prostep IVIP

White Paper

Guard Rails for “Simulation Credibility Standards and Recommendation”

prostep ivip White Paper

SmartSE

Guard Rails for “Simulation Credibility Standards and Recommendation”

Version 1, March 2024

Abstract

This white paper aims to describe a process framework for embedding numerical engineering simulations in the decision-making process of complex technical products and systems and thus to lay the foundations and guidelines for a "Simulation Credibility Standard and Recommendation" yet to be created. This document is based on the white paper "Simulation-based decision making and release" published in 2021 by the project group Smart Systems Engineering - SmartSE of the prostep ivip Association and goes beyond the contents described therein by describing a possible way to create an international and cross-industry simulation credibility approach. This is intended to create a further basis for joint discussions with international standardization bodies and future standardization activities with regards to "Simulation Credibility Standards and Recommendation”.

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1 Introduction

In an era in which product development cycles are becoming shorter and shorter and the demands on the performance and reliability of complex products are constantly increasing, companies are faced with the challenge of establishing efficient and cost-effective development processes. One method that has become increasingly important in recent decades is numerical simulation. Through the use of computer simulations and mathematical models, numerical simulation opens up a new dimension in product development.

Traditional approaches to product development, which relied heavily on physical prototypes and empirical testing, are reaching their limits in the face of growing complexity and high costs. Numerical simulation, on the other hand, offers the possibility of virtually creating, analyzing and optimizing products and systems even before a physical prototype is created. This paradigm shift has revolutionized the way products are developed, enabling companies to bring innovative solutions to market faster, more accurately and at lower cost. In addition, numerical simulations play a crucial role in decision making and the release of technical solutions.

By using simulation-based analysis, engineers and designers can gain comprehensive insight into the behavior and performance of a product or system before it is actually built or implemented. These simulations provide valuable information about the effects of various design options, operating conditions, and environmental parameters. Based on the accurate and detailed results of the simulations, informed decisions can be taken and optimal engineering solutions identified. This enables efficient use of resources, shortens development time, and minimizes the risk of costly errors or rework. The increasing importance of numerical simulations provides companies with the certainty that their technical decisions are based on a solid foundation and that their released solutions meet requirements and expectations.

The prostep ivip Association is a globally active, independent network comprising the manufacturing industry, IT vendors and service providers, and the research community. The primary focus of its work lies in the digital transformation of the product engineering and production processes. The SmartSE project provides building blocks for distributed, collaborative system development between partners as its major goal. It formulates and bundles the requirements of manufacturers and suppliers in the manufacturing industry, defines standards and interfaces, provides IT vendors with forums for improving interoperability and carries out vendor-independent benchmarks.

The prostep ivip Association's Smart Systems Engineering (SmartSE) project group comprises participants from almost 30 companies and research institutions. SmartSE develops application-oriented concepts for mastering the common challenges posed by systems engineering (SE). The project formulates recommendations for process design, drives technical standards for the collaborative development of complex mechatronic systems forward and encourages improved transparency for systems engineering objects.

In addition to other topics, SmartSE is also involved with simulation-based decision making and release. Approaches for ensuring the traceability and reproducibility of virtual validation and verification play an important role in this context. Another work area involves evaluating the need for criteria to assess the quality of simulation models and simulation results.

The aim of this white paper is to present a process framework for embedding numerical engineering simulations in the decision-making process of complex technical products based on the need identified in 2021 for the creation of an internationally available credibility recommendation. This process framework is intended on the one hand to emphasize the growing importance of numerical simulations in product development and on the other hand to describe basic guard rails for the creation of an internationally available credibility recommendation or standard. This paper is based on the white paper “Simulation-based decision making and release” published in 2021 by the prostep ivip association and the associated survey and its results.

1.1 Clarification of terms simulation-based and simulation-informed

In order to explain this white paper and the process framework "Credible Process Framework for Simulation", the different usage of the terms Simulation-based decisions and Simulation-informed decisions should be pointed out. In the context of the prostep SmartSE project and especially among the German automotive OEMS and suppliers participating in it, the term "simulation-based decisions" is more commonly used. This was also used in the prostep ivip white paper "Simulation-based Decision Making and Release" published in 2021. In the technical discussion of engineering simulations in the context of decision-making in the product development process with international standardization bodies, the term "simulation-informed decisions" has become more established. This is especially true in the English-speaking world and the simulation communities there.

> ***Simulation-based decisions*** *refer to decisions where simulation results are used directly as the basis for decision making. This means that simulations serve as the main source of information and decision makers directly consider simulation results to make their decisions. Simulation-based decisions can be particularly relevant when complex scenarios need to be analyzed and an accurate quantitative assessment is required.*
>
> ***Simulation-informed decisions*** *refer to decisions where simulation results play a role but are not the sole basis for decision making. In simulation-informed decisions, simulation results are considered as an important source of information, along with other factors and information used in the decision-making process. The simulations provide additional insights and knowledge that help decision makers make better-informed decisions.*

Both terms have a different focus. Simulation-based decisions rather emphasize that simulation results are the main factor for the decision, whereas in simulation-informed decisions, with simulation as one of several information sources, the informed aspect is important – meaning that the simulation results together with their associated risks, their credibility and their significance to the decision are evaluated and considered. Both terms can therefore be used largely interchangeably, simulation-based decisions have to be simulation-informed decisions, and simulation-informed decisions can be simulation-based decisions.

1.2 Participation and support in detailing of the process framework

This white paper " Guard Rails for Simulation Credibility Standards and Recommendation" is the result of detailed discussions and coordination within the SmartSE project but also with standardization bodies such as ASME / INCOSE and NAFEMS. It pursues the approach of expanding existing activities of various working groups to include the overarching aspects of product-related decision-making processes from a SmartSE perspective and to place engineering simulations in this context.

2 Challenges of digitalization in product development

The development of increasingly complex products and their functions – in the field of automated driving in the automotive industry or in the context of the complex system functions of products in the aerospace industry –requires the growing use of systems engineering methods such as model-based development to manage product development. This results in a growing need to maintain and develop advanced simulation capabilities for a variety of applications.

The need to shorten product development times and the steadily increasing proportion of embedded software used to implement product features and functions mean that these can often no longer be validated using physical testing but only by means of simulations, especially in the early product development phase. The proportion of simulations compared to physical testing has therefore been growing significantly for years and will continue to increase in the future. Particularly in future growth areas such as autonomous driving and intelligent mobility, which are expected to bring about disruptive changes in the state of the art, the quality of the simulation results and their traceability throughout the entire development process is essential to minimize the risks associated with incorrect development decisions and thus to rapidly develop these innovative business areas.The requirements to be validated range from safety and environmental requirements to product reliability. The trend towards further increases in the number of variants of end products and the resulting decrease in batch sizes for individual variants is also driving the need for virtual validation. Industries with low product quantities, including a batch size of 1, require a largely hardware-free approach to product development due to the high cost of setting up product tests.

Furthermore, the increasingly cross-company development of these products and systems, e.g., in cooperation between OEMs and system suppliers, between different OEMs and also new forms of cooperation between OEMs and software development partners, pose additional challenges. The traceability and reproducibility of decisions made on basis of virtual validation and verification in product development are of particular importance.

There is also an increasing need for the verifiability of simulation-based decisions and releases to third parties such as external certification bodies – for example regarding homologation. However, the traceability and reproducibility of simulation tasks also play a key role in the context of other industries and their products, for example in the field of power plant construction, mechanical and plant engineering, or the development of pharmaceutical and medical devices.

The introduction of the digital twin results in additional requirements relating to the reproducibility of simulations. In the future, it will be possible to reproduce the behavior of a physical product using its digital representation at any time. The importance of the traceability and reproducibility of virtual behavior is also increasing as result of the trend towards a greater number of variants and products and the associated reduction in batch sizes.

The growing importance of virtual validation and verification means that the key challenge is generating the necessary level of trust in simulations. It is difficult to establish this level of trust without simulation-based decision making and release in product development.

2.1 Simulation-based decision making and release

One of the main activities in the ongoing prostep ivip SmartSE project in recent years is enabling decision making and release based on numerical simulations as a key component of model-based development. This is a major motivator for current SmartSE activities such developing solutions for ensuring the traceability and reproducibility of simulation tasks.

During the hierarchically superior and usually sequential development process of the overall product, numerous decisions have to be made about the product design and release of subsystems, components and functions of the product. Many of these decisions could be made on basis of virtual validation and verification.

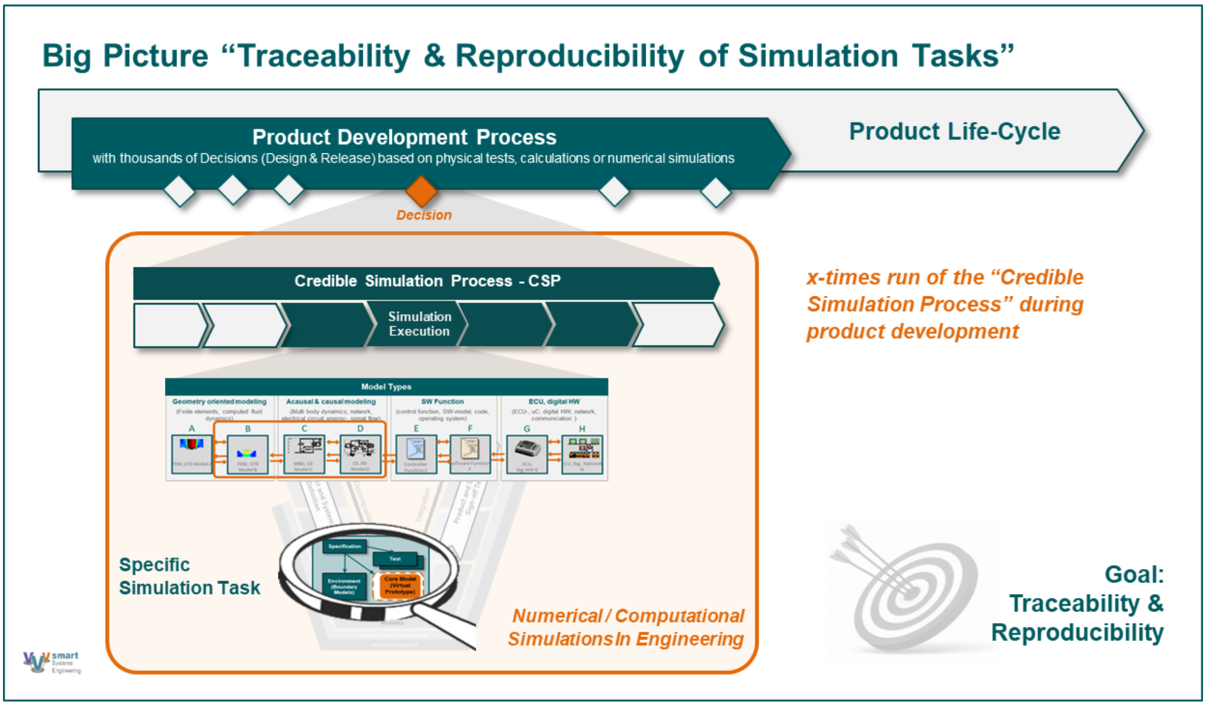


Figure 1: Traceability & Reproducibility of Simulation Tasks within the product development process

Basic requirements for **simulation-based decision making** are:

- The simulation must be integrated in the development processes.
- Statements about the credibility of the results must be available.
- Traceability and comprehensibility must be guaranteed.
- Support for increasingly cross-company development scenarios.
- Procedures and infrastructures for simulation-based decision making and release should therefore be coordinated industry wide.

2.2 Influencing factor “RISK” on decision making

The "risk" associated with the decision plays a central role in decision-making processes about a product or system to be developed, which are to be made on the basis of numerical simulations. It is therefore an important influencing factor for the decision to be made.

In general, the potential risk associated with a decision for a product or system to be developed is determined by a series of questions:

- Scenarios: ***What** could happen?*
- Likelihood: ***How** likely is it to happen?*
- Consequence: ***What** is the impact if it did happen?*

The credibility of simulations and their results strongly influences the decision to be made and the weighing up of the associated risk.

Inaccuracies in the input data, uncertainties in the model parameters or unforeseen external influences can affect the reliability and credibility of the simulation results. It is therefore crucial that decision-makers are able to assess and understand the risk associated with the simulation results.

On the other hand, a transparent presentation of uncertainties and risks strengthens the trustworthiness of the simulation results and makes it possible to recognize and evaluate potential weaknesses.

A distinction can be made between 3 levels when considering risk in the context of decision-making:

> ***Data** are the fundamental driving force for informed decisions. MBE methods (simulation, real testing, calculation) support the meaningful data generation.*
>
> ***Risk** is the potential for performance shortfalls which may be faced in the future. Thus, risks play a a central role as a further influencing factor in the decision-making process.*
>
> ***Human beings** are key for decisions as they evaluate the risks and eventually make a decision. The evaluation of the risk is not unique as human beings are complex beings which are influenced by many factors (e.g. emotions). Thus, the decisions at a given situation with given risks may differ completely.*

A simulation-based decision should provide a transparent, comprehensible link between the underlying data, the potential risk and the decision made.

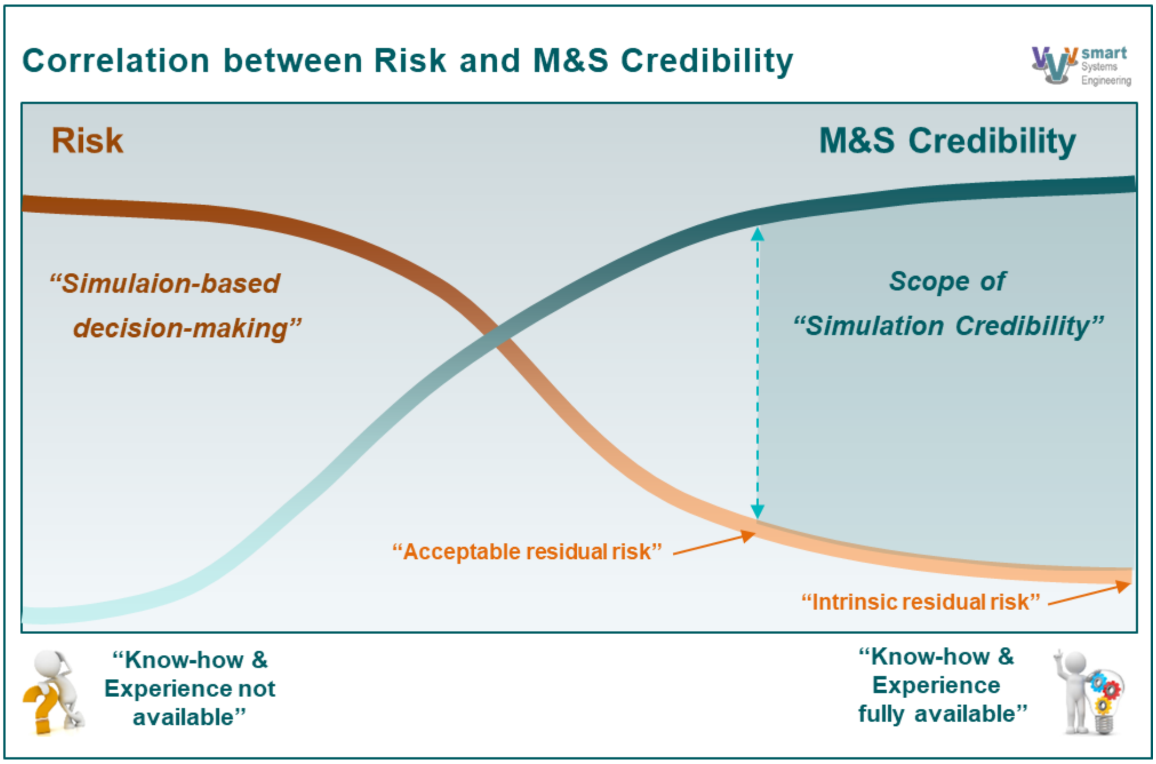


Figure 2: Correlation between risk and credibility

Overall, the inclusion of risk assessment in decision-making processes based on the results of simulations is an important factor in the development of complex products and systems.

2.3 Current use of virtual simulations for decision making and release

As part of the SmartSE project, in-depth interviews were conducted in 2020 with experts in virtual validation and verification in the aerospace and automotive industries on the current state of numerical simulation for decision-making purposes and the explicit release of subsystems, components and functionalities. The interviews focused on identifying examples, challenges and success factors for numerical simulations in both industries.

The current state of use of numerical simulations for decision making and release compared to real hardware-based tests in the automotive and aerospace industries can be summarized as follows:

> *In the **automotive industry**, people have so far been rather reluctant to "rely" on simulations. If possible, tests are carried out with real vehicles for final release. However, the advantages of simulations in the early development phase have been recognized and used. Simulation*

> *will gain in importance in the field of autonomous driving in the next few years. The reason for this is that, like in the aerospace industry, there is no alternative to simulations.*
>
> *Simulation has been used successfully in the **aerospace industry** for a long time. Here, people "trust" simulations because they have experience with them. In addition, they are "forced" to rely on simulations for certain validations, since there is no alternative.*

These assessments were also confirmed by the other members of the SmartSE project group.

For a detailed description of the current state of the use of numerical simulations for decision making and release based on the interviews conducted, please refer to the white paper "Simulation-based Decision Making and Release.

(link: https://www.prostep.org/fileadmin/downloads/PSI_WhitePaper_SimulationBasedDecisionMaking.zip).

3 Survey "Need for standardization of simulation criticality classes and model quality”

Accompanying the prostep ivip white paper "Simulation-based decision making and Release", a survey was conducted in the manufacturing industry with a focus on the automotive and aerospace industries on the importance and necessity of creating a quality standard for the criticality of simulation tasks and their meaningfulness.

The results of this survey are the starting point for the follow-up activities started in 2022 to initiate an international and cross-industry criticality standard or recommendation.

3.1 Criticality and need for quality standards or recommendation

If numerical simulations are to be integrated into decision-making and release processes to a greater extent, quality criteria for simulations and their artefacts must also be defined and taken into account. Appropriate quality criteria for the simulation models used, parameters, environment used and the evaluation of the criticality of a simulation task and thus the impact on the overall product are one of the success factors for simulation-based decision-making and release".

In the coming years, the ability to verify the quality of simulation tasks will not only be of particular importance to the automotive industry, e.g., for evaluating autonomous driving functions, but also other sectors such as the aerospace industry and others.

Since a simulation typically uses a large figure of simulation models from other areas and departments or from partners and suppliers, special attention must be paid to their quality. This means that minimum requirements regarding the quality and origin of a model must be defined and documented e.g., its origin and used V&V methods.

From the point of view of the SmartSE project group, this results in the following requirements regarding quality standards and criticality of the reliability of a simulation:

- Coordinated procedures and standards for determining and verifying simulation quality.
- Minimum requirements regarding the quality and origin of the models used.

At this point, it is useful to delineate the terms "credibility", "quality" and "fidelity" of a simulation and its results in the context of decision-making processes. All three terms are closely related, yet distinct concepts in the context of simulation and its results.

> *The **credibility of a simulation** refers to the confidence or reliability of a simulation and its results. It is about whether the simulation can be considered trustworthy and valid for making informed decisions. Credibility is therefore the quality that inspires and strengthens belief or trust in the simulation results. Credibility depends on several factors, such as the quality of the models used, the validation and verification of the simulation, the transparency of the assumptions used, and the traceability of the results. A credible simulation is robust, reproducible and has a solid basis on which decisions can be made.*
>
> *The **quality of a simulation** refers to the set of characteristics that determine the performance and reliability of the simulation. This involves the accuracy and reliability of the simulated models, compliance with standards and best practices, and consideration of the requirements of the use case.*
>
> *The **fidelity of a simulation** refers to the degree to which the simulation accurately represents the real system or phenomenon. It includes the detailed modeling of the relevant physical, functional, or behavioral properties of the system. High fidelity means that the simulation considers fine details and complex interactions between system components, thus providing a realistic representation of the system.*

The **credibility of a simulation** is closely related to its **quality. Quality** and **fidelity** depend on each other to a certain extent. As a rule, a high-quality simulation should also have a high "fidelity", since an accurate modelling of the real system properties contributes to the quality of a simulation". However, in certain cases, less accurate simulations may be sufficient if the quality of the results is acceptable for the specific application. However, "credibility" is an overarching concept that includes other factors such as validation, verification, and transparency to ensure that the simulation and its results can be trusted in a particular context.

Another relevant term for evaluating a simulation in the context of product development is the term **criticality**. Criticality is determined based on several factors, such as the accuracy of the simulation results, the impact of errors, and the decision relevance of the simulated aspects to the final product and thus the decisions made. The criticality of a simulation is used in the context of risk analysis, risk management, and decision making to ensure that resources and actions are appropriately focused on those areas or events that may have the greatest impact on safety, efficiency, or performance.

> ***Criticality of a simulation*** *refers to the importance and relevance of the results obtained by a simulation. It depends, among other things, on the accuracy and trustworthiness of models used, the validation and verification of your result, the impact of errors, the decision relevance, and the complexity of the simulation.*

High criticality means that the simulation results have a significant impact on the understanding, optimization, or validation of the product or system and the consequence of a wrong decision is dramatic. In such cases, credible simulation results are critical because they form the basis for important design decisions, performance improvements, or meeting specific requirements.

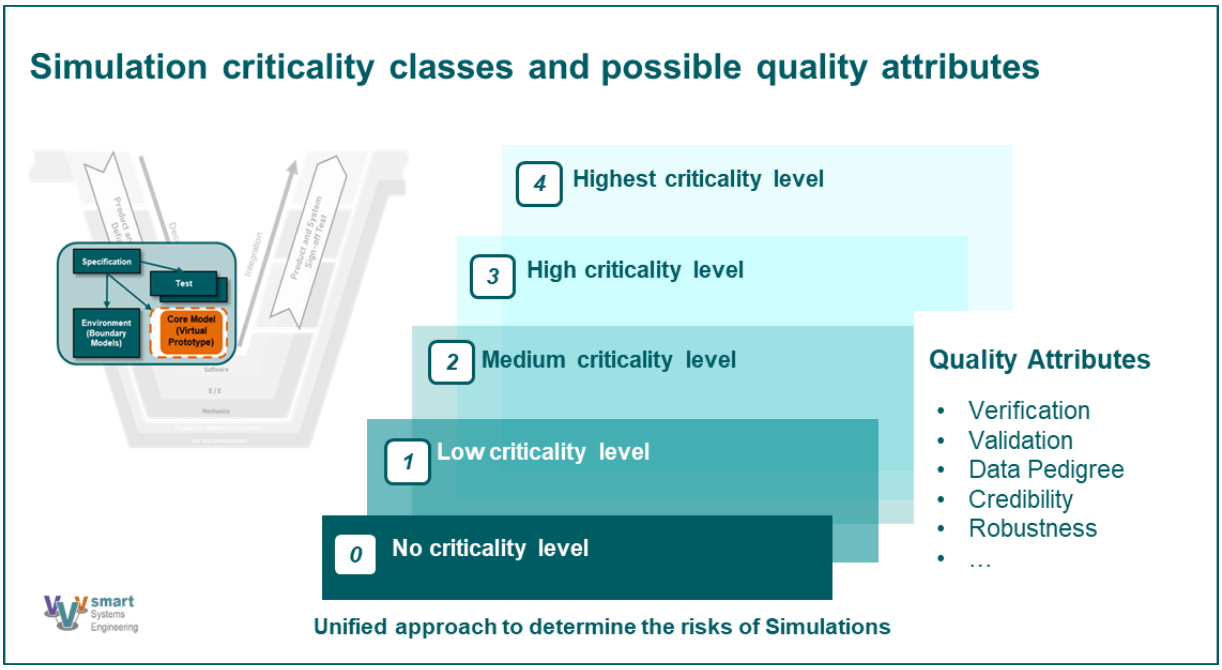


Figure 3: Simulation criticality classes and possible quality attributes

Figure 3 shows examples of possible criticality levels for classifying a simulation task and possible quality attributes.

3.2 Scope and results of the survey

By means of the questionnaire, the opinion of experts in the field of model-based development on the importance and necessity of creating a quality standard for the criticality of simulation tasks and the quality of the simulation models and artifacts used was requested.

The survey included the following questions:

1. *Do you see the need of an industry-wide quality standard?*

2. *Which of the characteristics of a quality standard do you consider useful?*

3. *There are three possible types of quality standards:*
   Which of the following characteristics of a quality standard do you consider as useful?
   - *A general standard for aerospace, automotive, pharmaceuticals, etc.*
   - *Industry-specific standards*
   - *A cross-industry core of the "quality standard") with industry-specific characteristics (significant for tool vendors))*

4. *Are you as a company willing to cooperate in the possible standardization of a quality standard?*

5. *Do you think that it should become a national or international quality standard?*

6. *Which national or international standardization body do you consider suitable?*

7. *Is your company willing to actively participate in the standardization of a quality standard and provide resources?*

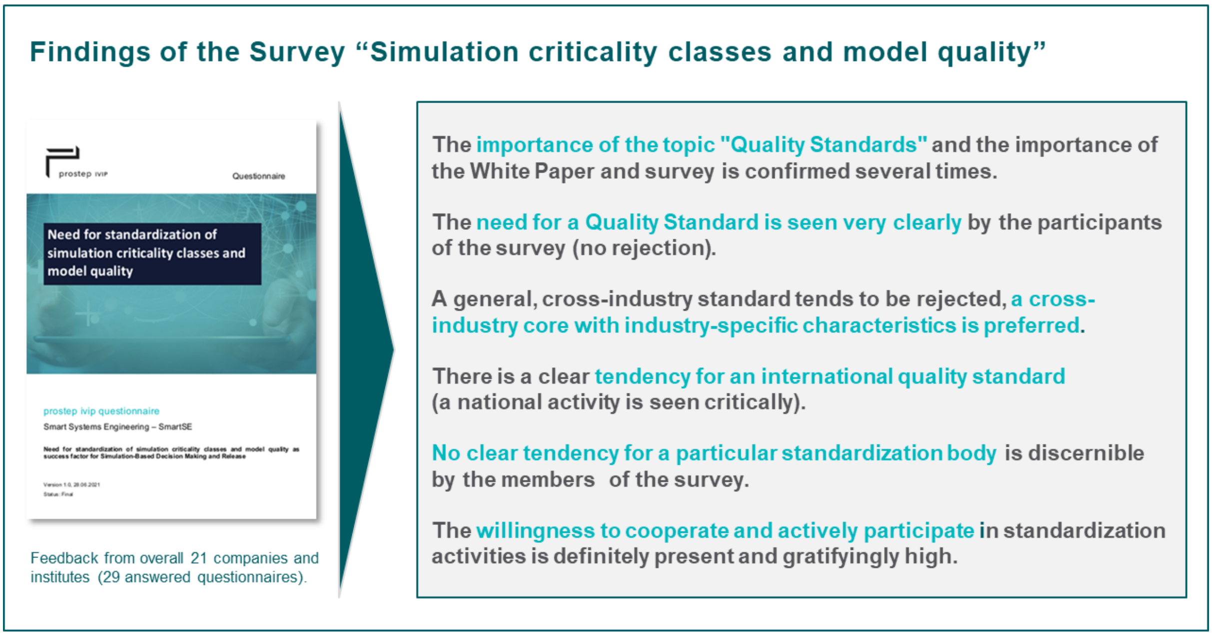
Companies from various sectors such as aerospace, automotive and power plant construction as well as research facilities with a focus on systems engineering took part in the survey. A total of 29 completed questionnaires from 21 companies were included in the evaluation of the survey.

The most important results are shown in Figure 4. The resulting objective of the SmartSE project can be summarized as follows:

SmartSE project group aims for:

(1) An industry-wide, international recommendation that is consistent with

(2) industry / domain-specific standards with high binding force.



Findings of the Survey “Simulation criticality classes and model quality”

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Questionnaire

Need for standardization of simulation criticality classes and model quality

prostep ivip questionnaire

Smart Systems Engineering – SmartSE

Need for standardization of simulation criticality classes and model quality as success factor for Simulation-Based Decision Making and Release

Version 1.0, 28.06.2021

Status: Final

Feedback from overall 21 companies and institutes (29 answered questionnaires).

The importance of the topic "Quality Standards" and the importance of the White Paper and survey is confirmed several times.

The need for a Quality Standard is seen very clearly by the participants of the survey (no rejection).

A general, cross-industry standard tends to be rejected, a cross-industry core with industry-specific characteristics is preferred.

There is a clear tendency for an international quality standard (a national activity is seen critically).

No clear tendency for a particular standardization body is discernible by the members of the survey.

The willingness to cooperate and actively participate in standardization activities is definitely present and gratifyingly high.

Figure 4: Findings of the Survey “Simulation criticality classes and model quality”

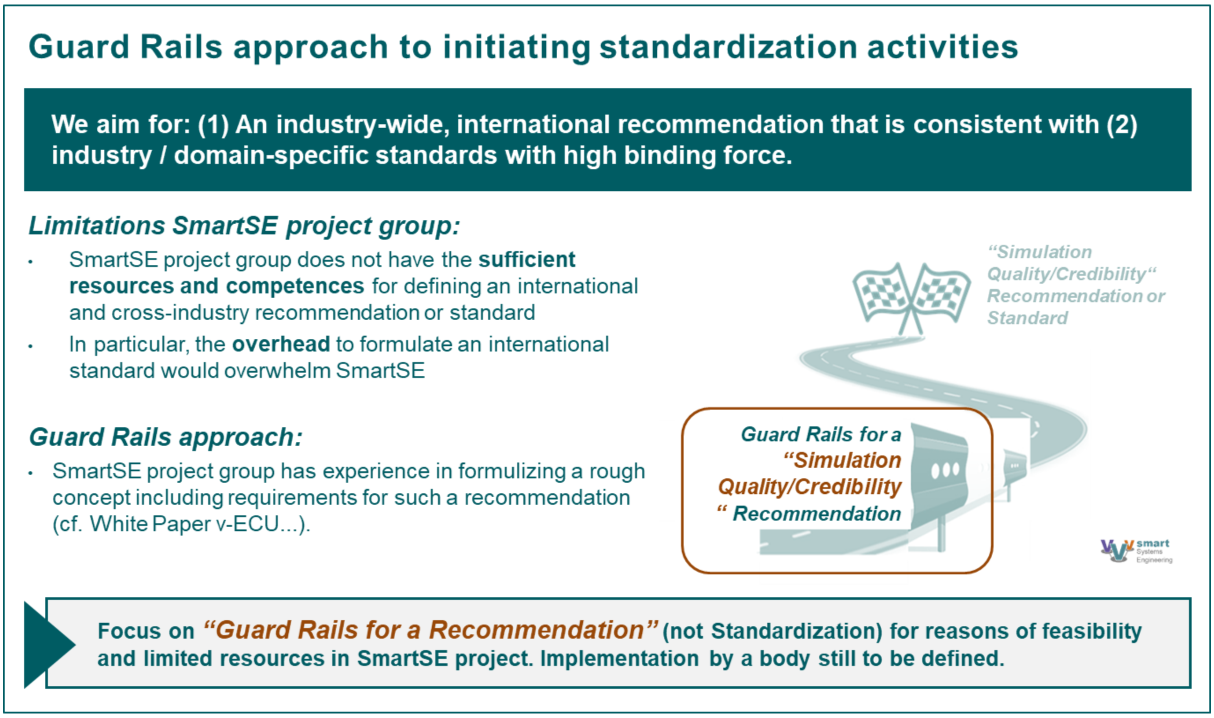
The feedback on the white paper "Simulation-based decision-making and release" and on the survey form the basis for the current follow-up activities of the SmartSE project group in 2022 and 2023.

3.3 Guard Rails approach to initiating standardization activities

Based on the previously presented results of the survey and the feedback on the white paper, the SmartSE project developed solution approaches such as the "Credible Process Framework for Simulation" and a possible procedure for the creation of an international credibility standard or recommendation.

The SmartSE project group confines itself to the formulation of a basic concept including requirements for such a recommendation (cf. White Paper v-ECU...). However, the standardization activities for such a Credibility Standard or Recommendation itself cannot be provided by the SmartSE project. This is due to the limited focus and objective of the SmartSE project on the one hand and the limited resources for standardization activities on the other hand. The expected effort for the development and coordination of a quality standard or recommendation cannot be provided by the SmartSE project. In addition, standardization should take existing activities and working groups in the simulation quality environment into account and, if possible, harmonize and further develop them.

For this reason, the SmartSE project follows a so-called Guard Rails approach. This approach is described in Figure 5.



Guard Rails approach to initiating standardization activities

We aim for: (1) An industry-wide, international recommendation that is consistent with (2) industry / domain-specific standards with high binding force.

Limitations SmartSE project group:

- SmartSE project group does not have the **sufficient resources and competences** for defining an international and cross-industry recommendation or standard
- In particular, the **overhead** to formulate an international standard would overwhelm SmartSE

Guard Rails approach:

- SmartSE project group has experience in formulizing a rough concept including requirements for such a recommendation (cf. White Paper v-ECU...).

Focus on *“Guard Rails for a Recommendation”* (not Standardization) for reasons of feasibility and limited resources in SmartSE project. Implementation by a body still to be defined.

Figure 5: Guard Rails approach to initiating standardization activities

The claim of this white paper is to describe a rough concept and the framework as well as the solution space for the design of an international, cross-industry credibility recommendation. Theses guard rails serve as a kind of high-level specifications for a credibility recommendation yet to be worked out.

The development of a final simulation credibility recommendation or standard can sensibly only be carried out by a standardization body with international and cross-industry competence that has yet to be determined.

4 Credible Process Framework for Simulation

Within the SmartSE project, different approaches, and tools for "Simulation-based decision making and release" will be developed and described. In addition, activities for a required "Simulation Credibility Recommendation or Standard" will be initiated and coordinated. An essential element for the initiation of these standardization activities is the development and description of a process framework "Credible Process Framework for Simulation". This process framework embeds engineering simulations into decision processes of product development, describes essential processes on the level of decision and coordination as well as on the level of simulation. In addition to the process framework, organizational aspects such as different decision-making levels on the one hand and the operational implementation of simulations and the associated roles on the other are also considered below.

The SmartSE project focuses on **numerical engineering simulations,** which are used for decision making within the product development process. However, it must be emphasized at this point that product-related decisions can be based on a wide range of information, data and experience. Only a part of it is based on numerical simulations.

> ***Engineering simulation:*** *The use of physics-based mathematical (numerical) models and/or logical models, including relevant data derived from their physical model counterparts, as representations of a conceptual or real-world system, phenomenon, or process in studying its technical requirements and operational behavior.*

One limitation of the "Credible Process Framework for Simulation" presented in the following is the decision-making processes and engineering simulations in the product development phase as part of the entire product lifecycle. This limitation is due to the focus of the SmartSE project and the competencies available there. However, it can be assumed that the process framework with its focus on simulation-based decisions can be extended and applied to the entire product lifecycle and thus also to the areas of manufacturing, operation, maintenance and disposal.

In addition to emphasizing the importance and inclusion of simulation in the product development process, the Credible Process Framework for Simulation is intended to bridge existing credibility standards in the field of simulation and modeling with the business processes of developing complex products and systems.

The “**Credible Process Framework for Simulation”** (Figure 6) provides a structured approach for using numerical simulation to support decision making and simulation-based approval in the product development process.

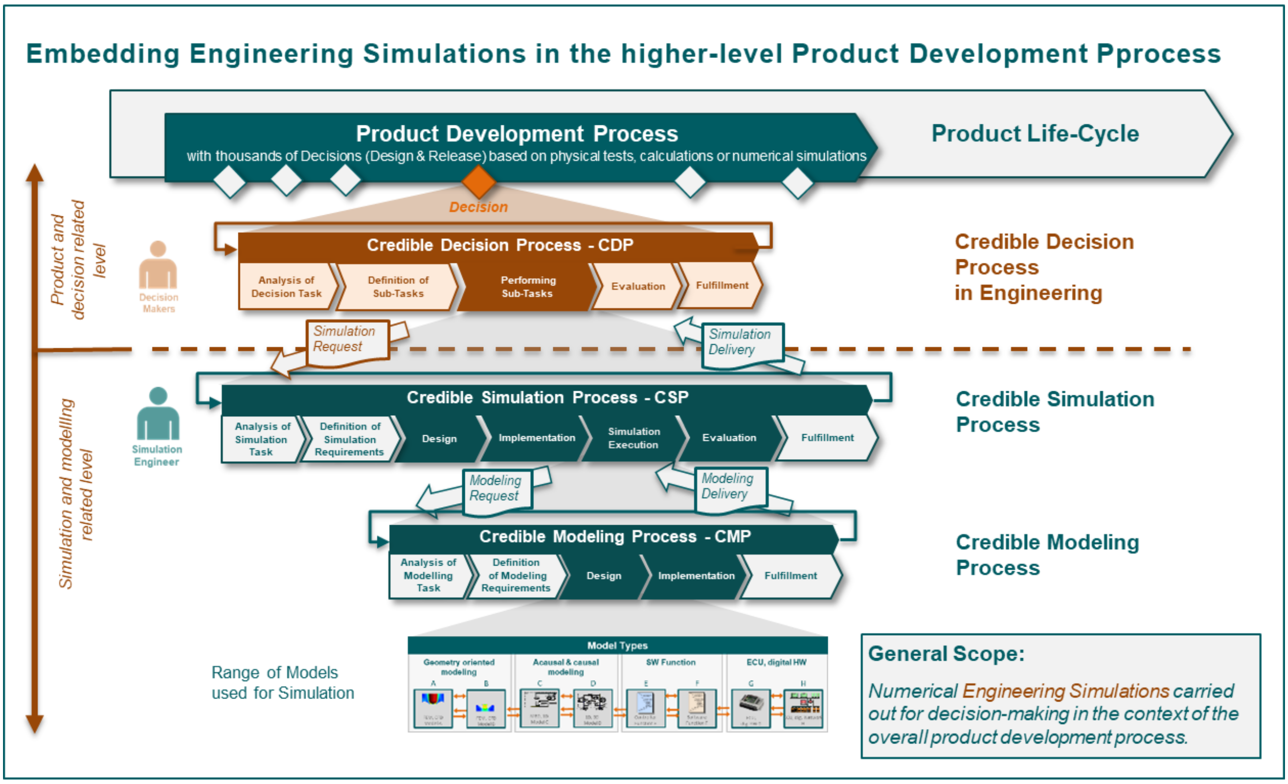


Figure 6: Embedding of engineering Simulations in the higher-level Product Development Process

Within the product development process, a large figure of product-related decisions have to be taken. These decisions are represented by the diamond symbols.

The process framework "Credible Decision Process Framework" represents a logical sequence but not a strictly temporal sequence of activities and sub-processes. The repeated execution of sub-processes (recursions, learning loops, ...) as well as their execution in different phases of the development process are explicitly possible.

Some of the decisions to be made may be based on the results of numerical simulations. However, it is important to emphasize that decisions can also be based on other results.

For decisions to be made can be used besides numerical simulations:

- *Expert judgement*
- *Calculation*
- *physical tests*
- *descriptive models (testing for (logical) correctness, completeness) Credibility is enhanced by learned patterns.*

A single decision within product development can be described and coordinated within this process framework by the **Credible Decision Process (in Engineering).** This process includes and considers both the definition of the decision objectives, the definition of the questions to be answered by the simulation, and the clarification of the decision criteria and the expected results.

Also, the criticality of the decision, the sub-system or component to be simulated and thus its impact on the overall system or product should be determined here.

A possible repeated execution (loop) of the Credible **Decision Process (in Engineering)** within the development process is symbolized by the loop/arrow (return). These loops symbolize learning loops, which serve to build up and use knowledge and experience.

*The **Credible Decision Process (in Engineering)** is described in detail in Chapter 4.2.*

On the level below, the **Simulation request** (trigger) of the **Credible Decision Process (in Engineering)** triggers the **Credible Simulation Process - CSP**. This describes the activities and steps necessary to plan and execute the engineering simulation. It includes the definition of the simulation methodology, the collection and preparation of the required data, the selection of the appropriate simulation tools and the definition of the assumptions and boundary conditions for the simulation.

*The **Credible Simulation Process – CSP** is described in detail in Chapter 4.3.*

The **Modeling Request** of the CSP then triggers the **Credible Modeling Process** at the next level down. Within this sub-process of the simulation, the models are created that are to represent the real world. This includes identifying the relevant influencing factors, defining mathematical equations and relationships that describe the system, and validating the models against real data.

*The **Credible Modeling Process** is described in detail in Chapter 4.4.*

According to the SmartSE project, the **Simulation Tasks** is the actual execution of the numerical simulation with the created models. It is thus the specific execution of the Credible Simulation Process (CSP). A Simulation Task combines models from different domains (mechanics, E/E, embedded software), different departments, but also from different partners in a specific simulation. In contrast to this, MBSE involves modeling at a domain-neutral level, e.g., using SysML.

A detailed description and clustering of the simulation tasks can be found in the SmartSE Recommendation V3 published in 2022 (link).

4.1 Organization aspects of the process framework

Within the process framework, a fundamental distinction can be made from the point of view of simulations between the higher level, strategic planning, coordination and safeguarding of the product development process with the decisions made on basis of simulations on the one hand, and the level of execution of the concrete simulations and creation of the models required for this on the other.

This results in different focal points of the activities with regards to simulation-based decision-making at these levels.

Aspects in product and decision related level (independent of simulation):

- *What is the specific environmental, economic, safety, and social decision criticality (hazard)?*
- *What contribution does the sub-tasks or process have to the decision-making process (M&S Influence)?*
- *What is the impact in case of a wrong decision (decision consequence)?*

To the level of simulation and modeling is passed:

- Context of use for Simulation
- Result of hazard and risk analysis
- Specifications for confidence of safeguard measures

Based on this input, protective measures are then implemented according to the risk analysis.

These fundamentally different focal points of the two levels of the process framework thus also result in different roles with regards to the execution of the above-mentioned activities.

At the level of planning and safeguarding the product development process, including the decision-making processes, this is the **decision-maker** as distinct from the **simulation engineer** at the level of the concrete simulation process and model building.

The Decision Maker defines the overall goals, identifies the decision needs, evaluates the simulation results and makes informed decisions. In contrast, the **simulation engineer** develops the mathematical models, prepares the data, runs the simulations, and analyzes the results.

> ***Decision Maker***
>
> *The decision makers initiate and coordinates the tasks. They understand the credibility assessments and uses them for informed decision making.*
>
> ***Simulation Engineer***
>
> *In credible simulation the Simulation Engineer is responsible for the implementation of safeguard measures in accordance with the risk analysis, both with reference to modeling and simulation. He provides understandable simulation results and credibility assessments for the decision-makers.*

In summary, the **Decision Maker** has an overall strategic role and makes the final decisions, while the **Simulation Engineer** has an operational role and is responsible for the practical implementation of the simulations. Both roles are closely linked and work together to support the product development process and make informed decisions.

Depending on the complexity of the product or system and the complexity of the organization, the two roles and tasks of the **Decision Maker** and the **Simulation Engineer** can also be performed by one and the same person.

4.2 Credible Decision Process in Engineering (in detail)

The **Credible Decision Process (in Engineering)** describes a single decision to be made within product development.

> *The **Credible Decision Process (in Engineering) - CSP** includes the identification and definition of the decision objectives. It includes the definition of the questions to be answered by the simulation and the clarification of the decision criteria and the expected results.*

Identifying decision objectives:

This is where the specific questions and objectives are defined that are to be answered with the help of the simulation. It is important to clearly formulate the decision objectives to ensure that the simulation provides relevant information.

Determination of the decision criteria:

The criteria against which the various simulation scenarios are to be compared and evaluated are defined. This may include, for example, cost, performance, safety, or other important factors relevant to decision making.

Definition of expected results:

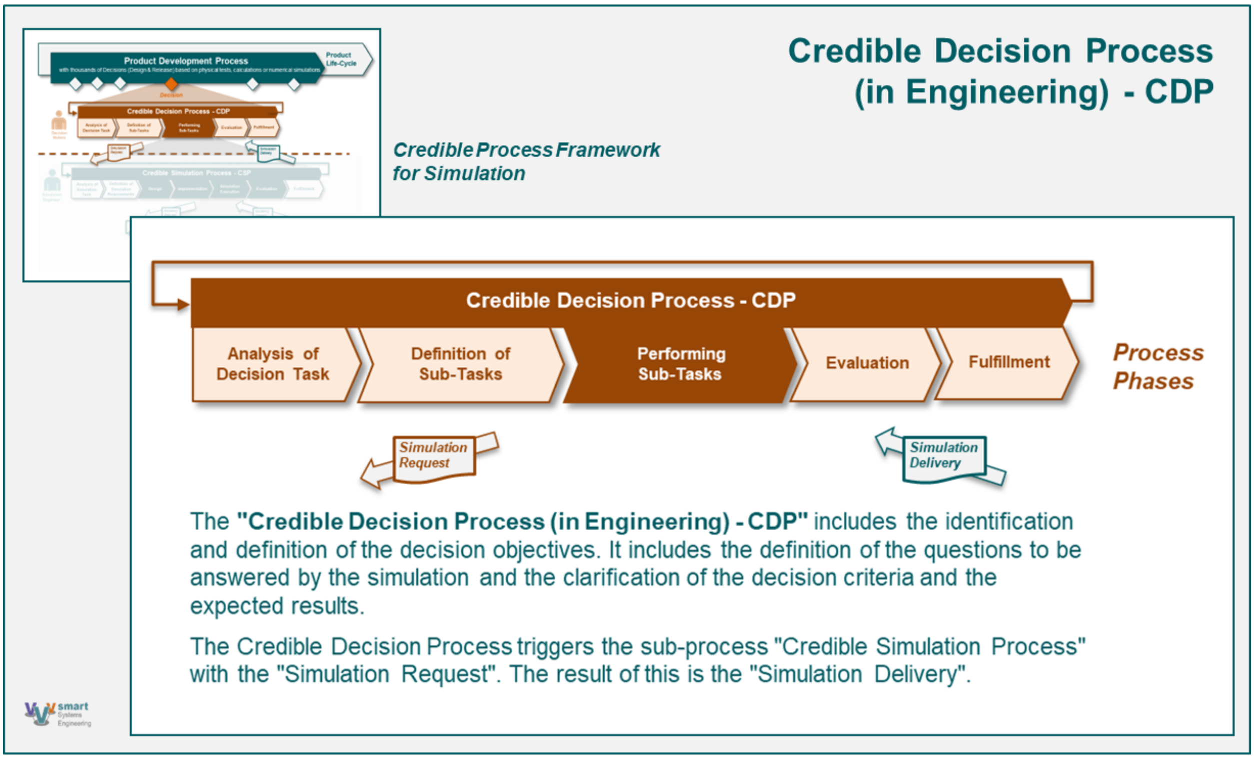
The expected results of the simulation are defined, including the desired information and metrics to be derived from the simulation results.

The **„Credible Decision Process in Engineering”** consists of the following process phases in detail:

- *Analysis of the Decision Task*
- *Definition of Sub-Tasks*
- *Performing Sub-Tasks*
- *Evaluation*
- *Fulfillment*

The Credible Decision Process triggers the sub-process **Credible Simulation Process** with the **Simulation Request**. The result of this is the **Simulation Delivery**.

The individual steps of the **Credible Decision Process (in Engineering) - CSP** are described in Figure 7.



The **"Credible Decision Process (in Engineering) - CDP"** includes the identification and definition of the decision objectives. It includes the definition of the questions to be answered by the simulation and the clarification of the decision criteria and the expected results.

The Credible Decision Process triggers the sub-process "Credible Simulation Process" with the "Simulation Request". The result of this is the "Simulation Delivery".

Figure 7: Process Phases of the "Credible Decision Process (in Engineering) - CDP"

4.3 Credible Simulation Process – CSP (in detail)

The **Credible Simulation Process - CSP** describes the activities and steps necessary to plan and execute engineering simulation.

> *The **Credible Simulation Process (CSP)** is a generic process, that intends to enable credible decision making with usage of simulation results. It supports the structured documentation of the relevant information and metadata within the execution of a specific simulation process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CSP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.*

Planning of the simulation:

This is where the flow of the simulation is planned, including timing, resource planning, and assignment of responsibilities.

Data collection and preparation:

The necessary data is collected to perform the simulation. This can include both historical data and future assumptions. The data must be prepared and, if necessary, cleaned to ensure that it is suitable for the simulation.

Selection of simulation tools:

Depending on the type of simulation, suitable software tools or platforms are selected to perform the simulation. The requirements of the simulation and the available resources are taken into account.

Determination of assumptions and boundary conditions:

The assumptions and boundary conditions that apply to the simulation are defined. This includes, for example, the assumption of certain parameter values, the definition of input variables and the consideration of constraints or limitations.

In detail, the **Credible Simulation Process (CSP)** comprises the following process phases:

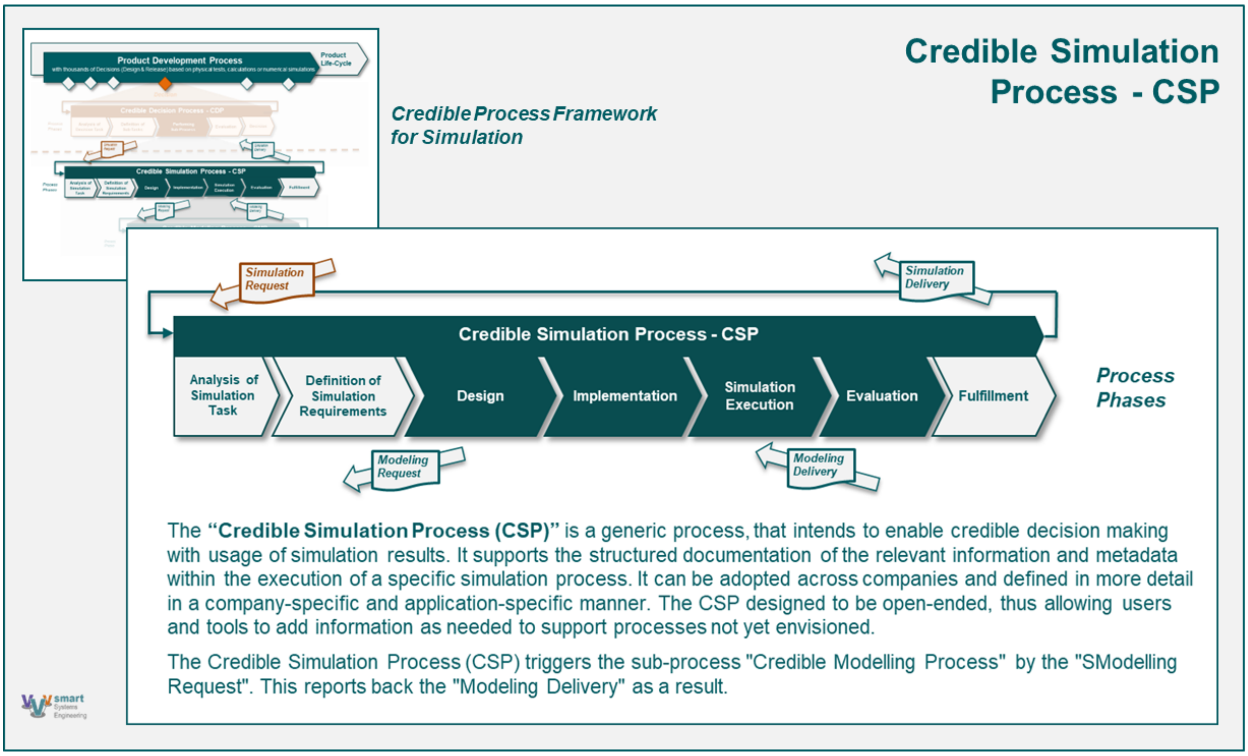
- *Analysis of Simulation Task **
- *Definition of Simulation Requirements **
- *Design (Specification for Simulation Setup) ***
- *Implementation (Simulation Models, Parameters, Tests, Simulation Environment) ***
- *Simulation Execution*
- *Evaluation (of Simulation Results & Assure Quality)*
- *Fulfillment (of Modelling Objectives)*

*) Product Know How flows into these two white phases must be done in close coordination with product experts.

**) Simulation setup includes relevant models, their parameters, test cases, the description of the simulation infrastructure and their interaction.

The **Credible Simulation Process (CSP)** triggers the sub-process **Credible Modeling Process** by the **Modeling Request**. This reports back the **Modeling Delivery** as a result.

The individual steps of the **Credible Simulation Process (CSP)** are described in Figure 8.



The **“Credible Simulation Process (CSP)”** is a generic process, that intends to enable credible decision making with usage of simulation results. It supports the structured documentation of the relevant information and metadata within the execution of a specific simulation process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CSP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.

The Credible Simulation Process (CSP) triggers the sub-process "Credible Modelling Process" by the "SModelling Request". This reports back the "Modeling Delivery" as a result.

Figure 8: Process Phases of the “Credible Simulation Process – CSP”

4.3.1 Loops of CSP for new and mature products (learned Patterns)

For the concrete execution of simulations according to the Credible Simulation Process (PSP), a general distinction should be made between new as well as established and mature products with regard to the product.

Use of simulation in new products and technologies:

For new products and technologies, the task and goal of the simulation as well as the relevant requirements are not yet known and must be defined by the product and domain experts. It is not possible to fall back on empirical knowledge.

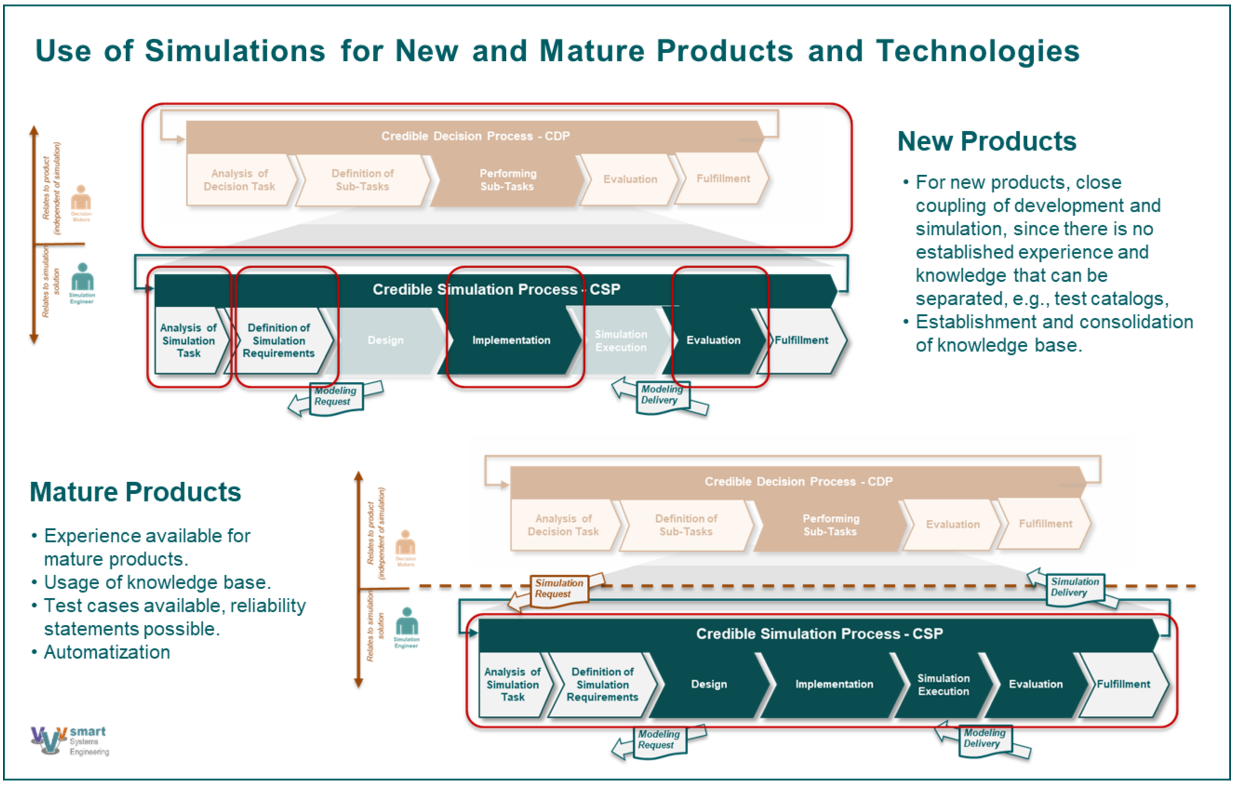
Among other things, this is to clarify:

- *What must be taken into account?*
- *What can be neglected?*
- *What is the credibility?*

The results of these clarifications and evaluations (learning loops) can be saved in knowledge and data bases and thus form the basis for validated predictions and statements.

Also the evaluation of the "quality" (phase 4) and 5 "evaluation" can only be done jointly between the product or domain experts and the simulation experts.

Figure 9 illustrates the relevant phases of the CSP for New Products and Mature Products respectively.



Use of Simulations for New and Mature Products and Technologies

New Products

- For new products, close coupling of development and simulation, since there is no established experience and knowledge that can be separated, e.g., test catalogs,
- Establishment and consolidation of knowledge base.

Mature Products

- Experience available for mature products.
- Usage of knowledge base.
- Test cases available, reliability statements possible.
- Automatization

Figure 9: Use of Simulations for New and Mature Products and Technologies

Use of simulation in mature products and technologies:

For mature products, knowledge about the task and goal of the simulation as well as the relevant requirements is ideally already available. Product and quality characteristics, for example, could be determined with the help of simulation on basis of test catalogues derived from databases and defined evaluation and interpretation criteria. In the case of simulation, a high degree of automation can also be achieved here.

This structure and use of knowledge and data bases is indicated by the recursion loops in the representations of the Credible Process Framework for Simulation and specifically in Figure 9.

If assumptions or boundary conditions change during development or use of the product (e.g.: load profiles over the lifetime), feedback loops must be present in the product-level processes to check whether the assumptions for the simulation have changed, and if so, whether the results are still valid.

4.4 Credible Modeling Process (in detail)

The specification and development of the models, the parameterization, the tests and the tool environment can be part of the CSP, but they can also be separate sub-processes that are then initiated by the higher-level CSP. The Credible Modeling Process (CMP) is specified for cooperation between different partners (client and contractor) and for reuse (model libraries).

The **Credible Modeling Process (CSP)** includes the steps of the models necessary to perform the simulation. This includes identifying the relevant influencing factors, defining mathematical equations and relationships that describe the system, and validating the models against real data.

> *The **Credible Modeling Process (CMP)** is a generic process, that intends to enable credible simulation. It supports the structured documentation of the relevant information and metadata within the modelling process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CMP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.*

Identification of relevant influencing factors:

Those factors that significantly influence the system to be simulated are identified. These can be physical properties, environmental conditions, operating parameters or other important variables.

Definition of mathematical equations and relations:

Mathematical models are developed that describe the relationships between the identified influencing factors. This can be done by differential equations, statistical models, empirical correlations or other mathematical methods.

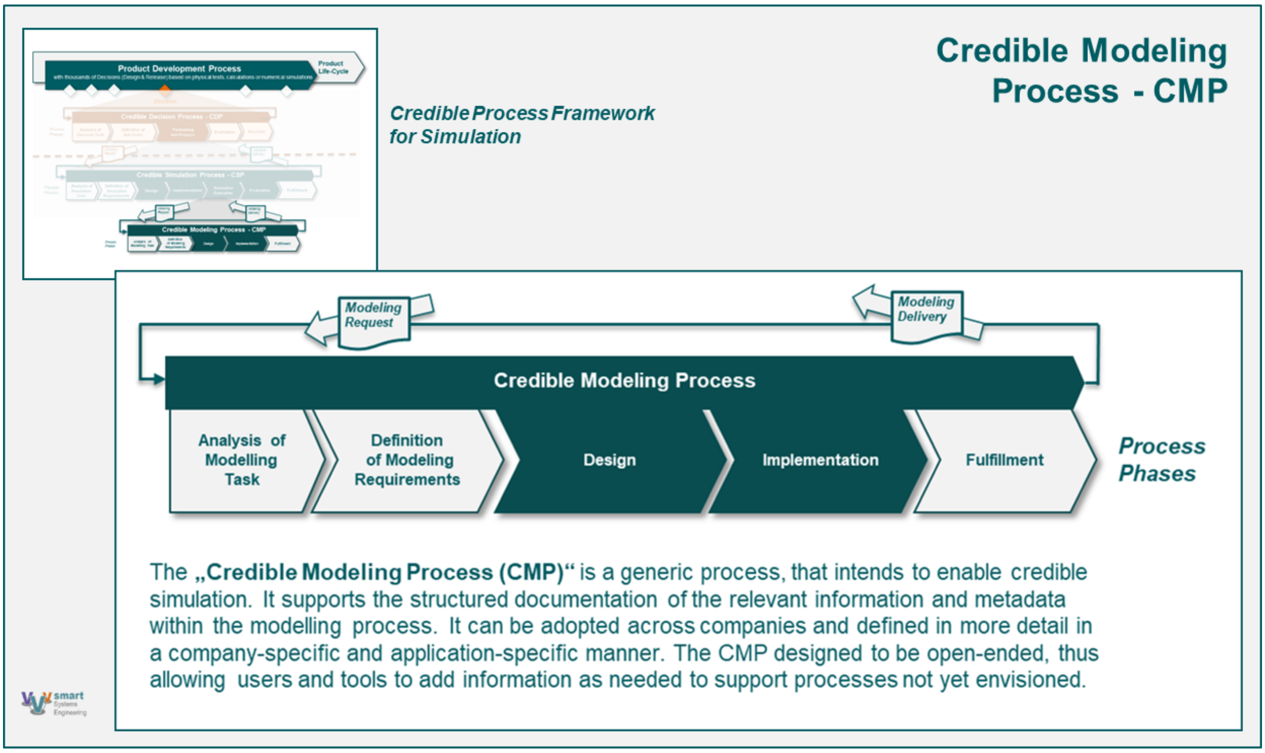
Validation of the models:

The models created are validated against real data or experimental results to ensure that they represent real conditions with sufficient accuracy. This involves comparing the simulated results with known reference data and checking the validity of the model.

The **Credible Modeling Process** includes the following process phases in detail:

- *Analysis of Modeling Task*
- *Modeling Requirements*
- *Design (Specification for Modeling Setup)*
- *Implementation*
- *Fulfillment (of Modelling Objectives)*

The individual steps of the **Credible Modeling Process** are described in Figure 10.



Credible Modeling Process - CMP

Credible Process Framework for Simulation

The **„Credible Modeling Process (CMP)“** is a generic process, that intends to enable credible simulation. It supports the structured documentation of the relevant information and metadata within the modelling process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CMP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.

Figure 10: Process Phases of the “Credible Modeling Process - CMP”

4.5 Sufficient terms and definitions explaining the credible simulation process framework

In this section, the terms used in the technical document to explain and better understand the approach of simulation-based decision making and approval as well as the Credible Simulation Process Framework are listed in a table and are important for its understanding. These are descriptions of the prostep ivip SmartSE project group based on definitions from international systems engineering working groups in such a way that they support the intention and understanding of the presented approach of "simulation-based decision-making and release" in the best possible and understandable way.

No.	Term	Brief description
1	**Simulation-based Decisions**	**Simulation-based Decisions** refer to decisions where simulation results are used directly as the basis for decision making. This means that simulations serve as the main source of information and decision makers directly consider simulation results to make their decisions. Simulation-based decisions can be particularly relevant when complex scenarios need to be analysed and an accurate quantitative assessment is required.
2	**Simulation-informed Decisions**	**Simulation-informed Decisions** refer to decisions where simulation results play a role but are not the sole basis for decision making. In simulation-informed decisions, simulation results are considered as an important source of information, along with other factors and information used in the decision-making process. The simulations provide additional insights and knowledge that help decision makers make better-informed decisions.
3	**Fidelity**	**Fidelity** is the accuracy of the model or simulation when compared to the real world. Simulation fidelity has to do with how well the simulation

		responds and how the results correspond to what the simulation is trying to represent.
4	**Credibility of a simulation**	The **Credibility of a Simulation** refers to the confidence or reliability of a simulation and its results. It is about whether the simulation can be considered trustworthy and valid for making informed decisions. Credibility is therefore the quality that inspires and strengthens belief or trust in the simulation results. Credibility depends on several factors, such as the quality of the models used, the validation and verification of the simulation, the transparency of the assumptions used, and the traceability of the results. A credible simulation is robust, reproducible and has a solid basis on which decisions can be made.
5	**Quality of a Simulation**	The **Quality of a Simulation** refers to the set of characteristics that determine the performance and reliability of the simulation. This involves the accuracy and reliability of the simulated models, compliance with standards and best practices, and consideration of the requirements of the use case.
6	**Fidelity of a Simulation**	The **Fidelity of a Simulation** refers to the degree to which the simulation accurately represents the real system or phenomenon. It includes the detailed modeling of the relevant physical, functional, or behavioral properties of the system. High fidelity means that the simulation considers fine details and complex interactions between system components, thus providing a realistic representation of the system.
7	**Criticality of a simulation**	**Criticality of a Simulation** refers to the importance and relevance of the results obtained by a simulation. It depends, among other things, on the accuracy and trustworthiness of models used, the validation and verification of your result, the impact of errors, the decision relevance, and the complexity of the simulation.
8	**Verification**	**Verification** ensures to implement the M&S correctly. In case of modelling it refers to whether a model meets the specified requirements. In this process, the models are checked for internal consistency, correctness and completeness. Verification ensures that the model has been created according to the defined modeling standards and that all internal connections and relationships are correct. Various techniques such as formal methods, model checking or simulation can be used for this purpose.
9	**Validation**	**Validation (BOSCH)** (M&S) ensures to implement the right M&S to obtain M&S results that represent close enough the real-world system. Validation is also Credibiltiy Attribute with credibility aspects Computational Model, Competitor Analysis, Applicability, Assessment.
10	**Engineering Simulation**	The use of physics-based mathematical (numerical) models and/or logical models, including relevant data derived from their physical model counterparts, as representations of a conceptual or real-world system, phenomenon, or process in studying its technical requirements and operational behavior.
11	**Credible Decision Process (in Engineering) - CDP**	The **“Credible Decision Process (in Engineering) – CDP”** includes the identification and definition of the decision objectives. It includes the definition of the questions to be answered by the simulation and the clarification of the decision criteria and the expected results.
12	**Credible Simulation Process (CSP)**	The **“Credible Simulation Process (CSP)”** is a generic process, that intends to enable credible decision making with usage of simulation results. It supports the structured documentation of the relevant information and metadata within the execution of a specific simulation process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CSP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.
13	**Credible Modeling Process (CMP)**	The “**Credible Modeling Process (CMP)”** is a generic process, that intends to enable credible simulation. It supports the structured

		documentation of the relevant information and metadata within the modelling process. It can be adopted across companies and defined in more detail in a company-specific and application-specific manner. The CMP designed to be open-ended, thus allowing users and tools to add information as needed to support processes not yet envisioned.
14	**Simulation Goal**	The **Simulation Goal** is the objective for which the simulation is being performed. It is usually part of some greater engineering task/goal.
15	**Simulation Tasks**	The **Simulation Tasks** is the actual execution of the numerical simulation with the created models. It is thus the specific execution of the Credible Simulation Process (CSP). A Simulation Task combines models from different domains (mechanics, E/E, embedded software), different departments, but also from different partners in a specific simulation. In contrast to this, MBSE involves modeling at a domain-neutral level, e.g., using SysML.
16	**Decision Makers**	The **Decision Makers** initiate and coordinate the tasks, are consumers of the credibility assessments, and are the ones who make decisions based on them.
17	**Simulation Engineer**	The **Simulation Engineer** is responsible for the execution and evaluation of the simulation including the modeling. In a credible simulation he is responsible for the implementation of safeguard measures in accordance with the risk analysis.

Table 1: Terms and definitions explaining the credible simulation process framework

A more comprehensive glossary of other terms relevant to model-based development from the SmartSE project group's perspective is currently being developed and is expected to be available via the prostep ivip association by the end of 2024. Our aim is to use different levels of detail for the terminology, which includes both comprehensive expert definitions and reduced descriptions for use in publications.

5 Exemplary characteristics of Simulation Credibility Levels and Assessment

Parallel to the creation of this white paper, a possible pragmatic approach for "M&S Criticality Assessment & M&S Credibility" was developed by BOSCH and presented and discussed in international standardization committees.

This approach will be presented here in brief in order to show exemplary aspects and sensible approaches as well as solution elements of a credibility recommendation or standard to be developed.

5.1 M&S Criticality Assessment & M&S Credibility

To unleash the benefits of Modeling and Simulation (M&S) and to enable simulation-informed decisions, the comprehensible communication of the criticality of the situation(s) or decision(s) to which the M&S results are applied must be established. The determination of the criticality is of paramount importance as it also specifies the rigor of the M&S efforts which are appropriate for the given engineering and simulation task.

Different approaches exist to determine the criticality of a decision or a situation respectively. However, the vast majority of the criticality assessments considers two aspects:

a) the consequences of a wrong decision, and
b) the degree of which M&S results influence a decision.

This approach enables a transparent determination of the criticality of a decision. Furthermore, it provides a proactive method to mitigate potential risks by supporting the derivation of appropriate M&S efforts.

5.2 Decision Consequence

The decision consequence assesses the impact of an M&S-influenced decision that may prove detrimental. The evaluation is carried out on the basis of various factors (e.g. safety, technology, costs and schedule).

Among other things, this is to clarify:

- **Safety** *from inconsequential to permanent disability or death*
- **Technical** *from no effect to severely degraded to none*
- **Cost** *from no effect to severe cost overruns*
- **Schedule** *from no effect to SOP missed*

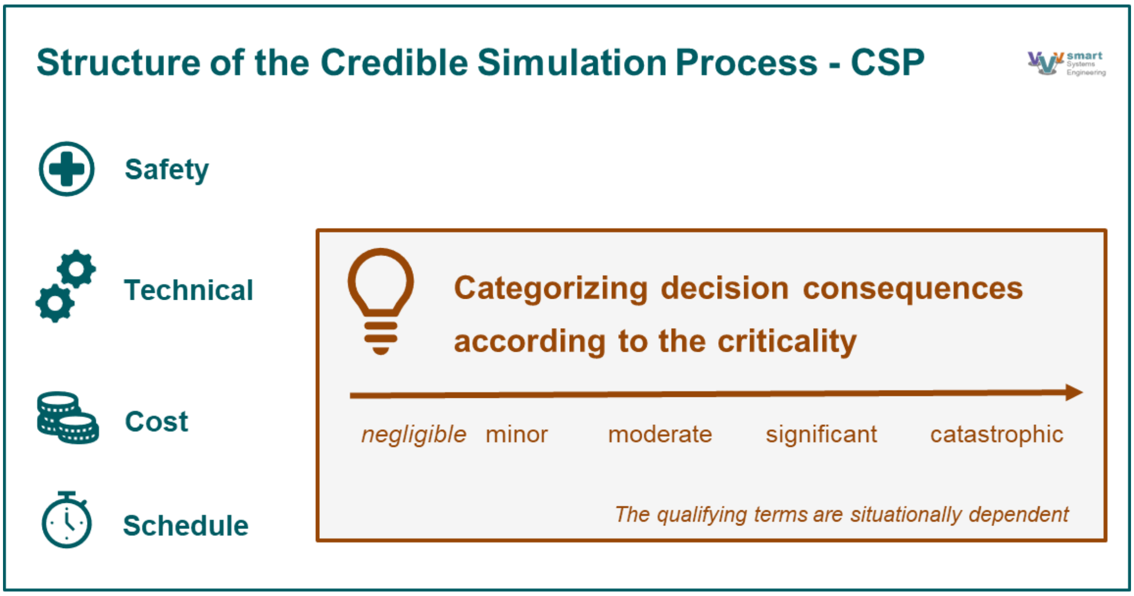
Depending on the project, product and business, stakeholders and technical authorities determine the dominating factor which is the most meaningful to the consequence assessment. Note, that the factors may express different points of views for the decision consequence. Nevertheless, the factors for the decision consequence can be categorized by consequence levels varying from negligible to catastrophic to support a comparability between the consequences (cf. table 2).

Decision Consequence factor	Negligible	Minor	Moderate	Significant	Catastrophic
Safety	Inconsequential	Minor detriment (first aid)	Minor injury or occupational illness	Severe injury or occupational illness	Permanent disability or death
Technical	Inconsequential	At most a temporary effect	Temporarily unavailable until restored; some minor degradation	Significant or permanent degradation until repaired	Severely degraded to none
Cost	Inconsequential	Minor cost impact but within nominal margins	Cost overruns beyond nominal margins, but not detrimental to program and project plan	Cost overruns detrimental to program or project execution or full completion	Cost overruns cause major program or project reductions or cancellation
Schedule	Inconsequential	Minor impact to schedule with no effect on major milestones	Internal schedule slips with no effect on major milestones	Impacts to major mission milestones	Operational (e.g., SOP start of production) windows missed

Table 2: Decision Consequences – adapted from NASA STD 7009A

5.3 M&S Influence

M&S influence estimates the degree to which M&S results impact the decision under consideration. This is predicated on the amount of other information available when making the impending decision (e.g. physical test results). As displayed in Figure11, the M&S influence can be categorized into levels which vary between negligible (e.g. other data or information will be available via physical tests) and controlling (e.g. no other data or information available).



Structure of the Credible Simulation Process - CSP

Safety

Technical

Cost

Schedule

Categorizing decision consequences according to the criticality

negligible minor moderate significant catastrophic

The qualifying terms are situationally dependent

Figure 11: M&S influence estimates

5.4 M&S Criticality Assessment Matrix

Using the two aspects Decision Consequence and M&S Influence, a M&S criticality assessment matrix can be built as depicted in Figure 12. This criticality assessment matrix can be used to transparently determine and to communicate the criticality of a decision.

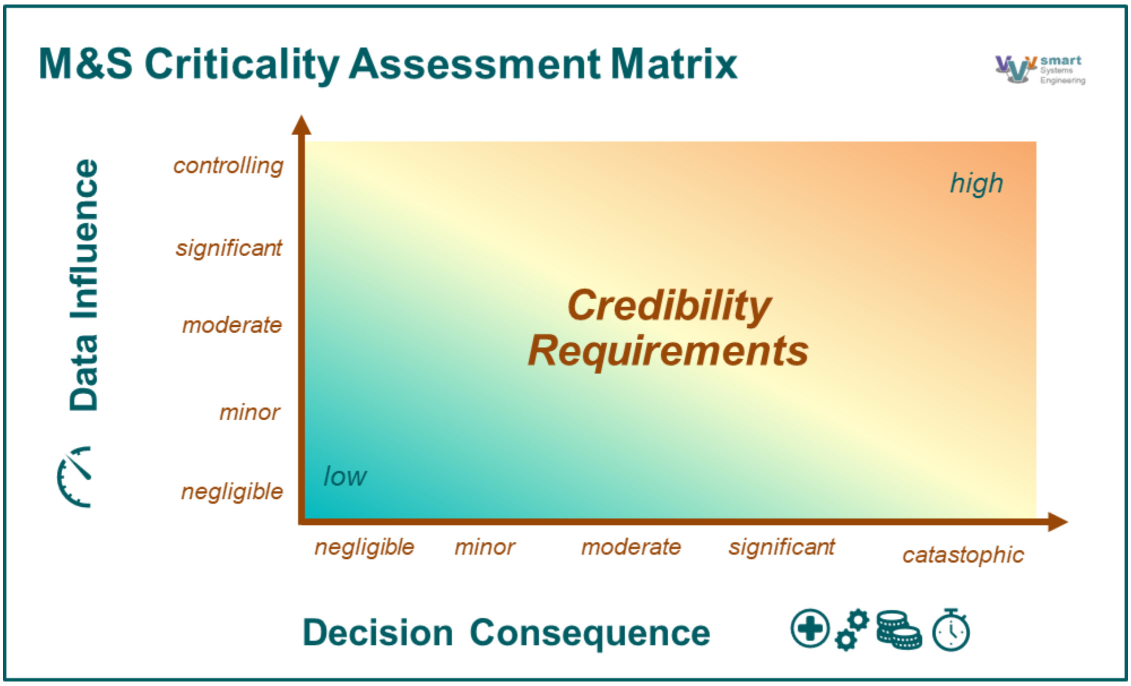


Figure 12: M&S Criticality Assessment Matrix

The determination of the criticality provides the necessary input to derive M&S activities to appropriately address the criticality of the decision. The more critical a decision, the higher the rigor of the quality requirements (i.e. credibility requirements) for the M&S results used in the decision-making process.

5.5 M&S Credibility

Once the criticality of the decision is determined, the M&S results need to satisfy the appropriate credibility level: low credibility level for low-critical decisions and high credibility level for high-critical decisions.

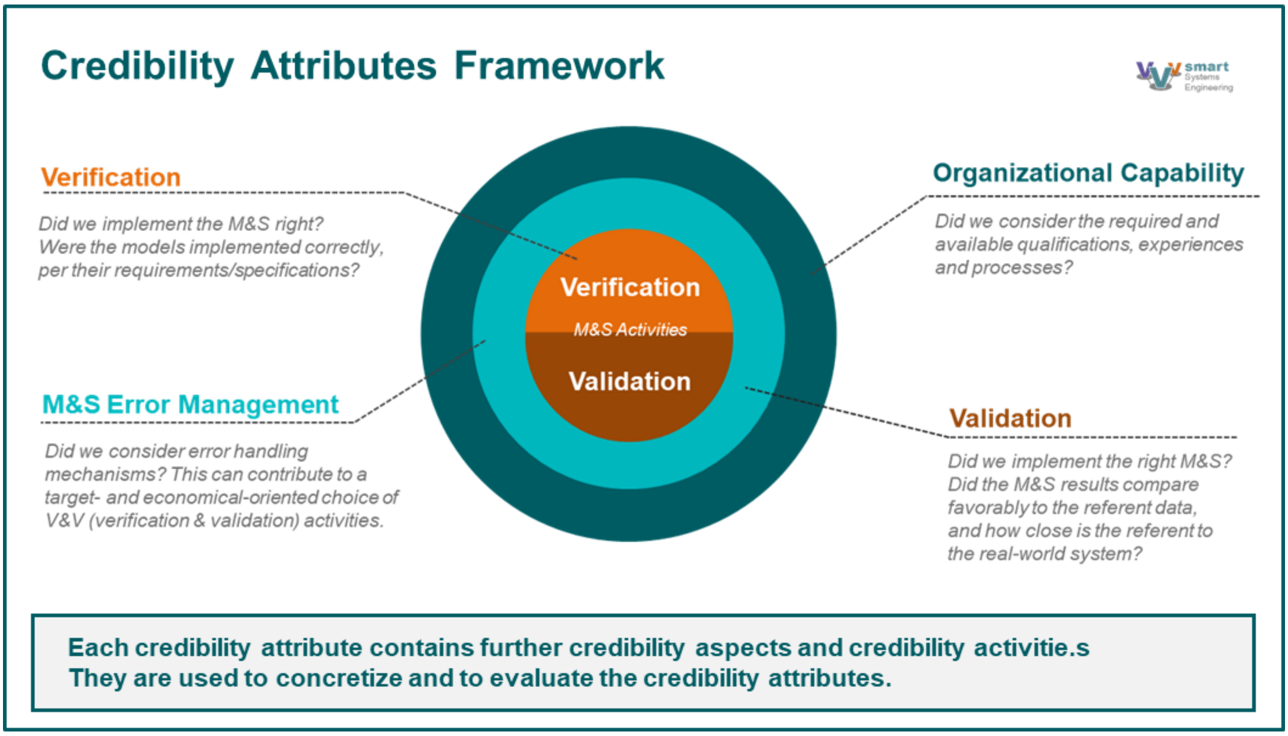
The credibility assessment of the M&S results is centered around the following four credibility attributes that address different perspectives of M&S credibility (cf. Figure 14):

1) ***Verification:*** *Did we implement the M&S right - according to their requirements/specifications?*

2) ***Validation::*** *Did we implement the right M&S? Did the M&S results compare favorably to the referent data, and how close is the referent to the real-world system?*

3) ***M&S Error Management****: Can we detect and mitigate M&S errors? This can contribute to a target- and economical-oriented choice of V&V (verification & validation) activities.*

4) ***Organizational Capability:*** *Did we consider the required and available competences, experiences, and processes?*



Credibility Attributes Framework

Verification

*Did we implement the M&S right?
Were the models implemented correctly, per their requirements/specifications?*

Organizational Capability

Did we consider the required and available qualifications, experiences and processes?

M&S Error Management

Did we consider error handling mechanisms? This can contribute to a target- and economical-oriented choice of V&V (verification & validation) activities.

Validation

*Did we implement the right M&S?
Did the M&S results compare favorably to the referent data, and how close is the referent to the real-world system?*

Verification

M&S Activities

Validation

**Each credibility attribute contains further credibility aspects and credibility activitie.s
They are used to concretize and to evaluate the credibility attributes.**

Figure 13: The four M&S credibility attributes

Each credibility attribute contains further credibility aspects and credibility activities. They are used to concretize and to evaluate the credibility attributes. The credibility aspects, in turn, can be divided in credibility levels (a) to (d), where level (a) represents the lowest credibility and level (d) stands for the highest credibility rigor. As indicated in Figure 14, especially the credibility aspects for the V&V activities serve as a basis for the systematic and transparent credibility assessment of the M&S results. The credibility spider chart, in turn, provides a compact summary of the credibility assessment and can be used for communicating the M&S credibility with the stakeholders (e.g. decision-makers and customers).

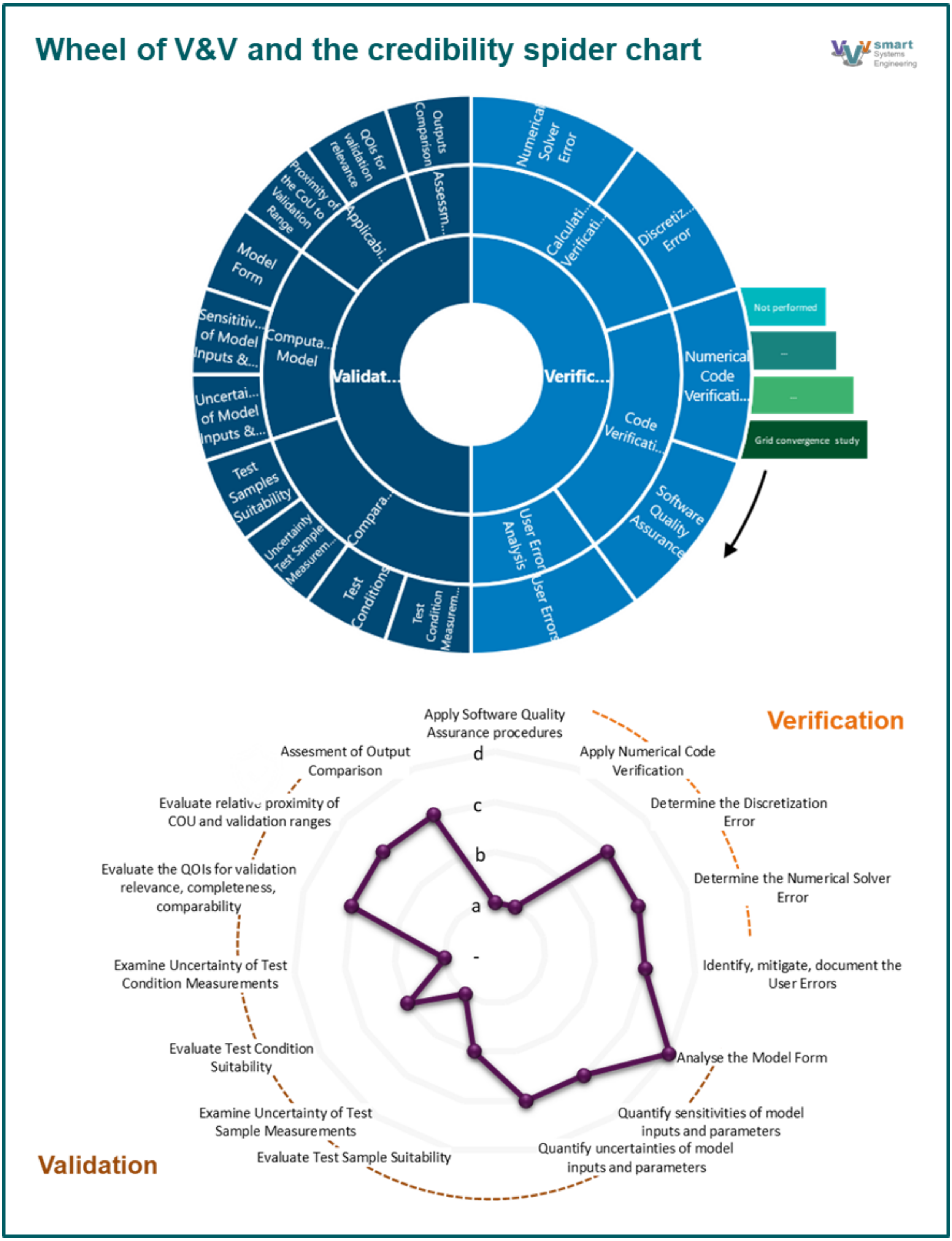


Figure 14: Wheel of V&V and the credibility spider chart

6 Roadmap for a "Simulation Credibility Standard and Recommendation"

This document, based on the white paper "Simulation-based decision making and release" published by the prostep ivip association in 2021, serves as a description of a possible procedure for embedding numerical engineering simulations in the decision-making process for complex technical products, as explained at the beginning. The goal of this process framework is primarily to describe basic guidelines for the creation of an internationally available credibility standard and recommendation.

A staged approach is proposed for the further procedure for creating an internationally available credibility standard and recommendation, which, however, only serves as a basis for discussion.

This document represents **“Step 0”** of such a procedure with the general description of the process framework and the explanation of key terms for understanding the framework.

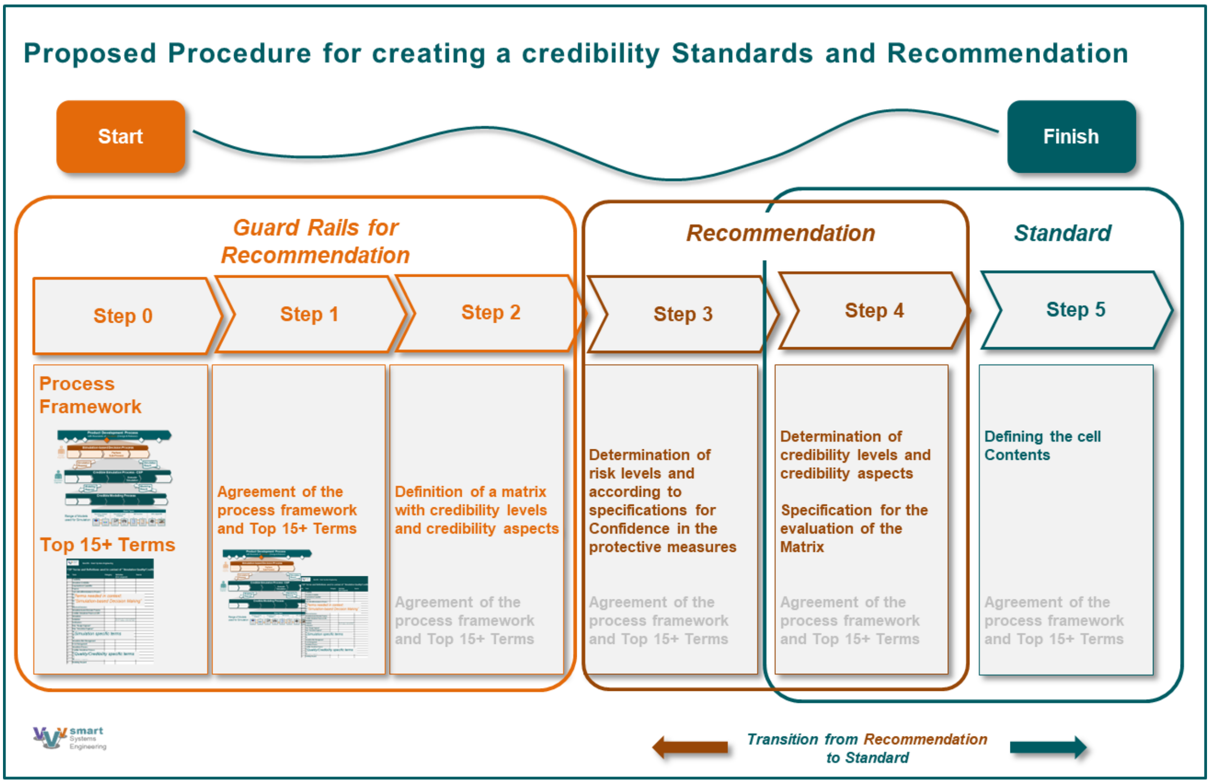
The following stages with work priorities appear to be useful for the further procedure:

> *We consider **"Step 1"** to be the official approval of possible standardization bodies for the Process Framework as a basis for future standardization activities. This ensures the accuracy and significance of this white paper.*
>
> *In **"Step 2",** the development of a matrix with credibility levels and credibility aspects is then considered appropriate.*
>
> *Based on this, the risk levels and corresponding specifications for confidence in the protective measures could be determined in **"Step 3".***
>
> ***"Stage 4"** should then include the determination of credibility aspects and credibility levels as well as the specification for the evaluation of the matrix.*
>
> *In **"Stage 5",** all cells of the credibility levels or matrix should then be filled as the core element of a credibility standard or recommendation.*

Another point that still needs to be clarified is up to which level it should be a general recommendation/standard and from which level an industry and domain-specific specification is necessary or useful.

This step-by-step approach can only serve as a rough procedural model for the creation of a recommendation or standard. This proposal is also intended to demonstrate the complexity of the task involved in achieving the goal of an international and cross-industry standardization activity.

The proposed procedure with the sensible steps is explained in Figure 15.



Proposed Procedure for creating a credibility Standards and Recommendation

Start

Finish

Guard Rails for Recommendation

Recommendation

Standard

Step 0

Process Framework

Top 15+ Terms

Step 1

Agreement of the process framework and Top 15+ Terms

Step 2

Definition of a matrix with credibility levels and credibility aspects

Agreement of the process framework and Top 15+ Terms

Step 3

Determination of risk levels and according to specifications for Confidence in the protective measures

Agreement of the process framework and Top 15+ Terms

Step 4

Determination of credibility levels and credibility aspects

Specification for the evaluation of the Matrix

Agreement of the process framework and Top 15+ Terms

Step 5

Defining the cell Contents

Agreement of the process framework and Top 15+ Terms

smart Systems Engineering

Transition from Recommendation to Standard

Figure 15: Proposed procedure for creating a credibility standard and recommendation

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