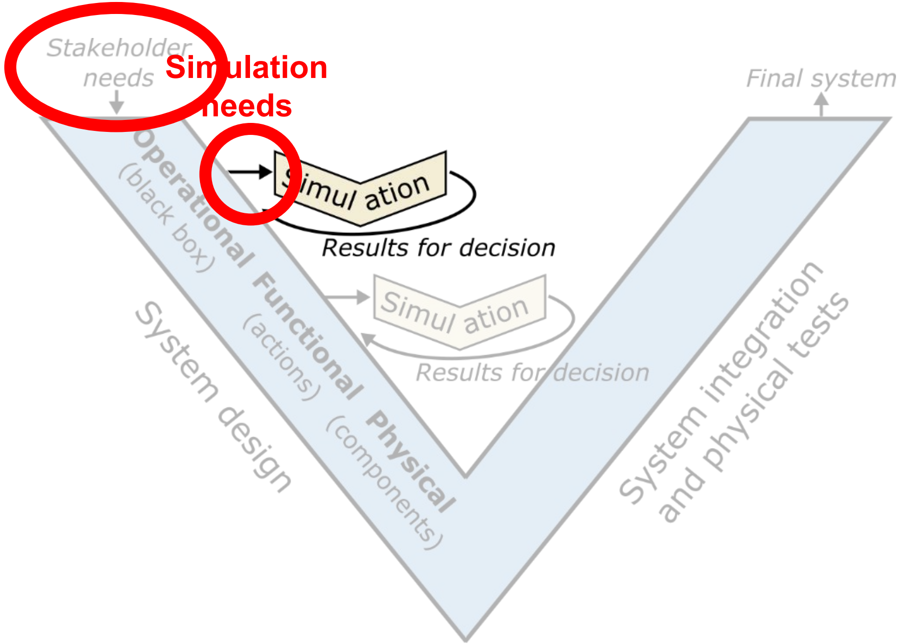


Simulation architecture



How fast should the simulation be?
How accurate should the simulation be?
What are the simplifying assumptions?
What are the simulation tools?
…

Simulation needs

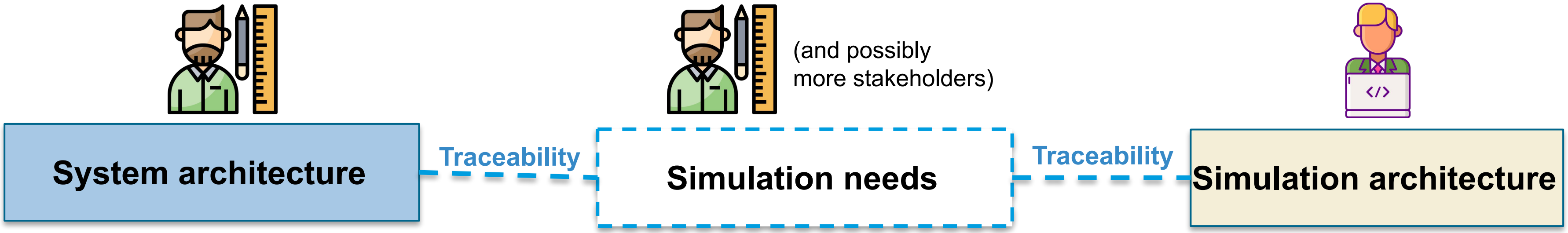


Necessary to get a simulation that meets the needs

Necessary to simulation validation

Necessary to simulation reuse

Process artefacts



What part of the system should
the simulation represent?
What is the simulation for?
(optimisation? comparison? validation?)
Is it critical ?
What are the test scenarios
to simulate?
…

- **Traceability for:**
  - High data quality (consistency, clarity, …)
  - Easy data processing (verification, recommendation, …)

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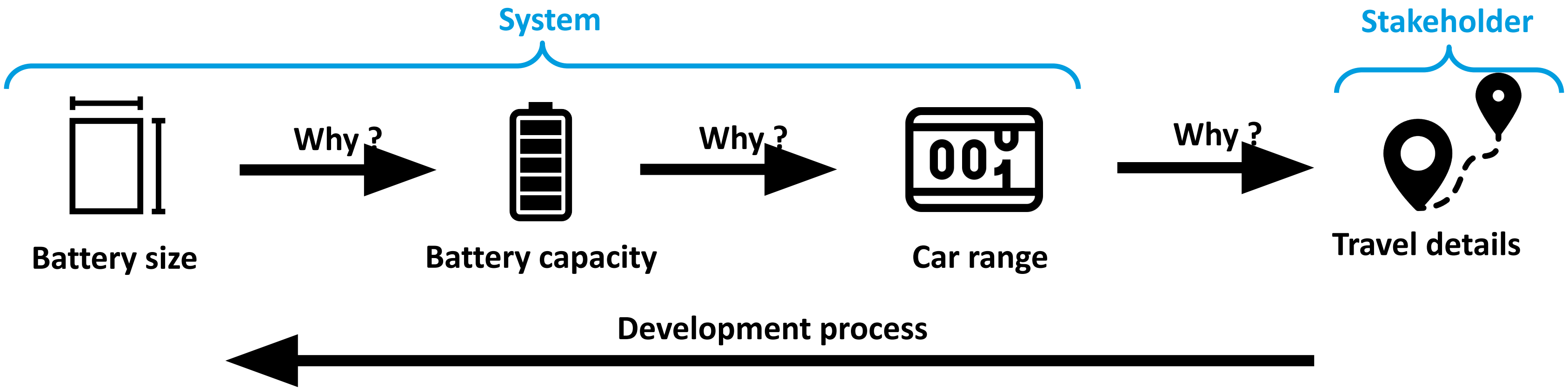
Requirements

- **Objective (ideally): Keep a traceability of every design choice and every test**



- **Stakeholder needs are sometimes similar to system requirements**
  - Ex. 1: The customer wants a blue car
  - Ex. 2: The marketing department says that the car range must be higher than what the competitor offers

Stakeholder needs

- **Involve everyone…**

Users

Programmers

Field workers

Regulators

Political associations

- **… and the whole lifecycle**

<table>
<tr><td rowspan="2">Concept stage</td><td rowspan="2">Development stage</td><td rowspan="2">Production stage</td><td>Utilization stage</td><td rowspan="2">Retirement stage</td></tr>
<tr><td>Support stage</td></tr>
</table>

References

- ISO/IEC/IEEE 15288:2015

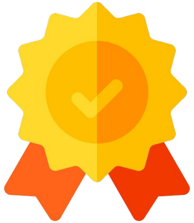
Requirements quality

- **Good requirements**

1. Necessary
2. Implementation independant
3. Unambiguous
4. Complete
5. Singular
6. Achievable
7. Verifiable
8. Conforming

- **Good set of requirements**

1. Complete
2. Consistent
3. Feasible/affordable
4. Bounded



References

- INCOSE Systems Engineering Handbook (4th ed.)
- ISO/IEC/IEEE 29148:2018
- INCOSE Guide for writing requirements

Quality requirements

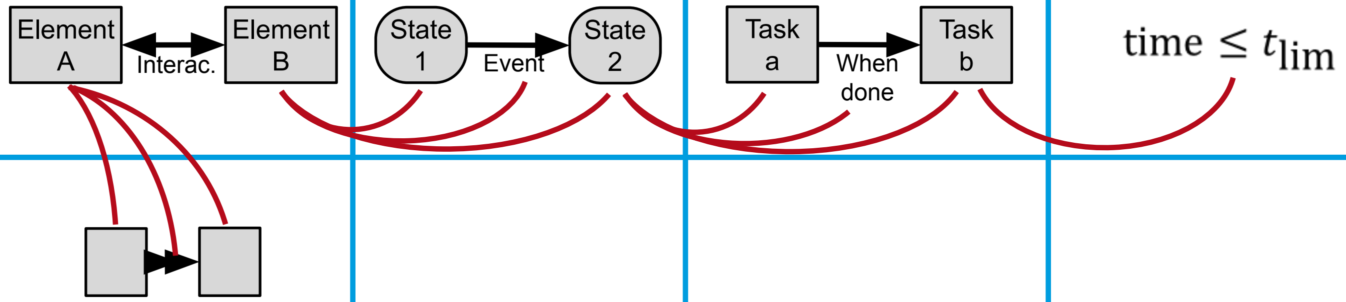
- « Ilities »,
  « Quality requirements »,
  « Non-Functional requirements »

Functional Suitability	Performance efficiency	Compatibility	Usability	Reliability	Security	Maintain-ability	Portability
Functional completeness Functional correctness Functional appropriateness	Time-behaviour Resource utilisation Capacity	Co-existence Interoperability	Appropriateness recognisability Learnability Operability User error protection User interface aesthetics Accessibility	Maturity Availability Fault tolerance Recoverability	Confidentiality Integrity Non-repudiation Accountability Authenticity	Modularity Reusability Analysability Modifiability Testability	Adaptability Installability Replaceability

ISO/IEC 25010:2011 System and software quality models

Requirements nature

	Structure « Constructional »	States « Behavior », « Functional »	Dynamics « Behavioral », « Functional », « Temporal », « Scenarios »	Performance « Non-functional »
Black box Why? « Operational » « System »				
Internal actions How? « Functional » « Logical »				
Components What? « Physical »				



1. **Who we are**
2. **Scope**
3. **Introduction to specification**
4. **Introduction to complex simulations**
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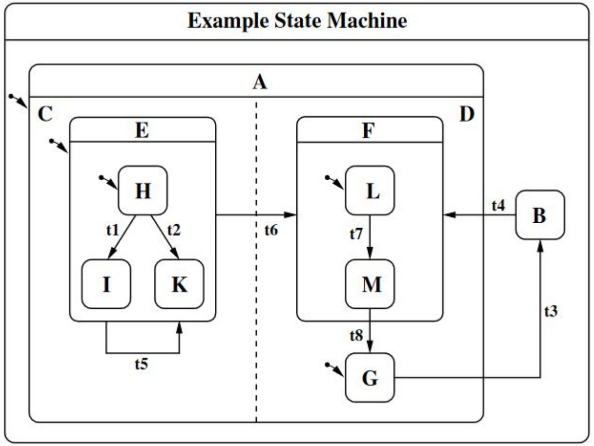
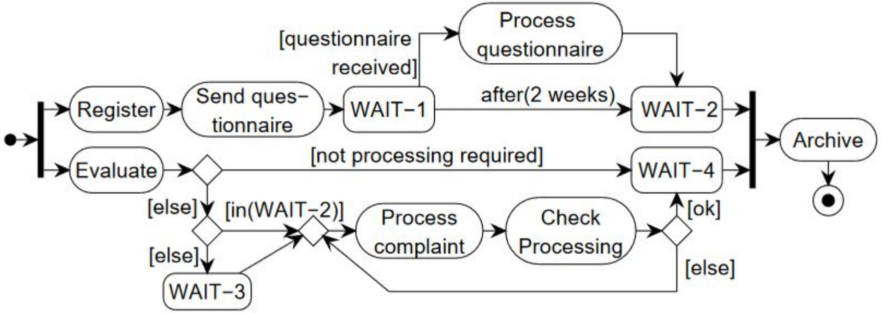
6. **Applications**
7. **Conclusion**

Specification execution in software engineering

- **Model-based testing**
  - Execute and test the model
  - Requires a formal specification



Santen et al. Executing UML State Machines. 2006.



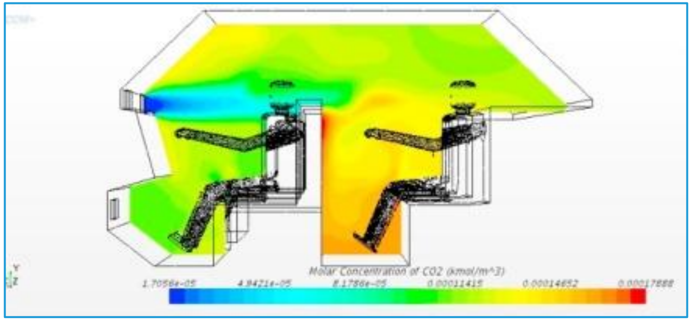
Eshuis et al. An Execution Algorithm for UML Activity Graphs. 2001.

Example of runnable UML state machine

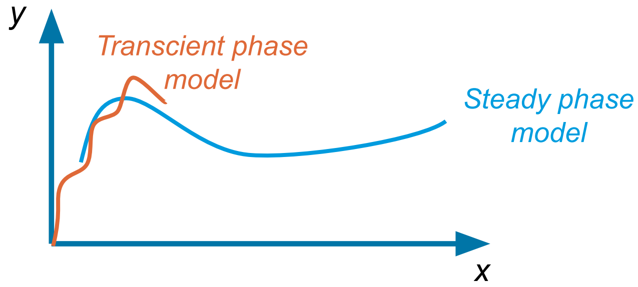
Example of runnable UML activity graph

Simulation as a product

- **A simulation is always fit for specific needs: It's never good at everything**

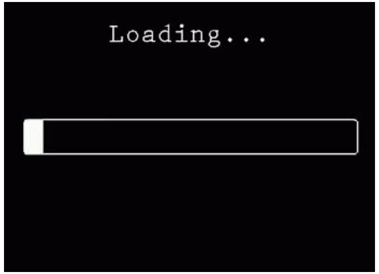


https://www.sciencedirect.com/science/article/abs/pii/S1361920917309744

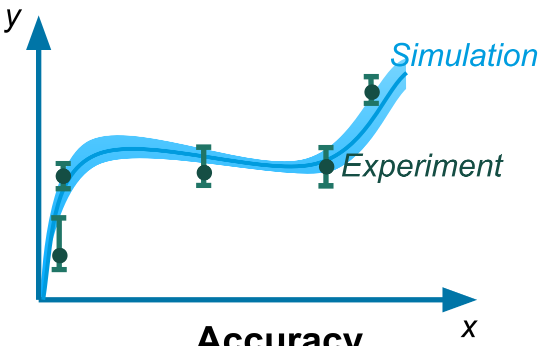


Simulation as a product

- **A simulation is always fit for specific needs: It's never good at everything**
- **A simulation has its own requirements**



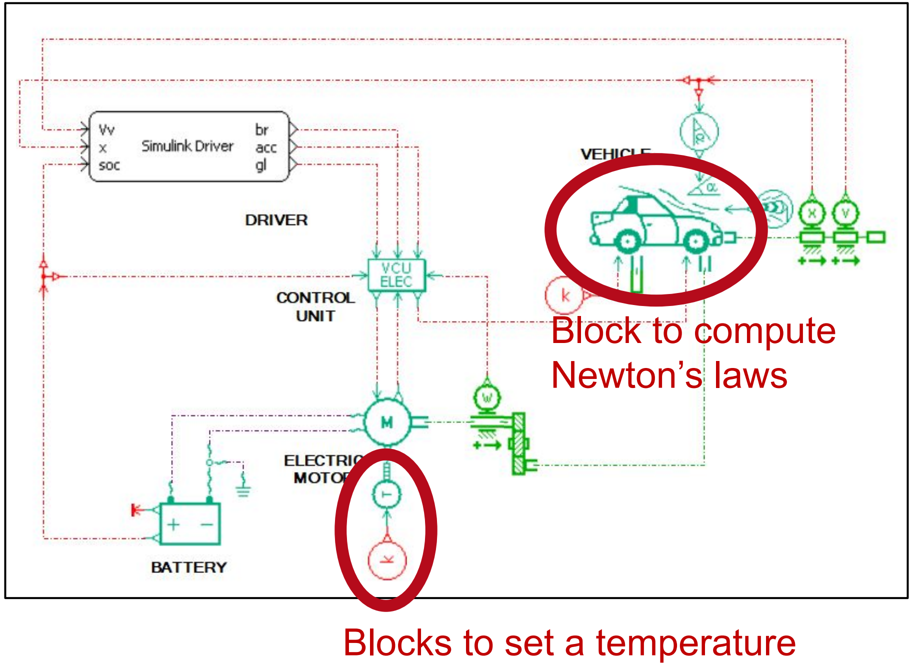
Execution time



Accuracy

Simulation as a product

- A simulation is always fit for specific needs: It's never good at everything
- A simulation has its own requirements
- A simulation has its own topology



Simulation as a product

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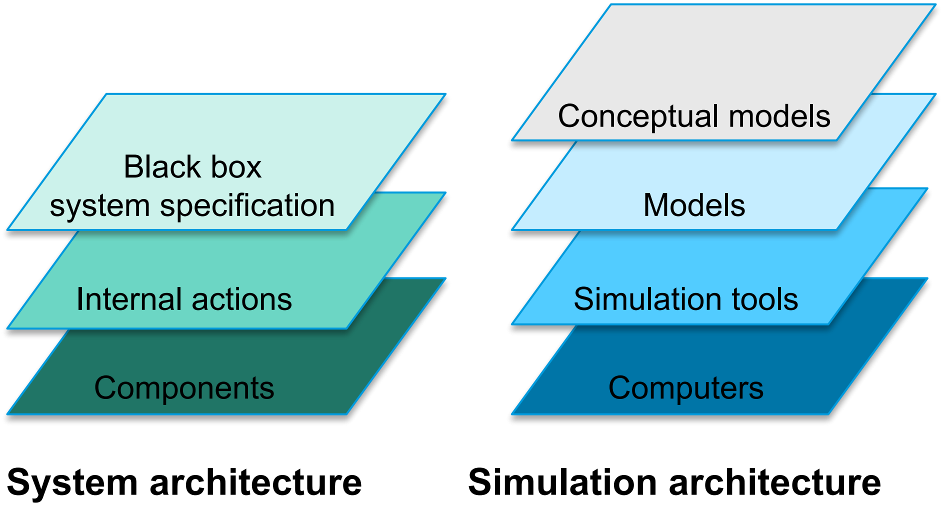
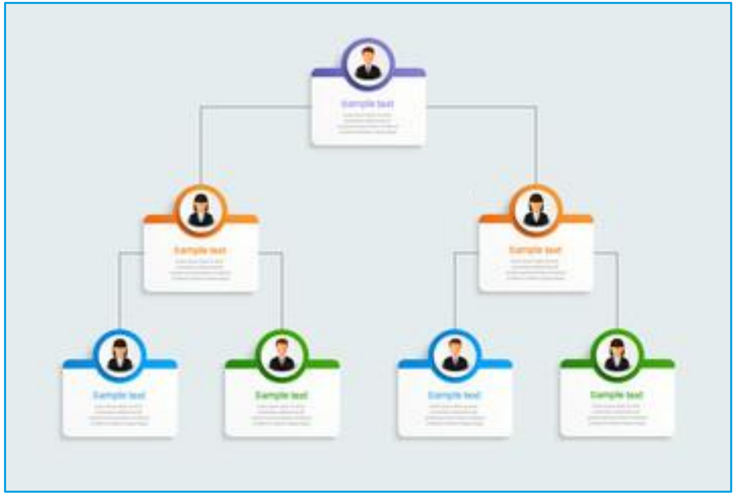


Simulation as a product

- A simulation is always fit for specific needs: It's never good at everything
- A simulation has its own requirements
- A simulation has its own topology
- A simulation has its own architecture
- A simulation often has its own development team, with specific skills



Simulation as a product

- **A simulation is always fit for specific needs:**
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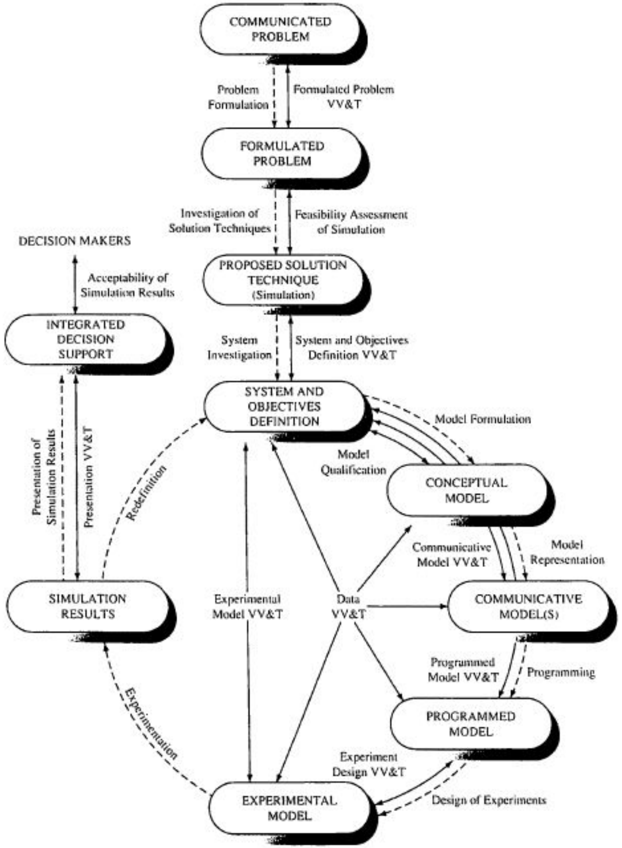
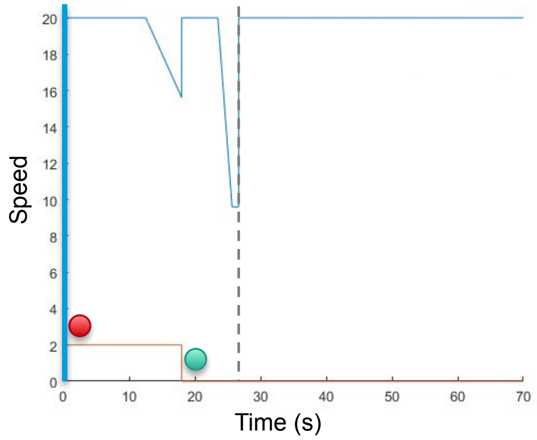
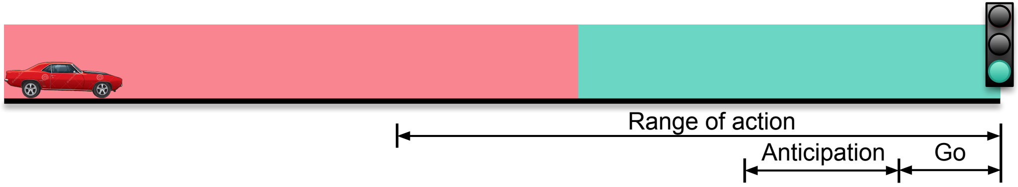
- **A simulation has its own requirements**
- **A simulation has its own topology**
- **A simulation has its own architecture**
- **A simulation often has its own development team, with specific skills**
- **A simulation has its own life cycle**



Balci. Validation, verification, and testing techniques throughout the life cycle of a simulation study. 1994.

Example of simulation





Example of sequence of events :

1) Vehicle cruising
2) Decision to slow down because of the red traffic light
3) The traffic light turns green
4) Decision to slow down to anticipate a possible color change
5) The vehicle passes the traffic light, even if it turns orange

Control parameters :

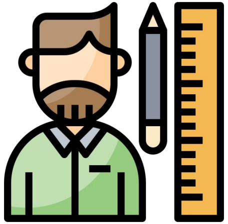
- Range of action
- Deceleration in anticipation of a color change

Sensor subject to an uncertainty :

- Detection range

Question: What are the best parameters and sensor to minimize both the energy consumption and the sensor cost?

Simulation needs



System

Part of the system to be simulated

Objective of the simulation

Simulation requirements

Test scenarios

Data for simulation calibration and validation

Agreement on the V&V of the simulation

Simulation

Sohier, H, Lamothe, P, Guermazi, S, Yagoubi, M, Menegazzi, P, Maddaloni, A.
Improving simulation specification with MBSE for better simulation validation and reuse.
Systems Engineering. 2021; 1– 14.

Available at https://doi.org/10.1002/sys.21594

INCOSE

WILEY

Simulation requirements

Quality

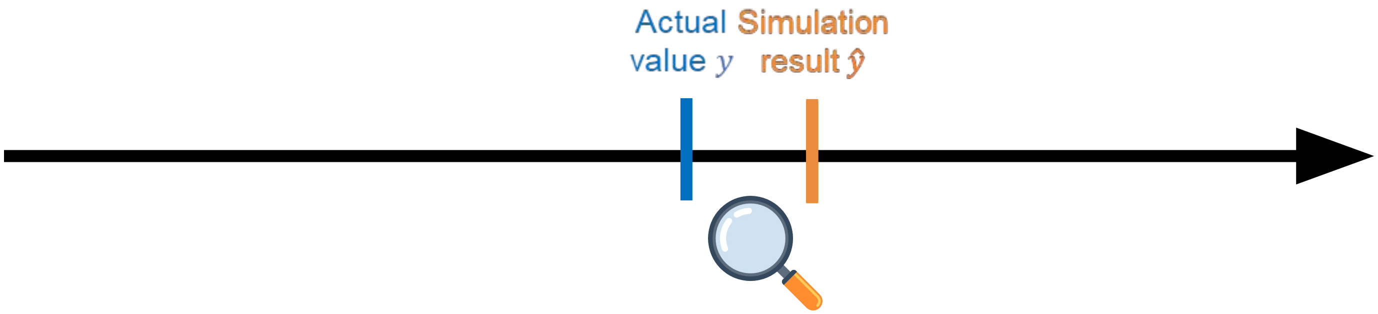
Fidelity

…

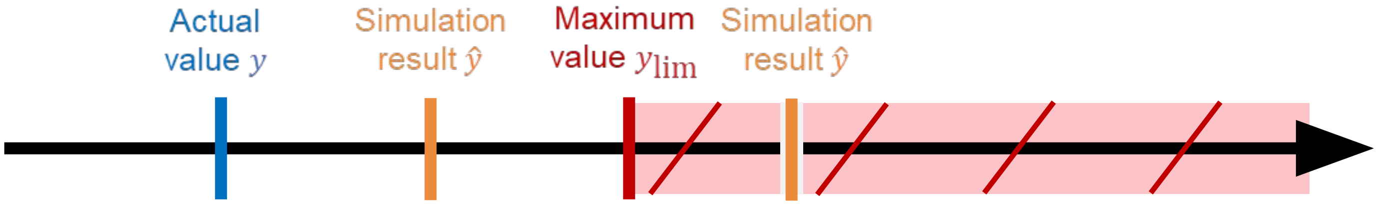
Credibility

Accuracy

When is a simulation accurate enough ?

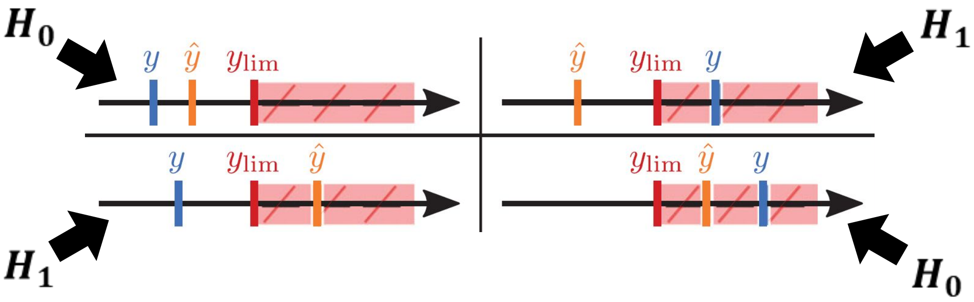


Simulation requirements



Null hypothesis H_0: Simulation close enough to reality

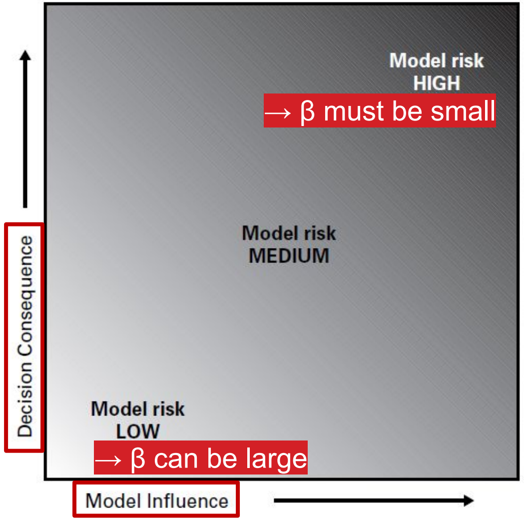
Alternative hypothesis H_1



	H_0 is true	H_1 is true
Believe H_0	Valid results	Invalid results
Believe H_1	Over-engineering	Under improvement

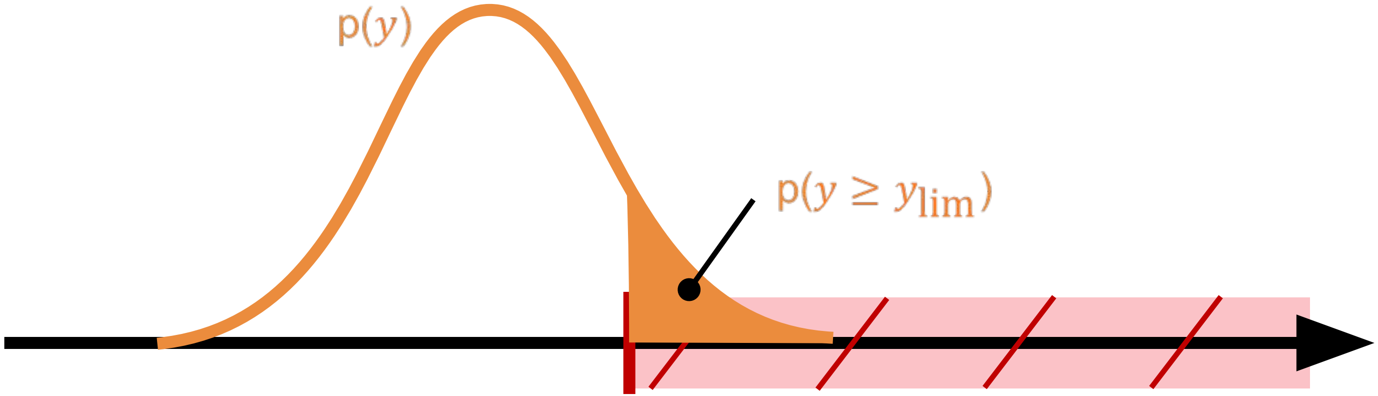
Simulation requirements

- Overengineering = Type I error
- Invalid results = Type II error
  - $\beta = P(\text{believe } H_0 \mid H_1 \text{ is true})$
- What probability β of type II error can you accept ?
  - Linked to the criticity of the simulation (see V&V 40)
  - Linked to the decision you need the simulation for
    - Can the decision have serious consequences ?
    - Will the decision only be based on this simulation ?
- Qualitative approach :
  "improbable type II error", "possible type II error"...
- Reducing the risk of type II error
  statistically increases the risk of type I error
- The risk of type II error is not easy to estimate,



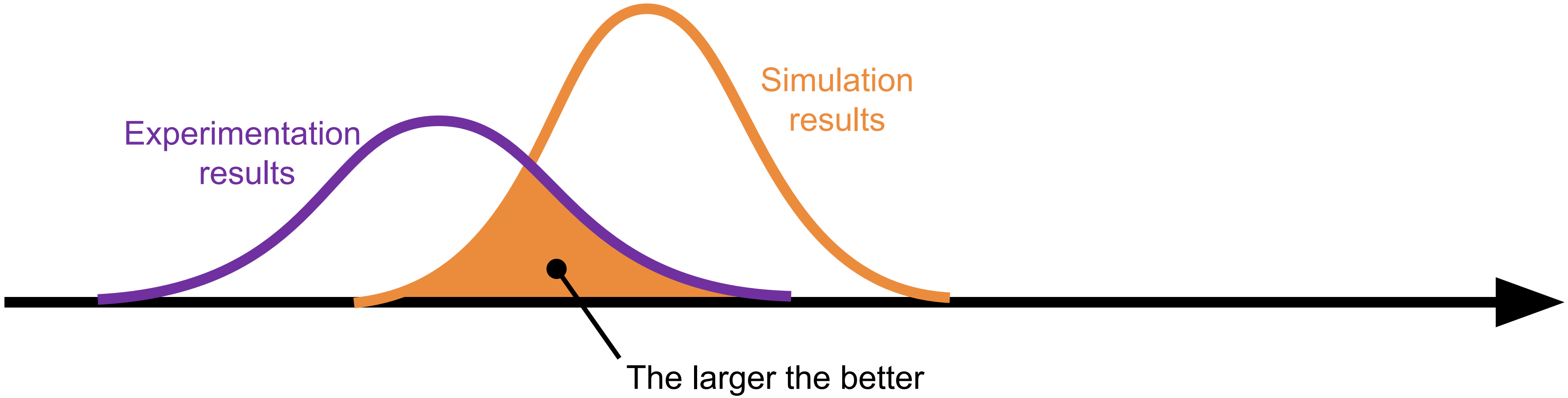
ASME V&V 40-2018
(Assessing Credibility of Computational Modeling Through Verification and Validation: Application to Medical Devices)

Simulation requirements



- Ideally, simulation should not provide a simple estimator $\hat{y}$, but an exact probability density function $p(y)$
- The criticity of the simulation then simply constrains $p(y \geq y_{\text{lim}})$
- $p(y)$ = Holy Grail of simulation
- $p(y)$ is a function of neglected physics, solver approximations, code errors, …
- $p(y)$ is not a simple propagation of input uncertainties

Simulation requirements

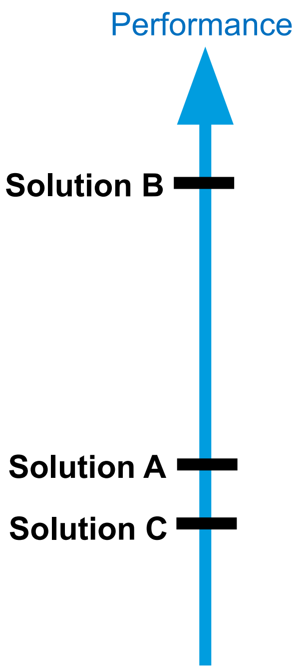


- The comparison of simulation and experimentation results is not an end in itself (how close should the results be?)
- Be careful to:
  - What simulation uncertainties cover
  - How accurate the experimentation results are
  - How many experimentation results are available
  - How to deal with time dependency
  - …

Simulation requirements

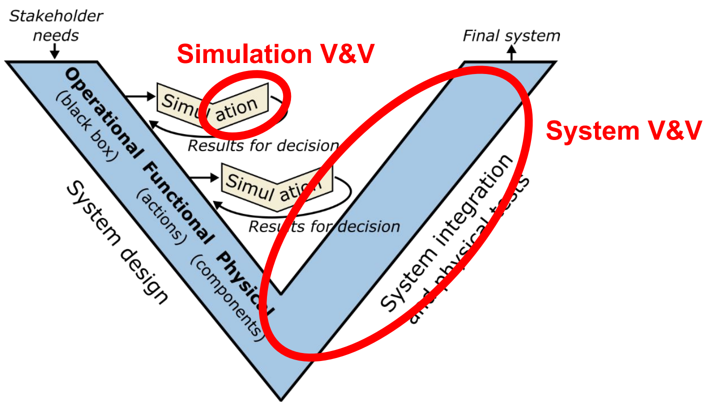
- Ranking solutions also requires a discrimination threshold
- If the difference between Solution A and solution C is greater than the discrimination threshold, A can be considered as better than C
- Probability β of type II error (A is actually not better)

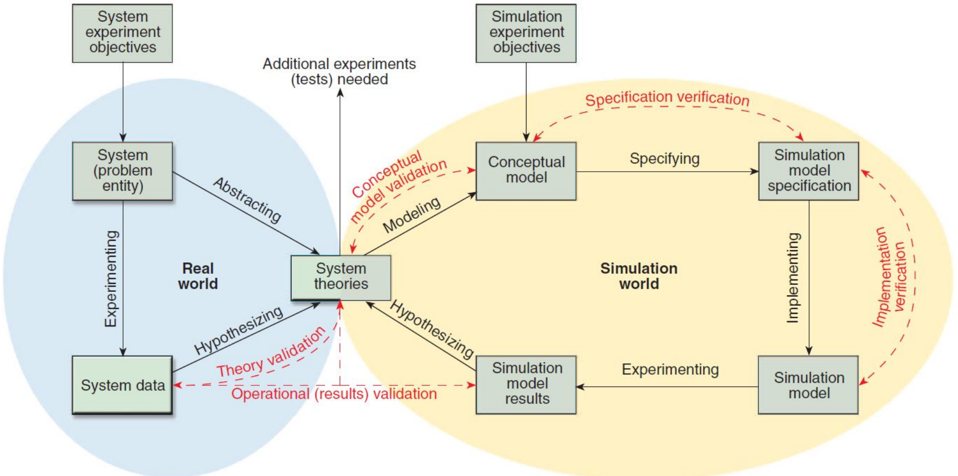
- The simulation may be specific to solutions A, B and C (and not able to rank other solutions)



Verification and validation of the simulation

- Verification = Did I build the thing right ?
- Validation = Did I build the right thing ?
- Covers various aspects: Correct representation of the system (conceptual model validation) ? Accurate enough (operational validation) ? No programming errors (implementation verification) ?...
- Often not well distinguished in simulation

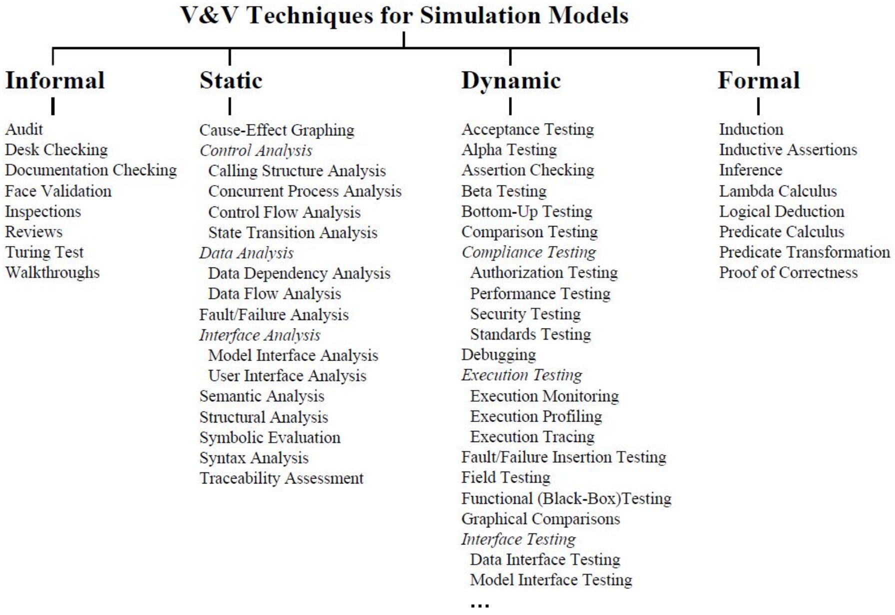




Pace. Modeling and Simulation Verification and Validation Challenges. 2004. (from Balci)

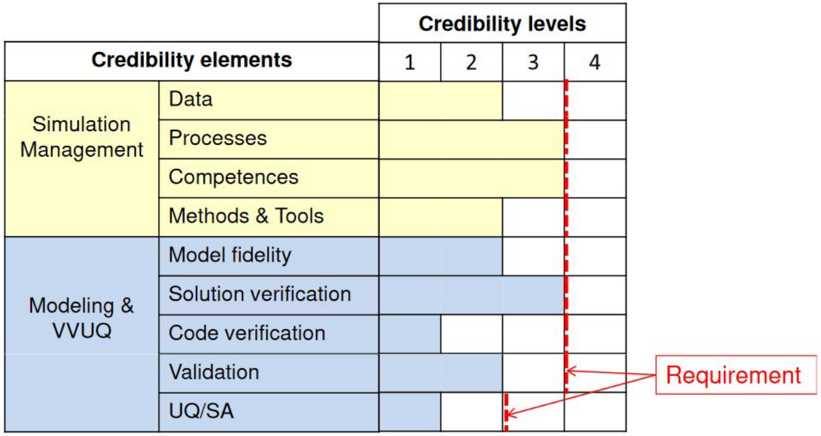
Verification and validation of the simulation

- Various techniques:



Balci. Verification, Validation and Accreditation of Simulation Models. 1997.

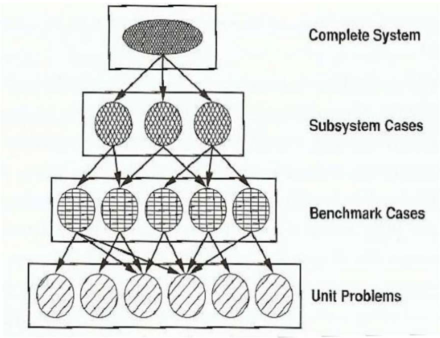
- Process oriented considerations



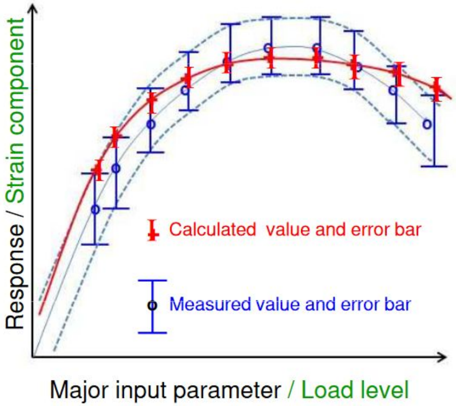
Building simulation credibility in an industrial context (2022 NAFEMS training by Imbert and Pasquet)

Verification and validation of the simulation

- To take into account:
  - Simulation V&V is difficult
  - It is often done without clear process and with limited budget
  - Simulation V&V is often less progressive than system V&V
    (where the upward phase of the V-model is more carefully respected)
  - The simple comparison of simulation and experimental results if often difficult



AIAA Guide for the Verification and Validation of Computational Fluid Dynamics Simulations



Building simulation credibility in an industrial context (2022 NAFEMS training by Imbert and Pasquet)

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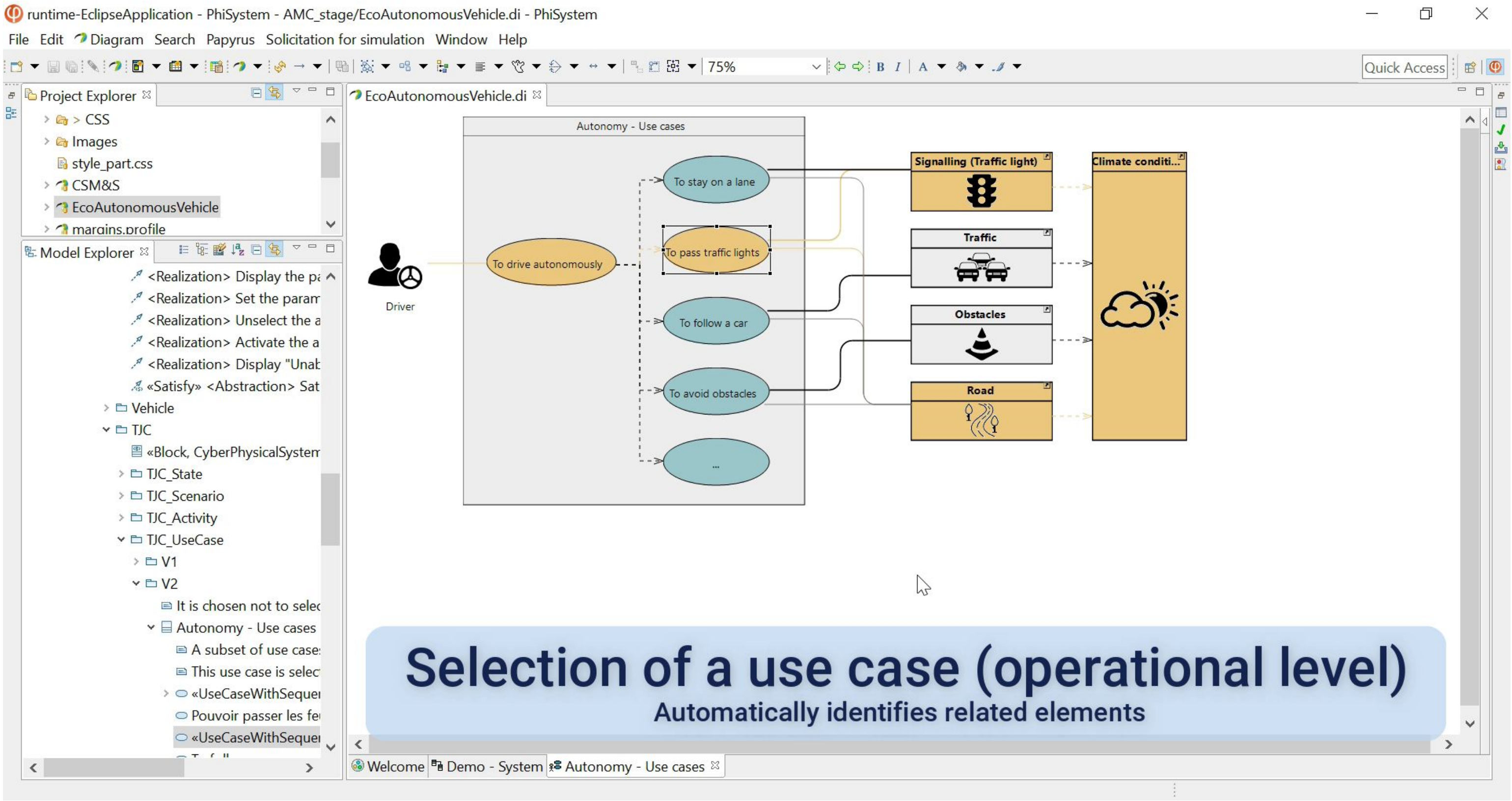
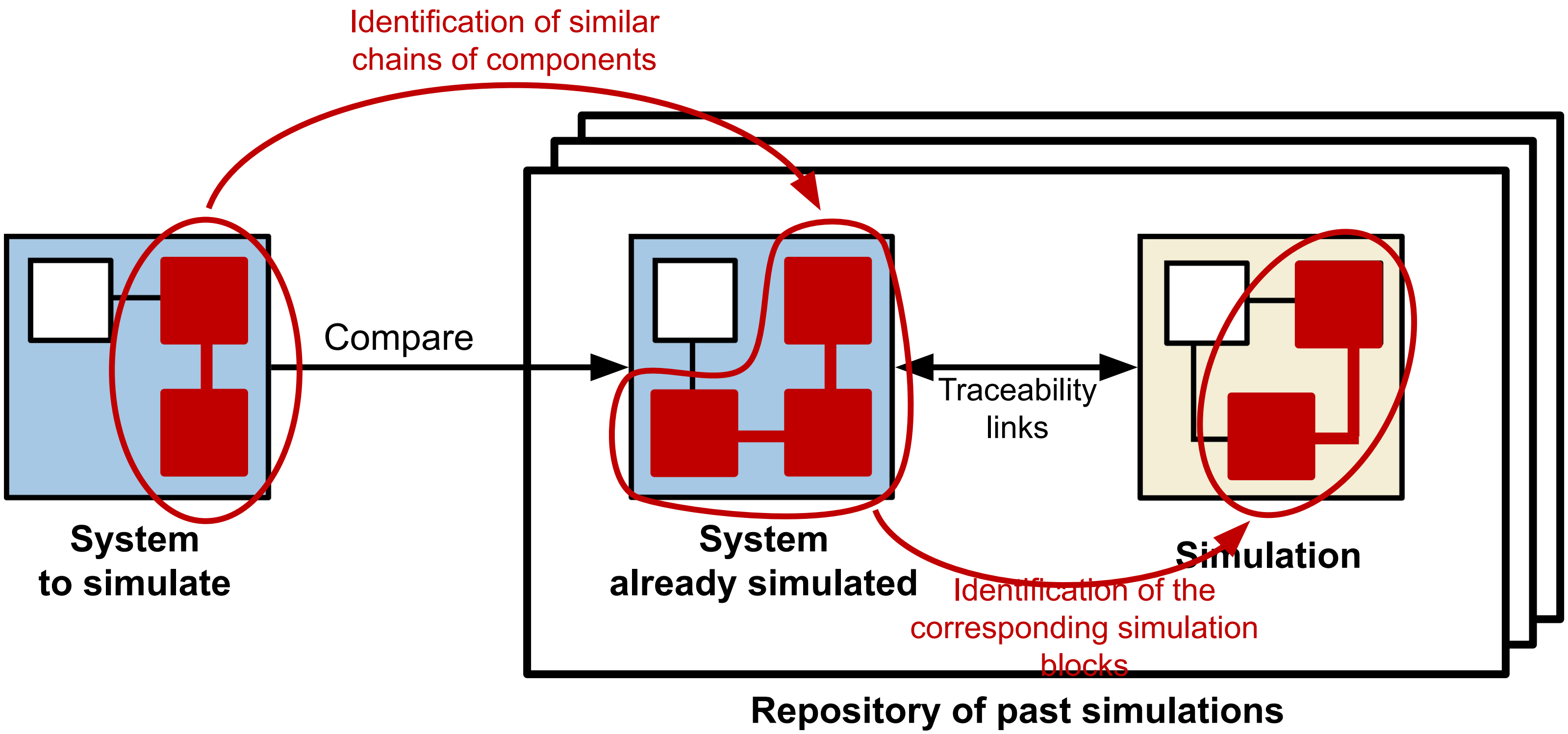
Tool for simulation specification

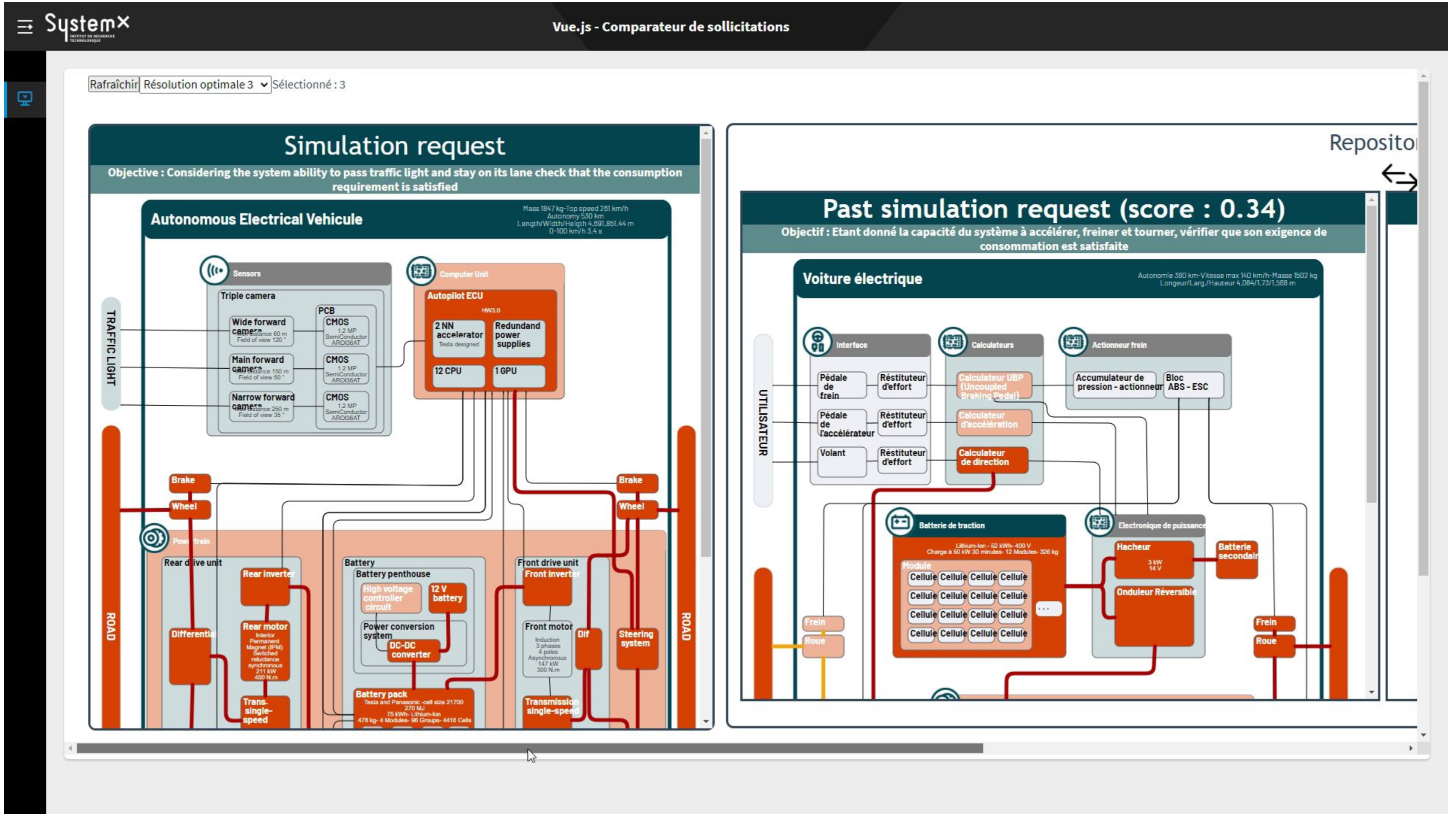


Tool for simulation reuse

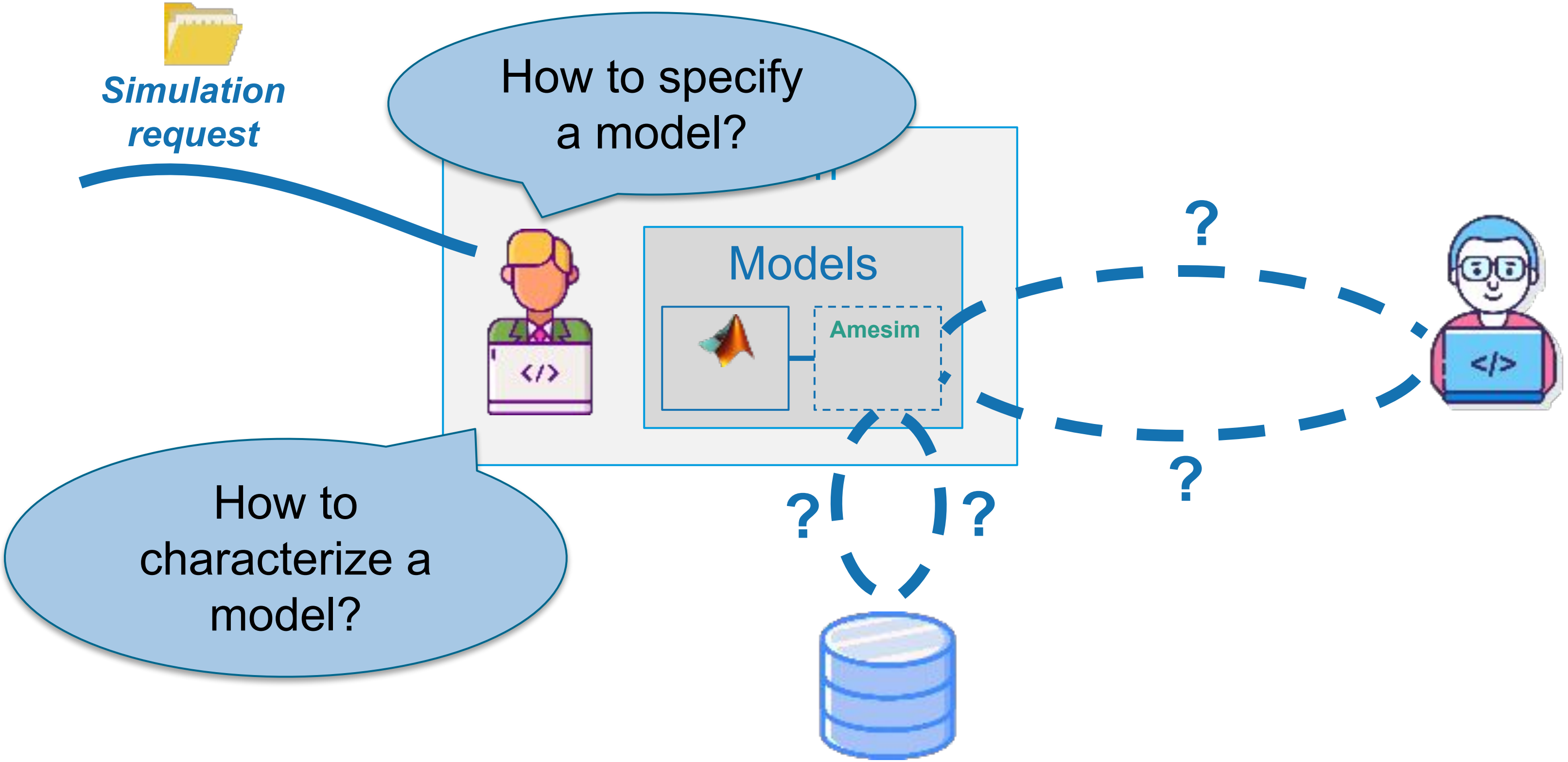


Sohier, H., Petitdemange, L., & Lamothe, P.
Identification of Systems With Similar Chains of Components for Simulation Reuse.
2021 IEEE International Conference on Recent Advances in Systems Science and Engineering (RASSE)

Tool for simulation reuse



Characterization of simulation models



Model Identity Card (MIC)

- **Model Identity Card (MIC)**
- **Metadata for the characterization of simulation models**
- **Can be used for specification, search, integration, …**
- **MIC-Core: Standardization lead by IRT SystemX, Prostep and ATLAS**
  - ID, name and description
  - Modelled entity and model purpose
  - Modelling choices and model limitations
  - Software and hardware requirements
  - Confidentiality
  - Verification and validation
  - …
- **Let us know if you are interested!**

MIC-Core

Jully 2023 : Common publication of MIC-Core,
A core set of metadata to characterize simulation models

https://mic-core.github.io/MIC-Core/main

To augment simulation engineering with interoperable tools
To be used for simulation specification/reuse/integration/exchange/..

More info:

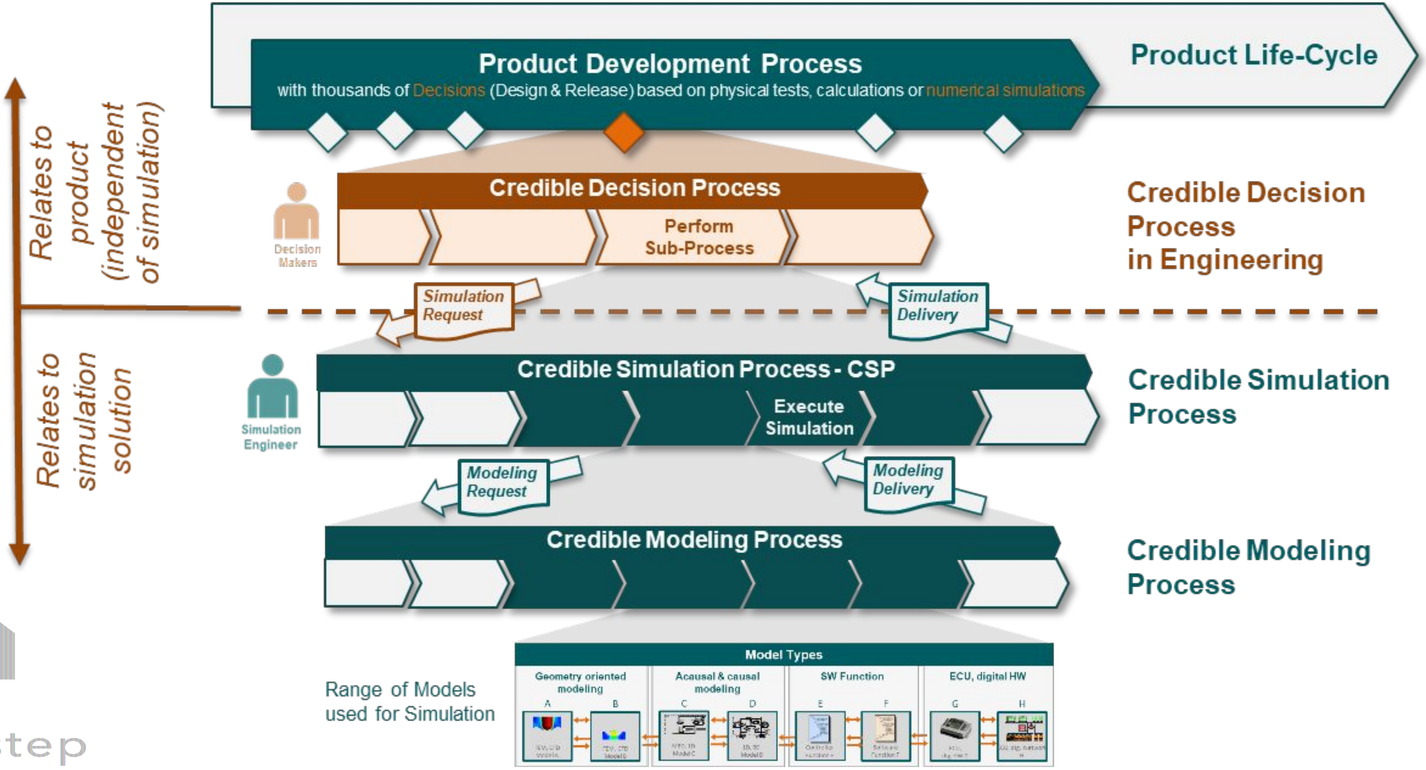
AFS & AMC projects
(Renault, Stellantis,
ESI, Plastic Omnium, …)

X

SmartSE project
(Bosch, Dassault Systèmes,
dSPACE, Siemens, …)

Methods and processes

Credible decision process from Prostep SmartSE



Methods and processes

- **MIL-STD-3022** Documentation of Verification, Validation, and Accreditation (VV&A) for models and simulations
    - Templates for documentation
    - Some paragraphs regarding the simulation needs:
        - “Problem statement”
        - “M&S requirements and acceptability criteria”
        - “Basis of comparison.”
    - Standard vocabulary
- **NASA-STD-7009** Standard for Models and Simulations
- **PCMM** (Predictive Capability Maturity Model)
- **V V 10** (Standard for Verification and Validation in Computational Solid Mechanics) by ASME
- **V V 40** (Assessing Credibility of Computational Modeling through Verification and Validation) by ASME
- **Simulation Verification and Validation for Managers** by NAFEMS
- **Verification and Validation in Scientific Computing** by Oberkampf

Methods and processes

Global processes to better meet the needs

Quality management

- ISO 9001, ISO 25000, …
- quality planning, quality assurance, quality control, quality improvement…

Can rely on the same needs categorization, can rely on similar solutions (e.g. good practices), …

Risk management

- ISO 31000, ISO Guide 73, …
- risk identification, risk analysis, risk evaluation, risk treatment, risk monitoring, …

Simulation is a (digital) product in its own right

1. Who we are
2. Scope
3. Introduction to specification
4. Introduction to complex simulations
5. Simulation needs and validation
6. Applications
7. Conclusion

Conclusion

- **A simulation is a digital product in its own right**
- **Simulation development should start with clear needs**
  - Improves validation
  - Improves reuse
- **Traceability improves data consistency and data processing**
- **Simulation should be subject to quality and risk management**
- **Challenges**
  - How to ensure traceability, in particular during the whole simulation development?
  - What are the new software functions required by simulation engineering?
  - How to further improve the management of digital twins and AI-based simulations ?
- **Towards a better standardization ?**

THANKS FOR YOUR ATTENTION

henri.sohier@irt-systemx.fr

SystemX
INSTITUT DE RECHERCHE TECHNOLOGIQUE