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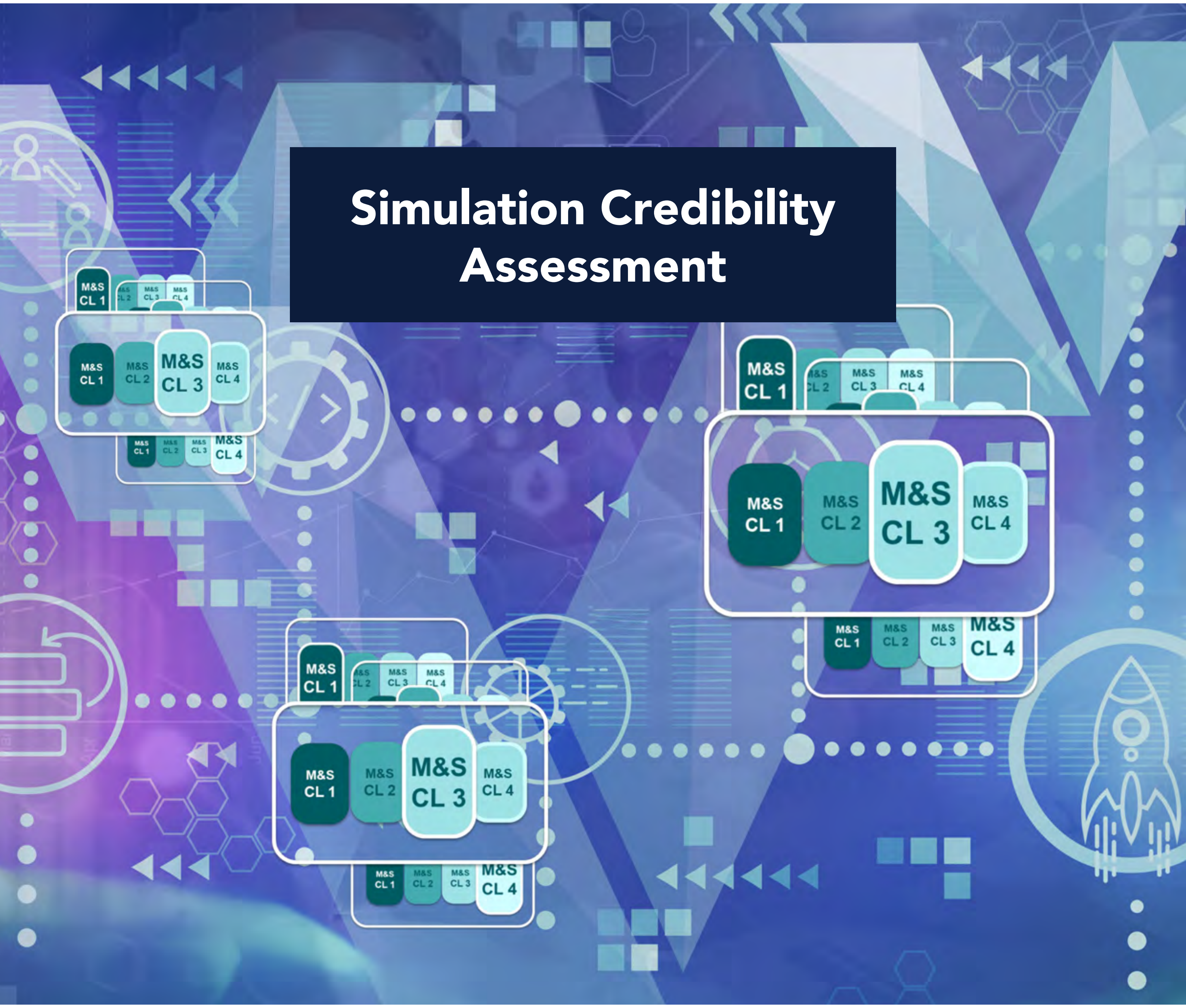
White Paper



prostep ivip White Paper

Smart Systems Engineering - SmartSE
Simulation Credibility Assessment

Version1, December 2025

Abstract

This white paper presents practical methodological approaches for determining and evaluating the simulation credibility of numerical simulations to be performed in the context of cross-company, model- and simulation-based development, as already used today in the automotive industry. These so-called "simulation credibility assessments" should be understood as an adaptable solution component on the way to a comprehensive simulation credibility standard or recommendation. The "M&S Credibility Level" presented serves as a comprehensible, qualitative evaluation criterion and link between product managers and decision-makers on the one hand and simulation engineers on the other. This document is based on the white paper "*Simulation-based Decision Making and Release*" published in 2021 by the SmartSE project group and the white paper "*Guard Rails for Simulation Credibility Standards and Recommendations*" from 2024. It expands on these with methodological approaches and industry examples for the necessary credibility determination and evaluation in connection with numerical simulations as an essential solution component.

Authors

This white paper, "Simulation Credibility Assessment," is a joint publication by the SmartSE – Smart Systems Engineering project group. The authors of the white paper are Robert Bosch GmbH, ZF and UNITY as consortium partners of the SmartSE project group.

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1 Introduction

Product development cycles are becoming increasingly shorter, while expectations for the performance, quality, and reliability of modern products continue to rise. As a result, companies face the challenge of making their development processes more efficient and cost-effective at the same time.

One method that has gained growing importance with the increasing virtualization of product development is the use of numerical simulations. The application of computer-based simulations and mathematical models has opened a new dimension in product design. It allows products and systems to be virtually created, analyzed, and optimized long before a physical prototype is built. This paradigm shift has revolutionized the way products are developed, enabling companies to bring products to market faster, with greater precision, and at lower cost.

Moreover, numerical simulations play a decisive role in engineering decision-making and technical release processes. Simulation-based analyses allow engineers to assess the behavior and performance of a product before it physically exists. They provide valuable insights into design options, operating conditions, and environmental factors - thereby supporting well-informed engineering decisions. On this basis, optimal technical solutions can be developed more quickly and efficiently, reducing both development time and the risk of costly errors or rework. Numerical simulations thus provide a reliable foundation for safe and robust product decisions.

Despite these advantages, the practical use of numerical simulations in many companies remains limited. Often, there is a lack of clear evaluation criteria and transparent measures for assessing the credibility and trustworthiness of simulation results. As a consequence, many decision-makers still rely on physical tests - even when meaningful simulation results are already available.

The **prostep ivip Association** is a global, independent network composed of members from manufacturing industries, IT providers, service companies, and the research community. Its mission is to drive the digital transformation of product development and production processes. The **Smart Systems Engineering (SmartSE)** project group within prostep ivip aims to provide building blocks for distributed, collaborative system development among partners. SmartSE develops application-oriented concepts to address the shared challenges of systems engineering (SE) and collaborative model-based development. The group consolidates and formulates the requirements of manufacturers and suppliers, defines standards and interfaces, and promotes technical norms that support the collaborative development of complex mechatronic systems.

A particular focus of SmartSE lies on **simulation-based decision-making and release processes**. Ensuring the traceability and reproducibility of virtual validation and verification is a central concern, as is the evaluation of criteria for assessing the quality of simulation models and their results.

Robert Bosch GmbH, ZF and UNITY, consortium partners in the SmartSE project group for the 2025 project year, are the authors of this white paper.

The goal of this white paper is to present **practical and adaptable methodological approaches** for assessing the credibility of numerical simulations, as they are already being applied in the automotive industry. These so-called **"Credibility Assessments"** can serve as a flexible framework on the path toward a comprehensive standard or industry recommendation for simulation credibility. The proposed **"M&S Credibility Levels"** are intended to provide a clear, qualitative evaluation scheme and a common communication interface between product managers and decision-makers on one side, and simulation engineers on the other. M&S stands for Modeling and Simulation.

This document extends the findings of the previously published **SmartSE White Paper "Simulation-based Decision Making and Release" (2021)** and the **"Guard Rails for Simulation Credibility Standards and Recommendations" (2024)** by adding methodological concepts and industry examples for determining and evaluating simulation credibility.

The intended audience of this white paper includes **quality managers** responsible for establishing methods and standards, **product managers and decision-makers** in product development, as well as **simulation engineers** involved in executing and validating simulations. For the latter, the proposed **four "M&S Credibility Levels"** provide a meaningful and standardized framework for communication and evaluation that can be consistently understood by all stakeholders.

2 Challenges of Virtualization in Product Development

The development of increasingly complex products and their functions - for example, automated driving in the automotive industry - requires a growing application of systems engineering methods, such as model-based development, to effectively manage product development. This, in turn, drives a rising demand for maintaining and advancing simulation capabilities across a wide range of applications.

The need to shorten product development cycles, combined with the steadily increasing share of embedded software for implementing product features and functions, often makes physical testing insufficient. Product validation increasingly relies on simulations, particularly in the early stages of product development. As a result, the proportion of numerical simulations relative to physical testing has significantly increased over recent years and is expected to continue growing. This trend is especially pronounced in emerging growth areas, such as autonomous driving and intelligent mobility, which are likely to drive disruptive changes in state-of-the-art technology. In these contexts, the **credibility of simulation results** and their **traceability** throughout the development process are critical to minimizing the risks of incorrect engineering decisions and to accelerating the development of innovative business domains.

Moreover, the growing **cross-company development** of these products and systems - for example, collaboration between OEMs and system suppliers, partnerships between different OEMs, and new forms of collaboration with software development partners - creates additional challenges. Ensuring the **traceability and reproducibility** of decisions based on virtual validation and verification is particularly important. There is also an increasing need for **third-party verification** of simulation-based decisions and approvals, for example by external certification bodies in the context of homologation. The introduction of the **digital twin** adds further requirements for reproducibility, enabling the behavior of a physical product to be replicated at any time based on its digital representation. The importance of traceability and reproducibility is further amplified by trends toward higher product variety and smaller batch sizes. However, traceability and reproducibility of simulation tasks are also critical in other industries, such as power generation, machinery and plant engineering, and the development of pharmaceutical and medical devices.

The key challenges of virtualization and simulation-based decision-making are illustrated in Figure 1.

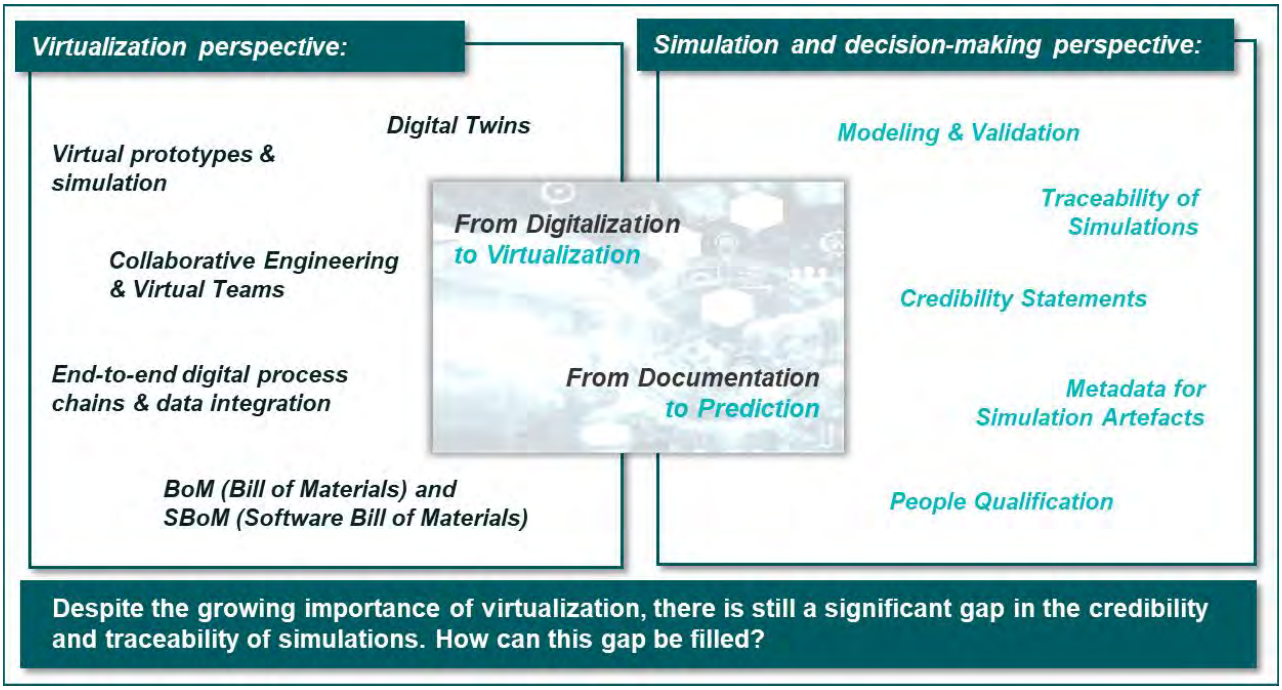


Figure 1 : Key challenges of virtualization and simulation-based decision-making

The increasing significance of virtual validation and verification, combined with the challenges outlined above, highlights the central issue of establishing an appropriate **level of trust in numerical simulations**. Depending on the **criticality of the decisions to be made**, it is therefore essential that simulations are **credible, transparent, and verifiable**. This creates a clear need for appropriate **methods to assess simulation credibility**.

3 Steps toward a Simulation Credibility Standard or Recommendation

“**Simulation-based development”** and the associated concept of **“Simulation Credibility”** have been central topics for the SmartSE project for many years. This work has led to the publication of two white papers: *“Simulation-based Decision Making and Release”* (2021) and *“Guard Rails for Simulation Credibility Standards and Recommendations”* (2024). These documents describe both the current state of numerical simulation use in model-based development and release processes and the need for a simulation credibility standard or recommendation.

In recent years, various topic-specific release standards - such as those in the context of autonomous driving - have emerged, allowing the use of numerical simulations for approvals. The overarching goal of the SmartSE project group has been to initiate a “general, cross-industry, and adaptable standard” for numerical simulation. Since SmartSE does not have the resources to fully develop such a standard, the project group has focused on establishing **guidelines and guard rails** for a future standard or recommendation. It remains open which organizations will ultimately develop and formalize such a standard or recommendation.

The use of numerical simulations instead of physical testing involves multiple critical success factors, including the quality of input data, the required level of credibility in simulation results, and the employed simulation methods and models. Standardizing approaches to assess the criticality of simulation tasks and defining quality-specific criteria for simulation models - based on product-level decisions and risk assessment - is a current focus of the SmartSE project. These approaches form essential methodological building blocks for a prospective **Simulation Credibility Standard or Recommendation**.

Numerical simulations are increasingly important in industries such as the automotive sector. Companies employ a wide variety of methods and training to ensure and achieve the required credibility of simulations. These so-called “Credibility Assessments” are, however, applied very differently across organizations. The goal of the SmartSE project is to harmonize these credibility approaches to enable consistent and comparable **M&S Credibility Levels**, especially in cross-company development and simulation activities.

Typically, the term “assessment” in the context of industrial standards (e.g., ISO norms, ASME V&V guidelines, INCOSE standards) refers to verifying compliance with and implementation of a specific standard in practice. The purpose of such assessments is to evaluate the maturity, quality, or credibility of processes, methods, or simulations.

Within the SmartSE project, a **“Simulation Credibility Assessment”** is understood as a methodological approach to evaluate the required credibility of a numerical simulation in the context of a product-level decision and its criticality. **M&S Credibility Levels** serve as a clear, qualitative evaluation criterion and as a communication link between product managers and decision-makers on one side, and simulation engineers on the other.

> ***SmartSE aims to create an applicable de facto “Credibility Standard*”** *by providing methodological approaches and practical building blocks, such as Simulation Credibility Assessments, until an international, industry-wide Credibility Standard or Recommendation becomes available.*

Figure 2 illustrates the steps from conducting Credibility Assessments to establishing a comprehensive, international Credibility Standard or Recommendation.

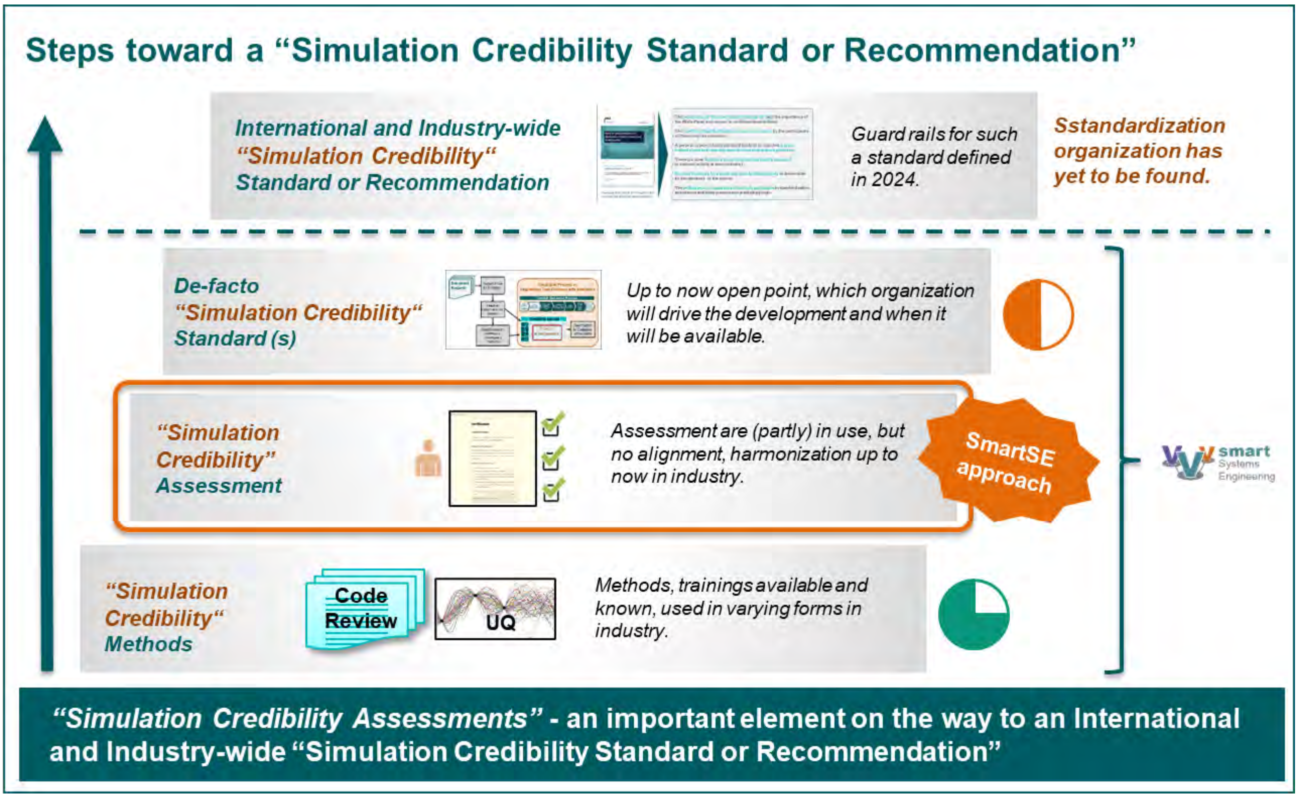


Figure 2: Steps toward a "Simulation Credibility Standard or Recommendation"

4 Credibility of Numerical Simulations and risk-based Decisions

Requirements for the credibility of a simulation result depend strongly on the specific application and the potential risk of a wrong decision. More precisely, if the modeling and simulation caused risk w.r.t. the engineering decision (M&S risk) is high, the requirements for the credibility of a simulation result will be high, leading to high requirements for M&S validation, which typically correlates with high effort for M&S validation

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".

Since a simulation typically uses a large figure of simulation models from several 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" and "fidelity" of a simulation and its results in the context of decision-making processes. Both 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 **credibility of a simulation** is closely related to its **fidelity**. High fidelity - meaning the precise representation of real system characteristics - significantly contributes to the perception of a simulation as credible. However, credibility encompasses more than just fidelity: it also involves aspects such as validation, verification, and transparency. Only the interplay of these factors ensures that a simulation and its results can be considered trustworthy within a specific application context.

Fidelity refers to how accurately a simulation replicates the real-world system, emphasizing detail and realism in modeling. While high fidelity contributes to credibility, it is not a prerequisite . What matters more is that the error margin of the simulation model is known and well-characterized, allowing users to assess the reliability of the results. Thus, fidelity is about precision, while credibility is about confidence and informed decision-making.

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 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 decision relevance of the results obtained by a simulation and the impact of errors in M&S, which may increase with the complexity of the simulation. The criticality of a simulation determines the requirements, among other things, on the accuracy and trustworthiness of models used and the validation and verification of M&S results.*

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.

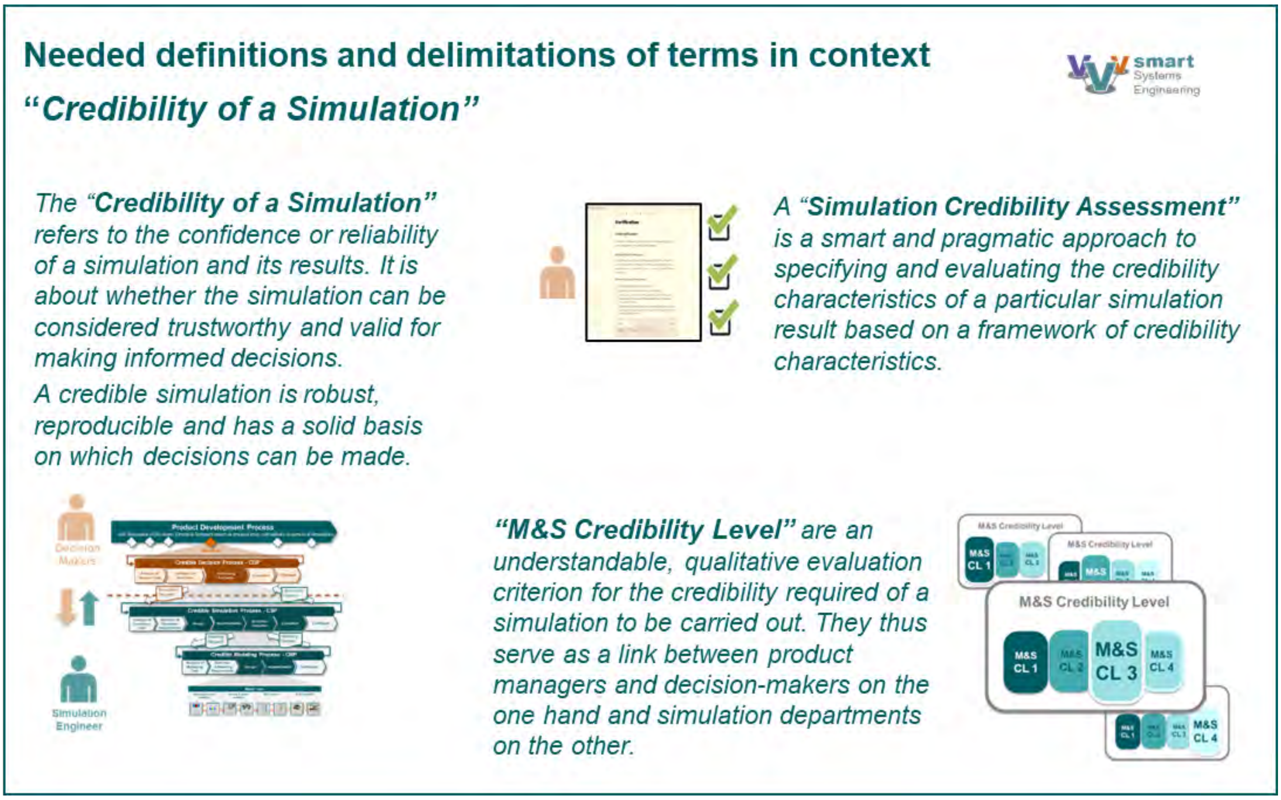


Figure 3: Needed definitions and delimitations of terms in context “Credibility of a Simulation”

4.1 Aspects of Simulation Credibility

The **“Credibility of a Simulation”** relies on several interconnected dimensions or aspects. First and foremost are the **process-related aspects**. For simulations and their results to be used reliably and transparently, process integrity is essential. To address this, the SmartSE project has developed the **“Credible Simulation Process Framework”**, which clearly distinguishes between the product level and the simulation level. At the **product level**, key requirements for the engineering methods including simulations to be conducted must be defined, along with the associated decisions based on their results. At the **simulation level**, the relevant information is processed. Exchange and alignment between these two levels are necessary, with responsibilities clearly defined and observed.

In addition, **methodological aspects** play a crucial role. Each simulation and its specific task must apply appropriate verification and validation procedures to ensure the required simulation credibility. Particularly important is the **documentation of the methods used** and the execution of a **Credibility Assessment**, which transparently evaluates the level of trust in the simulation.

Finally, the **human factor** also influences the credibility of a simulation. The competencies and qualifications of the personnel conducting simulations and using their results are key. Companies implement this aspect of employee qualification according to their specific needs within the framework of **competence management**. Only well-trained and experienced staff can ensure that simulations are used not only methodologically correctly but also responsibly and purposefully.

The key aspects of **Simulation Credibility** are illustrated in **Figure 4.**

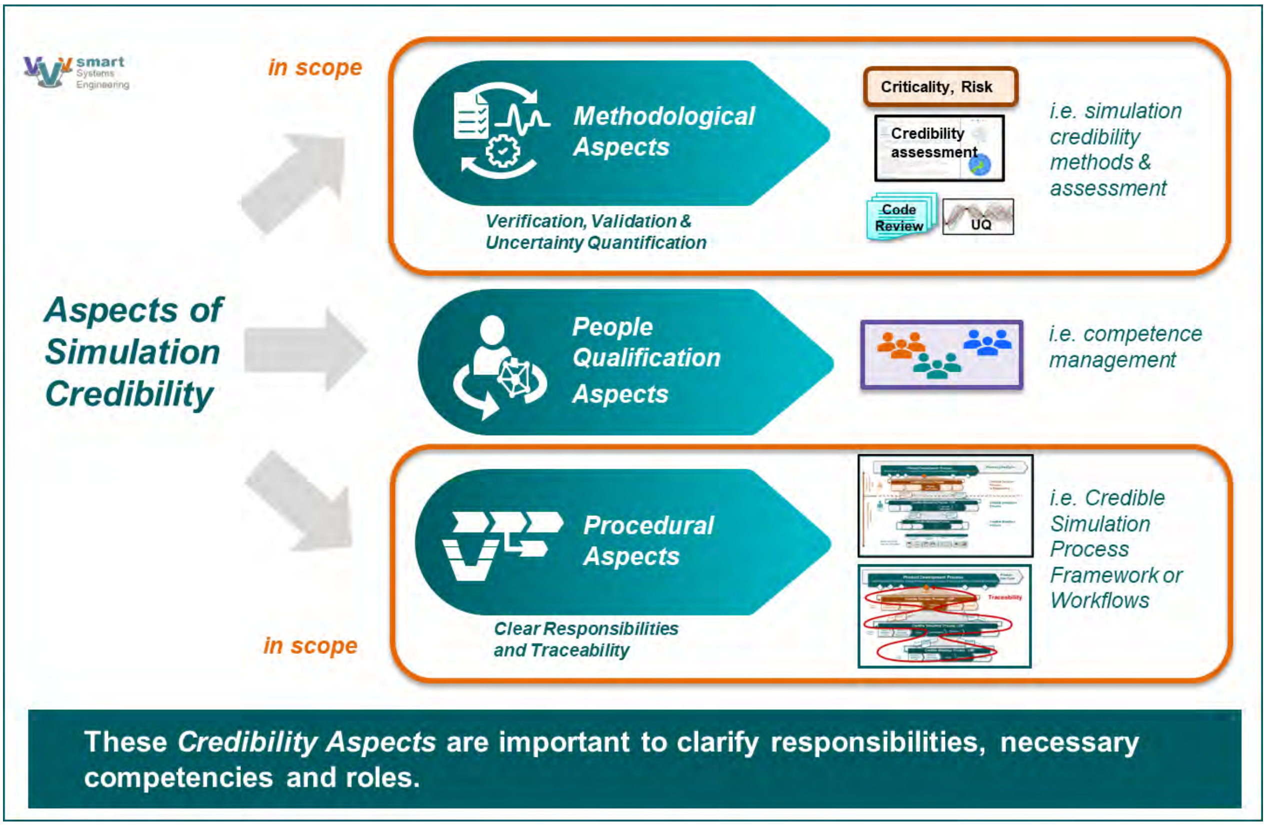


Figure 4: Aspects of Simulation Credibility

This white paper focuses on methodological and procedural aspects and, in particular, on available and practical solutions from industry for the necessary "Credibility Assessments".

4.2 Risk based Decisions and Credible Simulation Process Framework

When developing complex products and systems, a multitude of decisions must be made. The "risk" associated with the respective decision options plays a central role in this process. Risk assessment is therefore an important factor that influences the decision to be made.

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

- **Scenarios:** *What could happen?*
- **Probability:** *How likely is it to happen?*
- **Consequence:** *What are the impacts if it happens?*

These decision-making processes are increasingly based on numerical simulations. The credibility of simulations and their results have a strong influence on the decision to be made and the assessment of the associated risk.

Inaccuracies in the input data, uncertainties in the model parameters, or unforeseen external influences can compromise 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 credibility of the simulation results and makes it possible to identify and evaluate potential weaknesses.

When considering risks in the context of decision-making, a distinction can be made between three levels:

Data *is the fundamental driving force behind informed decisions. MBE - Model Based Engineering methods (simulation, real-world testing, calculation) support meaningful data generation.*

Risk *is the potential for performance deficits that may occur in the future. Risks therefore play a central role as another influencing factor in the decision-making process.*

People *are crucial to decision-making because they assess the risks and ultimately make a decision. Risk assessment is not straightforward because people are complex beings who are influenced by many factors (e.g., emotions). Therefore, decisions in a given situation with specific risks can vary greatly.*

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

Figure 5 illustrates the relationship between accepted residual risk at product level and the derivation of the necessary simulation credibility.

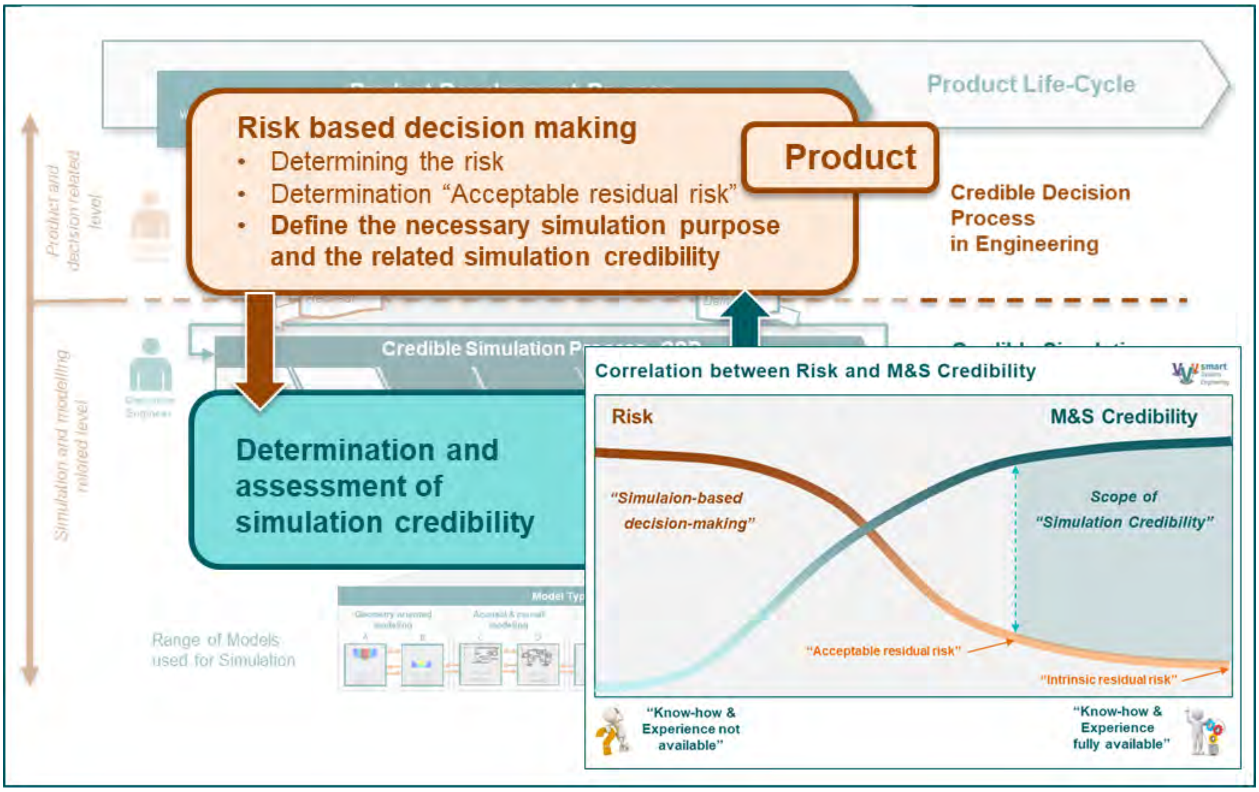


Figure 5: Relationship between accepted residual risk and necessary simulation credibility

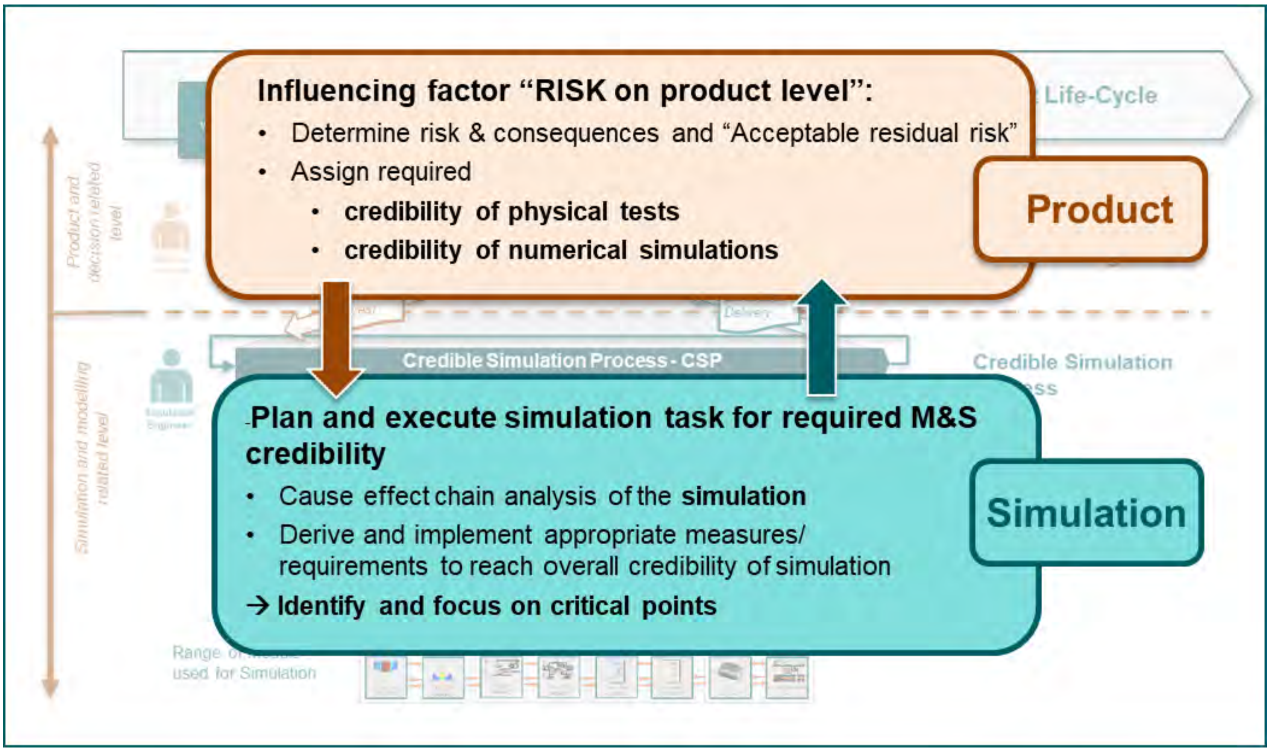


Figure 6: Determining the necessary credibility of the simulation

4.3 Credible Process Framework for Simulations

A key outcome of the SmartSE working group's work in recent years and an important component of “**Simulation Credibility”** is the description of the “Credible Process Framework for Simulations.” This process framework embeds technical simulations in product development decision-making processes and describes essential processes at both the decision-making and coordination level and the simulation level. The process framework focuses on numerical technical simulations that are used for decision-making in the product development process. However, it should be noted that product-related decisions can be based on a wide range of information, data, and experience. Only part of this is based on numerical simulations.

> *The **“Credible Process Framework for Simulation”** provides a structured approach for using numerical simulations to support decision-making and simulation-based release in the product development process.*

The “**Credible Process Framework for Simulation**” distinguishes between the following three process levels:

- *The **Credible Decision Process (in Engineering) – CDP***
- *The **Credible Simulation Process – CSP***
- *The **Credible Modeling Process – CMP***

Figure 7 shows the “Credible Process Framework for Simulation” in detail, including the sub-processes.

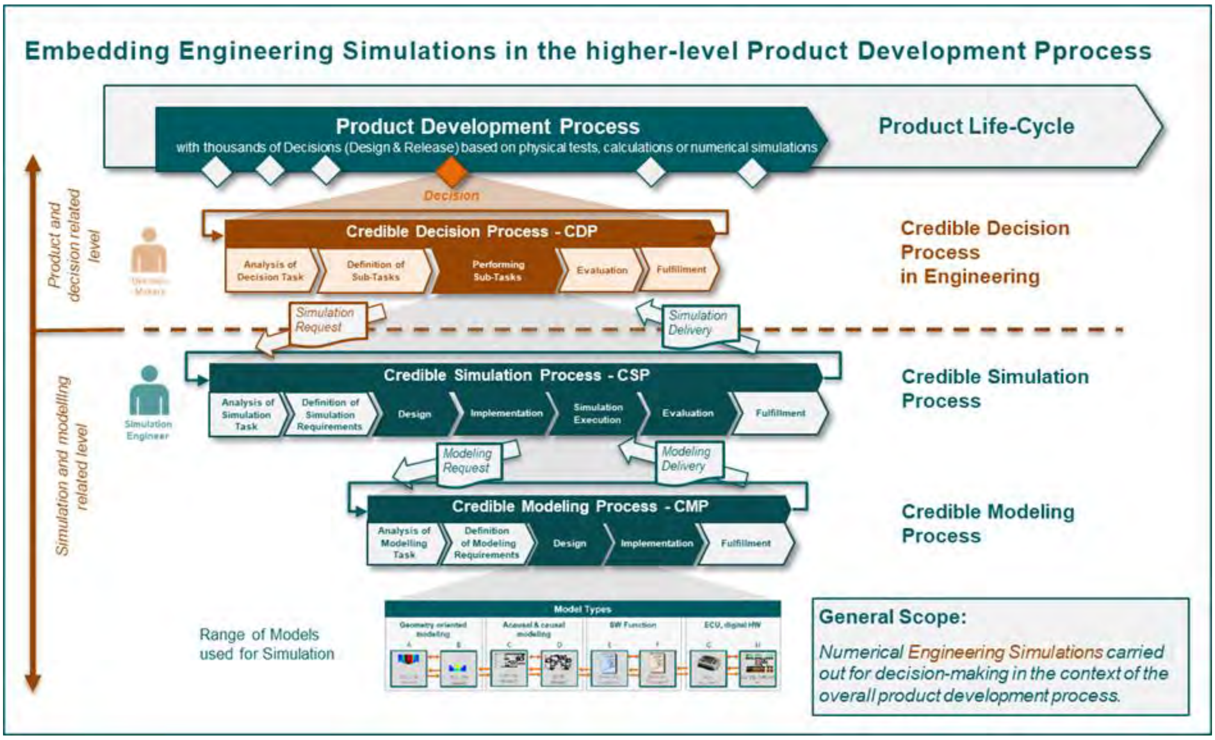


Figure 7: Embedding of engineering Simulations in the higher-level Product Development Process

In addition to emphasizing the importance and integration of simulation in the product development process, the "Credible Process Framework for Simulation" aims to link existing credibility standards in the field of simulation and modeling with the business processes involved in developing complex products and systems.

Numerous product-related decisions must be made as part of the product development process. A single decision within product development can be described and coordinated within this process framework by the **Credible Decision Process (in Engineering) - CDP**. This process includes and takes into account 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 expected results. In addition, 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.

At the level below, the **simulation requirement** (trigger) of the CDP triggers the **Credible Simulation Process (CSP).** This describes the activities and steps required to plan and execute the numerical simulation. These include defining the simulation methodology, collecting and preparing the necessary data, selecting the appropriate simulation tools, and defining the assumptions and boundary conditions for the simulation.

The CSP's **modeling requirement** then triggers the **Credible Modeling Process (CMP)** at the next level. Within this sub-process of the simulation, models are created 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 using appropriate comparative data.

According to the SmartSE project, the **Simulation Task is** the actual execution of the numerical simulation with the created models. It is therefore the concrete implementation of the Credible Simulation Process (CSP). A simulation task combines models from different domains (mechanics, E/E, embedded software), different departments and also from different partners in a specific simulation.

4.4 Organization Aspects of the Process Framework

Within the Credible Process Framework for Simulation, 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 a different focus 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 do the sub-tasks or processes 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 or 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 Maker initiates and coordinates the tasks. He understands 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 for M&S in accordance with the M&S risk analysis. He provides understandable simulation results and M&S credibility assessments for the Decision Makers.*

4.5 Credible Decision Process (in Engineering) – CDP in Detail

The **"Credible Decision Process (in Engineering) – CDP"** describes a single decision that must be made during product development as a sub-process of the "Credible Process Framework for Simulation."

> *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.*

Identifying decision objectives:

In this step, 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 triggers the **Credible Simulation Process (CSP)** sub-process with the **simulation request**. The result of this is the **simulation delivery**.

After analyzing the task, the potential risk and consequences of an incorrect decision must be determined. Then, the individual sub-processes must be created with the requirements for the necessary specific credibility. Clear requirements are assigned to the sub-processes. These then return their partial results to the higher-level process. After all subtasks have been completed, their results are evaluated. This evaluation includes confirmation that the required subtasks are credible and that the probable identified M&S risks are acceptable in relation to the decision to be made at product level. Upon completion, the decision at product level made based on the sufficiently credible, approved subtask results. This step confirms that all requirements for the development task have been met and that the identified risks are acceptable.

The individual steps of the **Credible Decision Process (in Engineering) – CDP** are shown in Figure 8. The decisions to be made can be based on real prototypes, calculations, or expert estimates.

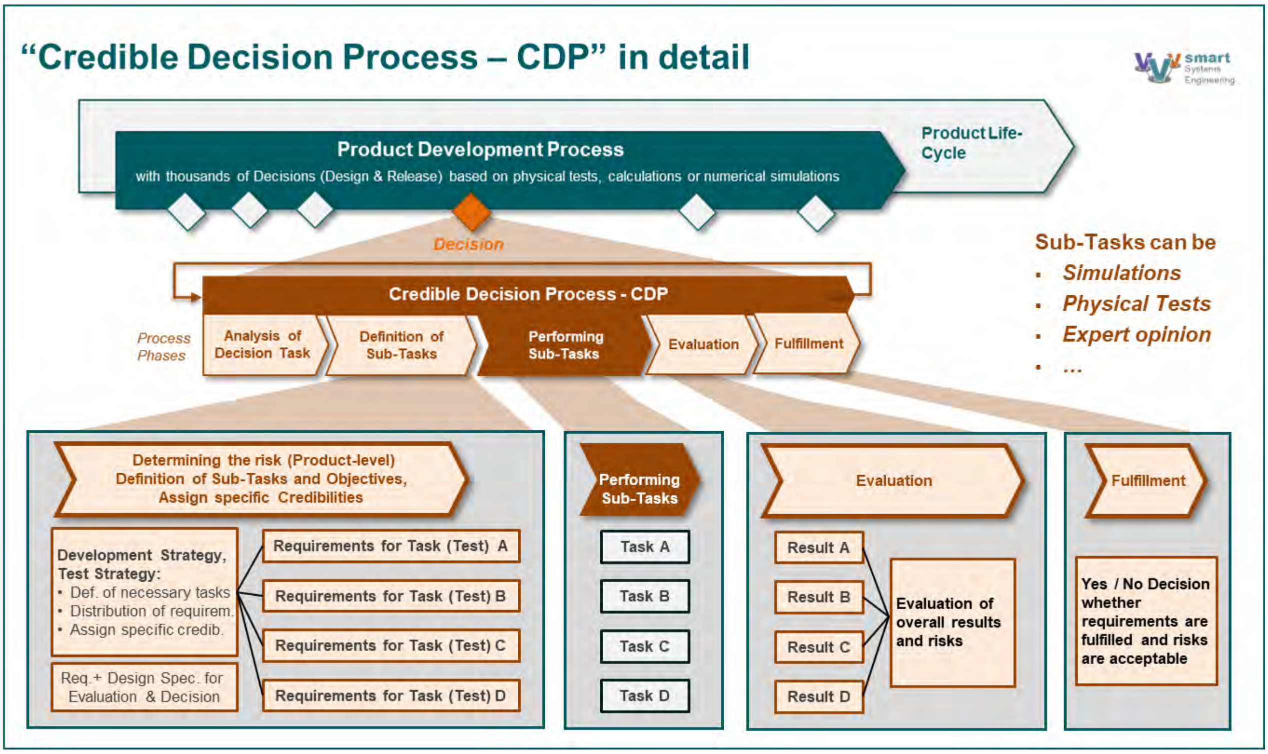


Figure 8: Detaillierte Darstellung des „Credible Decision Process – CDP“

5 Claim and Objective of Simulation Credibility Assessment

The use of numerical simulations offers tremendous potential for efficient, safe, and resource-efficient product development. Nevertheless, in many companies, simulations are still used far less frequently than physical tests. While established and widely recognized procedures exist for physical testing, numerical simulations often lack consistent evaluation standards and clear criteria for assessing their applicability and credibility. As a result, decision-makers often continue to rely on physical tests - even when reliable simulation results are already available.

The **Simulation Credibility Assessment** approach was developed by the **Smart-SE project group** to close this gap and systematically strengthen confidence in simulation results. The goal is to transfer the proven assessment principles from physical testing to numerical simulations, thereby enabling a transparent and standardized evaluation of their credibility. Just as with a physical test, simulations should in the future allow for a clear and traceable assessment - comparable to a simple “pass” or “fail.” This ensures that product managers and validation planners can rely on simulation results with the same level of confidence as on real test outcomes.

> ***“Credibility Assessments”*** *is a smart and pragmatic approach to specifying and evaluating the credibility characteristics of a particular simulation task based on a framework of credibility characteristics.*

A practical example illustrates the initial situation: Simulation results were available for an overload calculation for a steering system. Nevertheless, a physical test was also carried out because the simulation was not recognized as an equivalent validation measure, as the simulation did not provide a results report in the form of “requirements met” or “requirements not met.” This example shows that the acceptance of numerical simulations depends less on their technical quality than on their perceived credibility.

In order to make this credibility measurable, the SmartSE project group defines clear, practice-oriented minimum requirements for the quality and validation of simulations with the M&S Credibility Levels (M&S CL 1–4). These levels create a common basis for integrating simulation results into testing, approval, and decision-making processes in a targeted manner. They can be flexibly adapted to product- and company-specific requirements while promoting communication between product managers and simulation engineers. The decisive factor here is not the formal equivalence of testing and simulation, but the credibility of the respective results. Ultimately, decision-makers should receive clear and comprehensible information without having to interpret complex plots or curves.

To avoid confusion with other technical terms, the project group deliberately uses the term “M&S Credibility Level,” which is based on the international terminology for “modeling & simulation.” The overall result of this assessment is obtained by mapping the technical performance of the simulation tools and methods (“right side”) to the respective purpose of simulation (“left side”). The resulting levels 1–4 condense the complexity of this relationship into an understandable, application-oriented classification.

The relationship between the purpose of the simulation to be performed on the one hand and the performance of the simulation chain on the other, as well as the “M&S Credibility Level,” is shown in Figure 9.

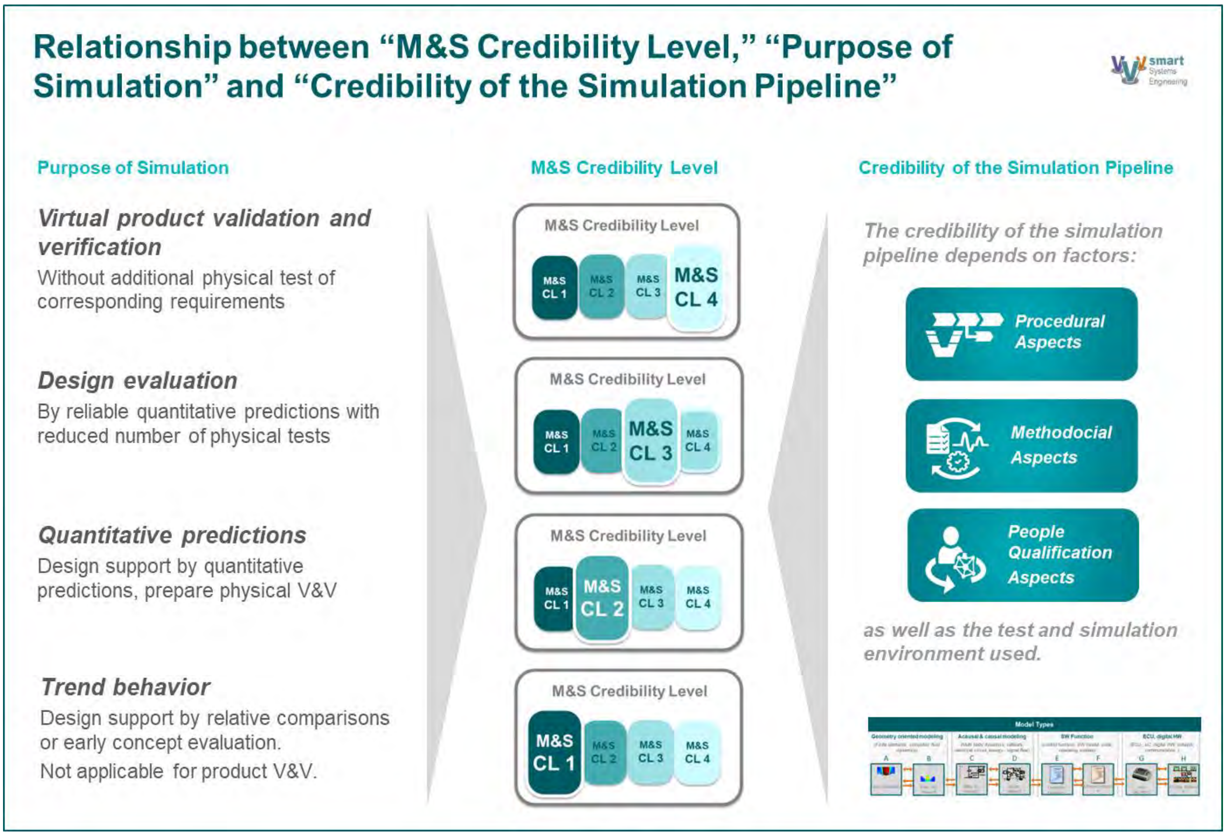


Figure 9; Relationship between “Purpose of a Simulation” and „M&S Credibility Level”

In addition, Simulation Credibility Assessment attaches great importance to a uniform language and a common understanding among all participants, which are the basis for a mutual recognition of Simulation Credibility Assessments across companies and regulatory board or services (Technische Dienste). Terms such as Purpose of Simulation and M&S Credibility Level serve as common points of reference to standardize communication between product managers, decision-makers, and simulation experts. This makes simulation results comprehensible, comparable, and trustworthy - regardless of the company or product area in which they are generated.

The Simulation Credibility Assessment approach makes a significant contribution to establishing numerical simulations as an equivalent and reliable basis for decision-making alongside real-world tests. It creates a uniform basis for trust, comparability, and transparency when using simulations and their results in virtual product development, paving the way for modern, fully virtual, and efficient product development. In addition, credibility assessments can be understood as an adaptable solution component on the path to a comprehensive simulation credibility standard or recommendation.

5.1 Target group of the “Simulation Credibility Assessments“

The presented approach of **Simulation Credibility Assessment** and the associated “M&S Credibility Level” is aimed at two key target groups in product development: On the one hand, product managers and decision-makers who depend on reliable, traceable, and evaluable results for their approval decisions, and on the other hand, simulation engineers who, as users, apply numerical methods and simulation tools and perform and evaluate simulations.

For both groups, the four proposed **M&S Credibility Levels (M&S CL 1–4)** form the connecting element. They create a common, clearly defined language and a uniform understanding of how credible and reliable a simulation result is in the respective application context. This graded system greatly facilitates communication between technical experts and decision-makers, reduces misunderstandings about the significance of simulation results, and strengthens the basis for well-founded, comprehensible product decisions.

In addition, this white paper is aimed at quality managers whose task is to ensure reliable, safe, standard-compliant, and customer-oriented product development. They play a key role in establishing, monitoring, and continuously developing methods and processes in the field of validation and verification. A central component of this responsibility is determining the product and the associated technical risks, as well as defining the accepted residual risk. This risk analysis forms the basis for all validation and verification measures – both in real-world testing and in simulation. Only when the risks and their effects are understood and evaluated can a decision be made as to what level of credibility is required for simulation results to serve as a basis for approval. In addition, it is the responsibility of quality managers to implement the adaptation and introduction of a company-specific methodology for credibility assessment. This methodology, anchored in the Simulation Credibility Assessment framework, ensures that simulation results can be evaluated in a comprehensible, comparable, and standards-compliant manner.

Overall, the **Simulation Credibility Assessment** supports all parties involved - from product responsibility to simulation to quality management - in creating a common understanding of the credibility of simulation results and establishing numerical simulations as an equivalent, reliable, and decision-relevant basis in modern product development.

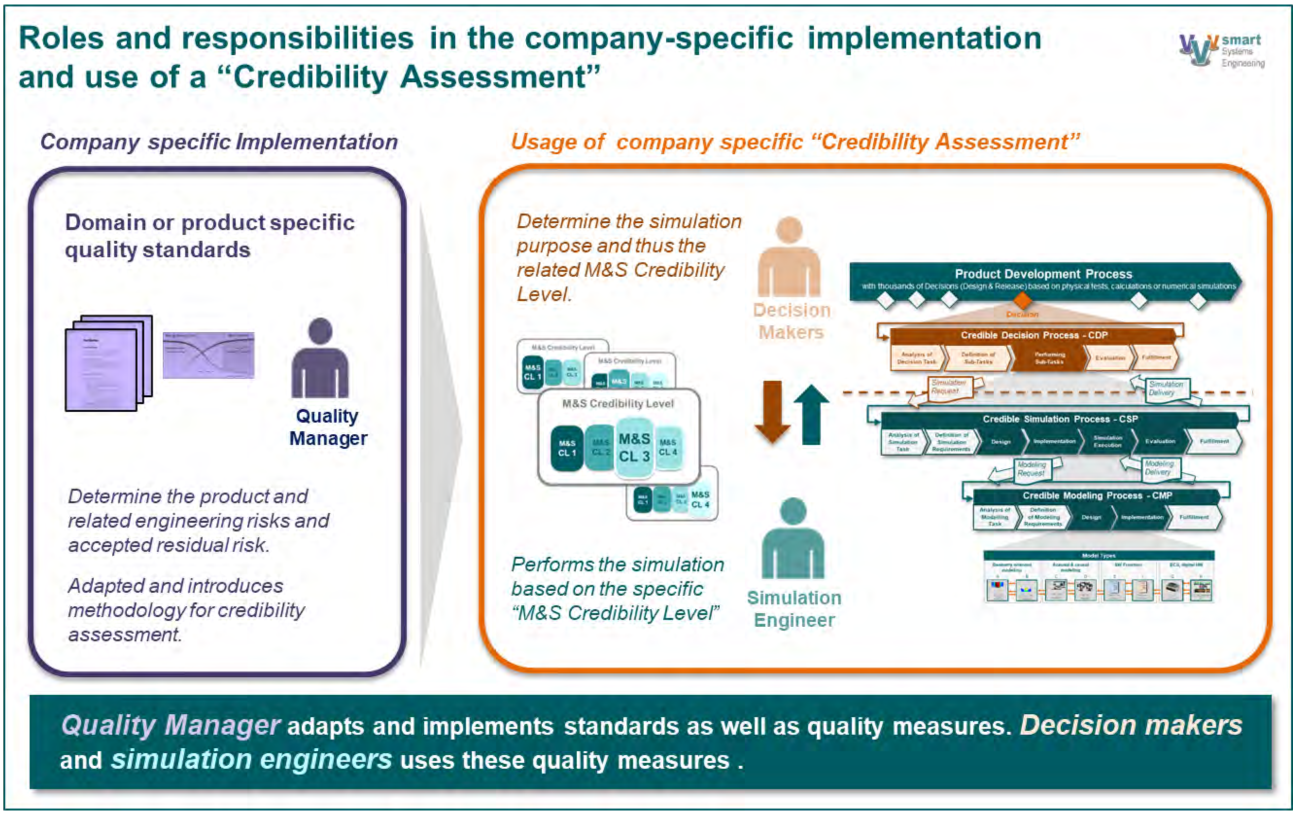


Figure 10: Roles and responsibilities in the company-specific implementation and use of a “Credibility Assessment”

5.2 Details of the „M&S Credibility Level“

Four basic M&S credibility levels have been defined for the systematic assessment of the reliability of simulations. These M&S credibility levels and the associated M&S credibility factors are described in detail in the following subsections.

> *A **“M&S Credibility Level”** focuses on the purpose of a simulation and describes the requirements for the credibility of a simulation results. They are independent from product, domain and company interpretation.*

Specifically, we as SmartSE project group propose the use of the following M&S credibility levels:

- M&S Credibility Level 1 “Trend Behavior” (M&S CL1)
- M&S Credibility Level 2 “Quantitative Predictions” (M&S CL2)
- M&S Credibility Level 3 “Design Evaluation” (M&S CL3)
- M&S Credibility Level 4 “Virtual Product Verification & Validation” (M&S CL4)

The purpose of a simulation is assigned a “M&S credibility level” in each case.

The four M&S credibility levels form a minimum approach that creates a uniform basis for assessing the credibility of simulation activities. However, depending on the company structure, the complexity of the product, and the maturity of the simulation technologies, further differentiation and adaptation of the levels may be possible and useful.

Figure 11 provides an overview of M&S Credibility Levels 1–4.

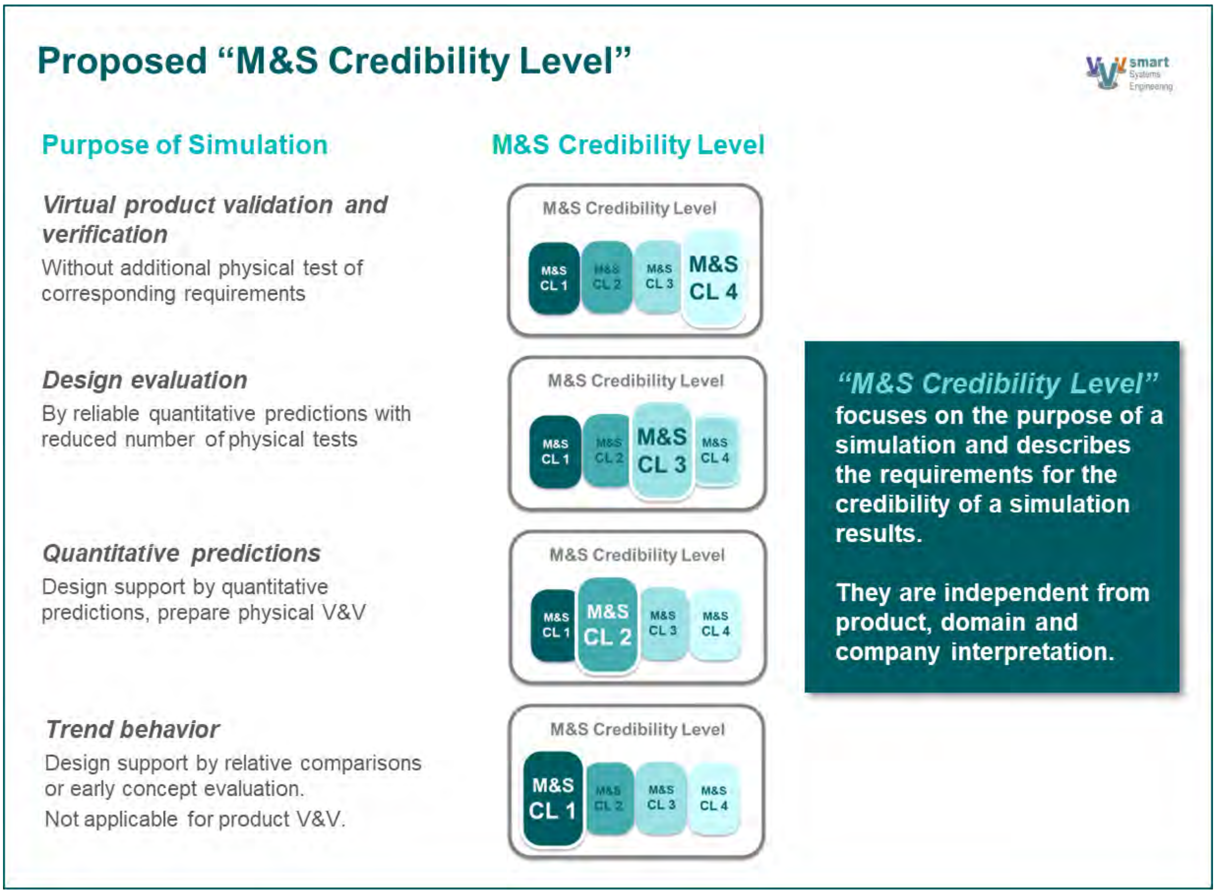


Figure 11: Proposed "M&S Credibility Level"

5.2.1 M&S Credibility Factors

Determination of acceptable residual product and development risk is implemented in company specific processes. Usually, standard methods are applied such as FMEA and reliability analysis. The residual product and development risk must be minimized to an acceptable threshold. If an M&S activity is initiated as a measure to control the product and development risk, this implies what credibility score is required for this M&S activity. In the above table, this is given in the "Purpose of simulations" column. An example is that the simulation is used in combination with physical tests during product verification. So, the simulation is part of the product verification and validation process, but not the only verification measure. According to the above table, this implies a required Credibility Score of 3. This example is illustrative and the mapping from the product and development risk to the purpose of simulation is a company specific step.

The 4 main factors influencing each "M&S Credibility Level," referred to below as "M&S Credibility Factors," are:

- *Process maturity*
- *People Qualification*
- *Verification*
- *Validation & Uncertainty Quantification*

The **Credibility Factors *"Process maturity"*** evaluates how structured, traceable, and compliant with standards the modeling and simulation process is carried out.

This factor expresses the degree to which Modeling and Simulation processes are integrated and established within the overall product development process. It reflects how effectively these processes are tailored to the organization’s specific use cases, how well the required competences and responsibilities are managed, and how appropriate and efficient the communication channels are between all affected stakeholders and organizational units.

The **Credibility Factors *“Verification”*** confirms that the model has been implemented correctly and is functioning without technical errors.

This factor refers to the systematic assessment of whether the modeling and simulation implementation correctly fulfills its defined requirements and specifications. It focuses on verifying the correctness of the mathematical representation, algorithms, and numerical implementation, thereby addressing the fundamental question of whether the model and simulation have been built and implemented the right way.

The **Credibility Factors *“Validation & Uncertainty Quantification”*** checks whether the model accurately represents the real system and whether the existing uncertainties have been quantified.

This factor focuses on determining whether the model and simulation are appropriate representations of the real system and whether their predictive accuracy remains credible across different operating conditions. It involves evaluating how closely simulation results agree with reference or experimental data, while also accounting for uncertainties in inputs, parameters, and assumptions. In essence, it answers the questions *“Did we implement the right M&S?”* and *“How close are the model and simulation results to the behavior of the real-world system?”*

The **Credibility Factor *“People Qualification”*** is not in focus of our approach and is therefore not described in detail here (company specific solutions).

The **credibility factors describe the minimum requirements** that must be fulfilled at the M&S credibility levels. They define the minimum requirements that must be present and implemented. However, no specifications are made as to how and how they are to be implemented

The characteristics of the “M&S Credibility Factors” for “M&S Credibility Levels 1” - 4 are described in the following illustration.

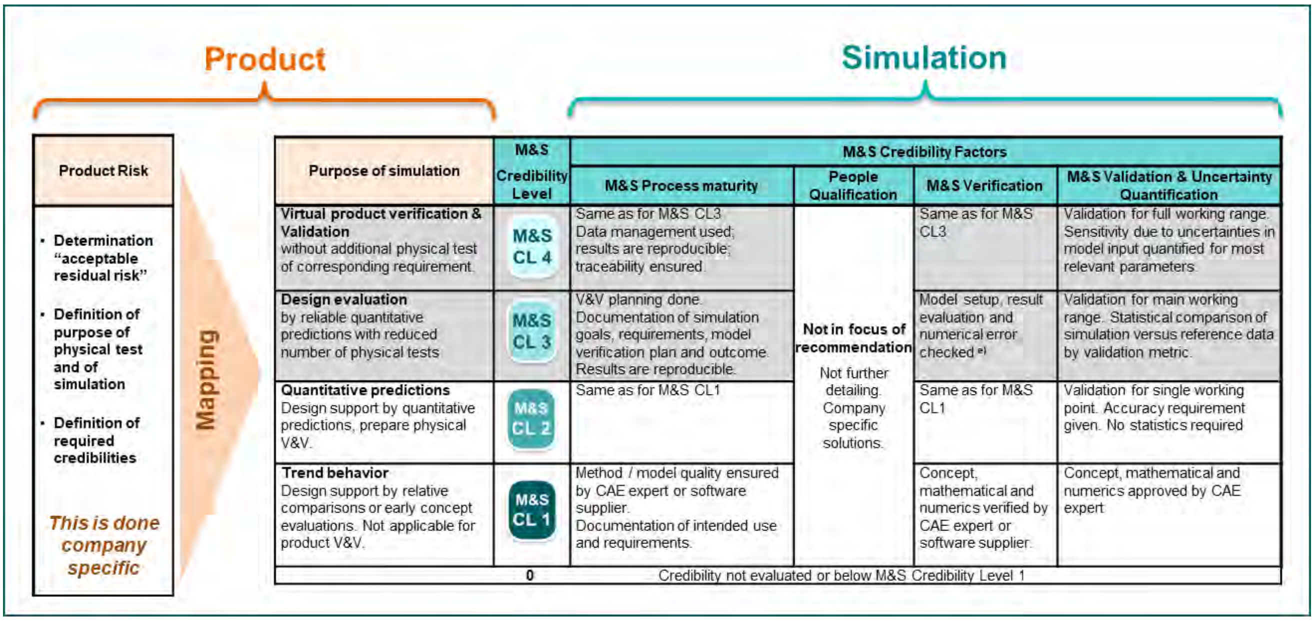


Figure 12: M&S Credibility Level, Simulation purpose and main M&S Credibility Factors

The following subchapters present the four M&S Credibility Levels in tabular form based on a template. This template contains a detailed description of each level and the characteristics of the M&S Credibility Factors Figure 15).

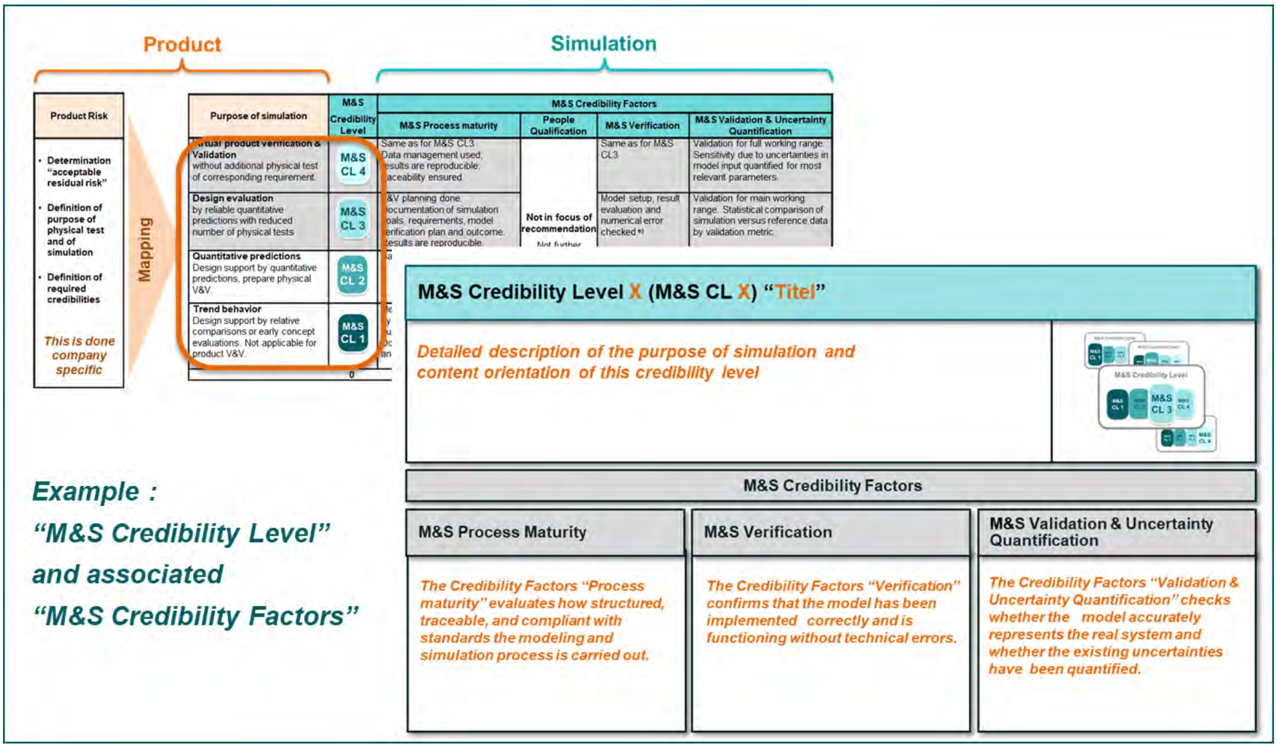


Figure 13: Example: “M&S Credibility Level” and associated “M&S Credibility Factors”

5.2.2 M&S Credibility Level 1 (M&S CL1) “Trend Behavior”

The M&S Credibility Level 1 is sufficient or fulfills the simulation purpose: ***“Trend Behavior”*** *Design support by relative comparisons or early concept evaluation. Not applicable for product V&V.*

Detailed description M&S CL1 “Trend Behavior”:

M&S results allow to compare design alternatives, typically in early phases of product engineering. Such comparisons are often rather qualitative, respectively the scope and required accuracy of quantitative predictions of product behavior and properties are quite limited. Thus, M&S results describe the key properties of product behaviors good enough to keep the risk manageable of wrong decisions about basic design alternatives. Not applicable for product V&V.

The associated “M&S Credibility Factors” of “M&S Credibility Level 1 (Trend Behavior)” are described in detail in Figure 14.

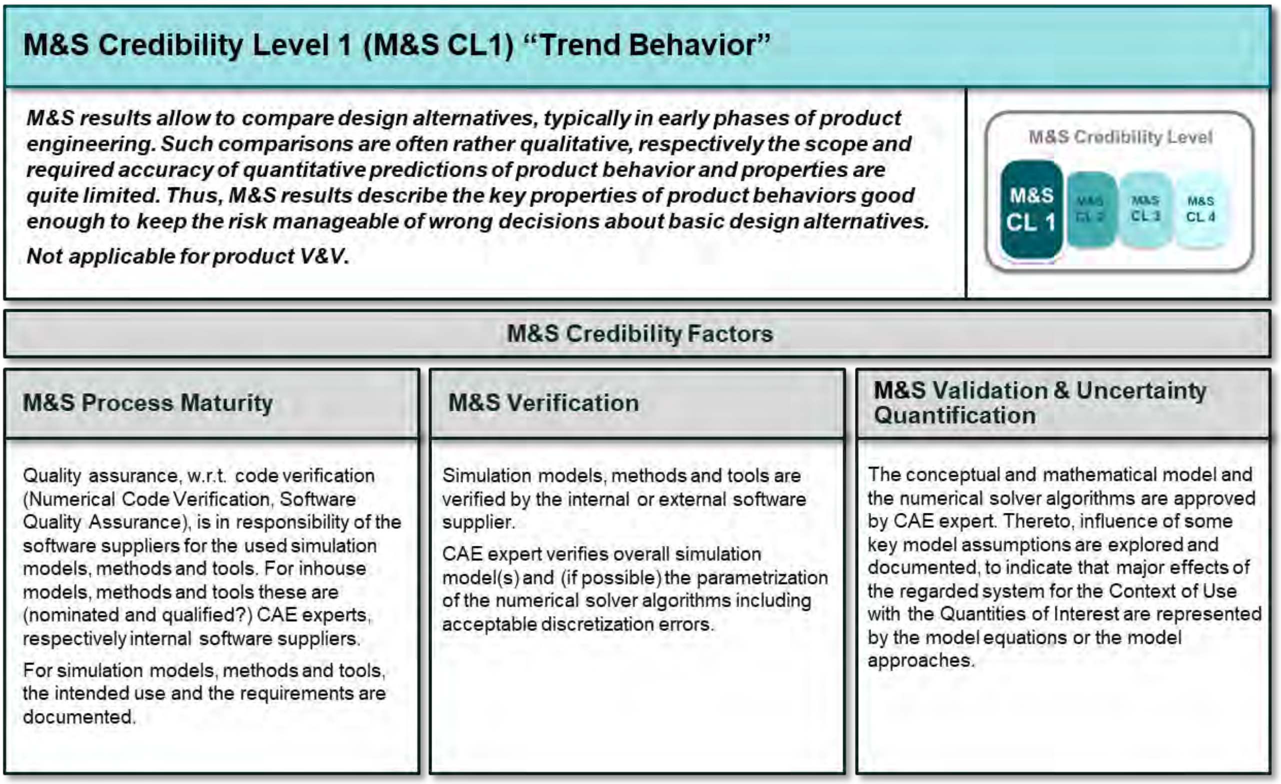


Figure 14: M&S Credibility Level 1 (M&S CL1) "Trend Behavior"

5.2.3 M&S Credibility Level 2 (M&S CL2) "Quantitative Predictions"

The M&S Credibility Level 2 is sufficient or fulfills the simulation purpose: ***"Quantitative Predictions"*** *Design support by quantitative predictions, prepare physical V&V*

Detailed description M&S CL2 "Quantitative Predictions":

M&S results support the product design with quantitative predictions of relevant product behaviour for major design parameters. These design studies are decisive for (first) physical prototypes and related product V&V – prepare physical V&V. Thus, the prediction quality of M&S results must be good enough in combination with other relevant engineering information to expect successful tests of the derived physical prototypes.

The associated "M&S Credibility Factors" of "M&S Credibility Level 1 (Quantitative Predictions)" are described in detail in Figure 15.

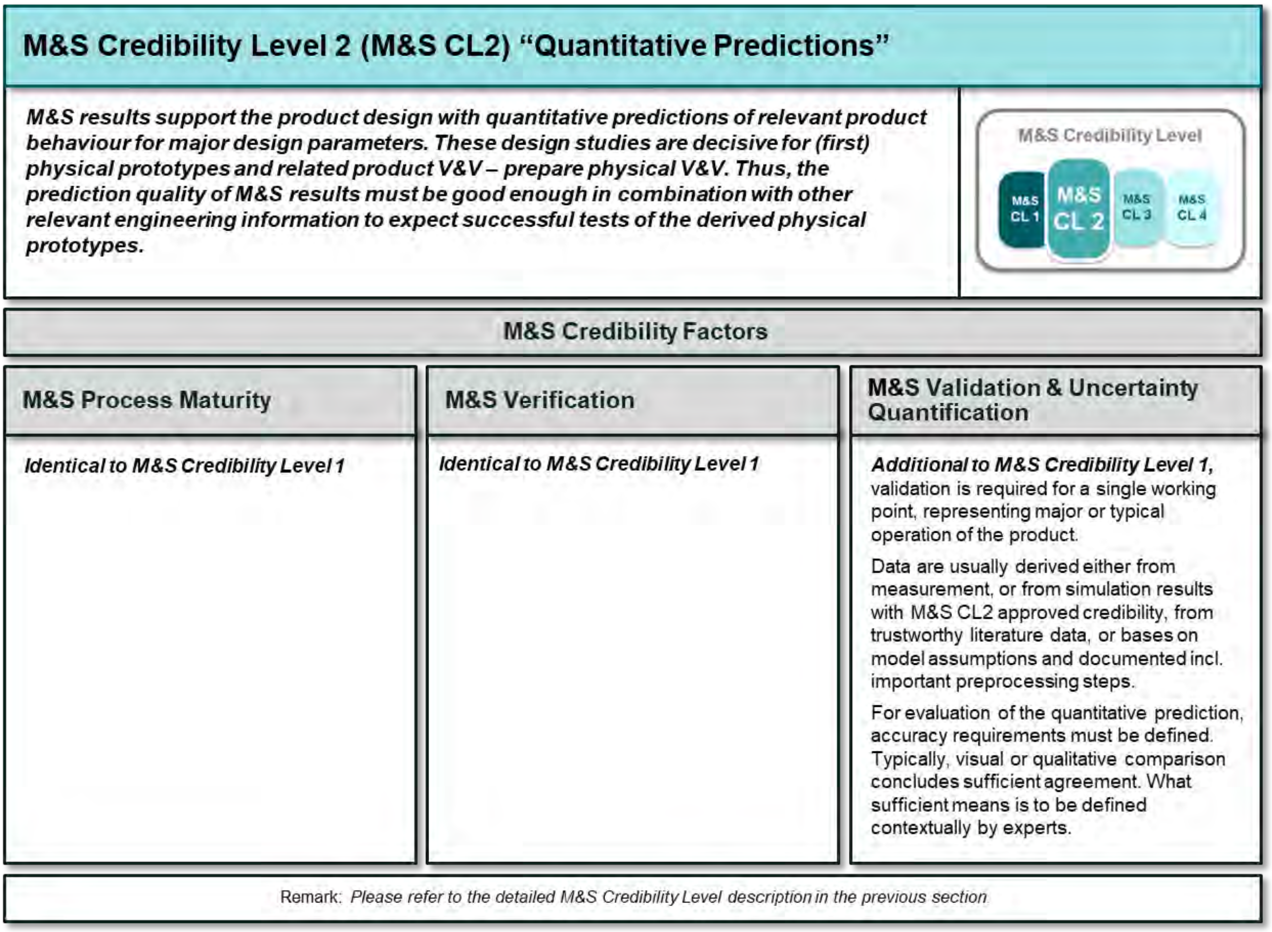


Figure 15: M&S Credibility Level 2 (M&S CL2) "Quantitative Predictions"

5.2.4 M&S Credibility Level 3 (M&S CL3) "Design Evaluation"

The M&S Credibility Level 3 is sufficient or fulfills the simulation purpose: ***"Design Evaluation"*** *By reliable quantitative predictions with reduced number of physical tests*

> **Detailed description M&S CL 3 "Design Evaluation":**
>
> *Prediction quality and repeatability of M&S results allows to forecast the product behaviour in a quantitative and reliable manner. This requires that results are validated with statistical proof for the main working range of the product. This allows to reduce the number of physical tests and or physical prototypes. Thus M&S results enable a comprehensive product design evaluation.*

The associated "M&S Credibility Factors" of "M&S Credibility Level 3 (Design Evaluation)" are described in detail in Figure 16.

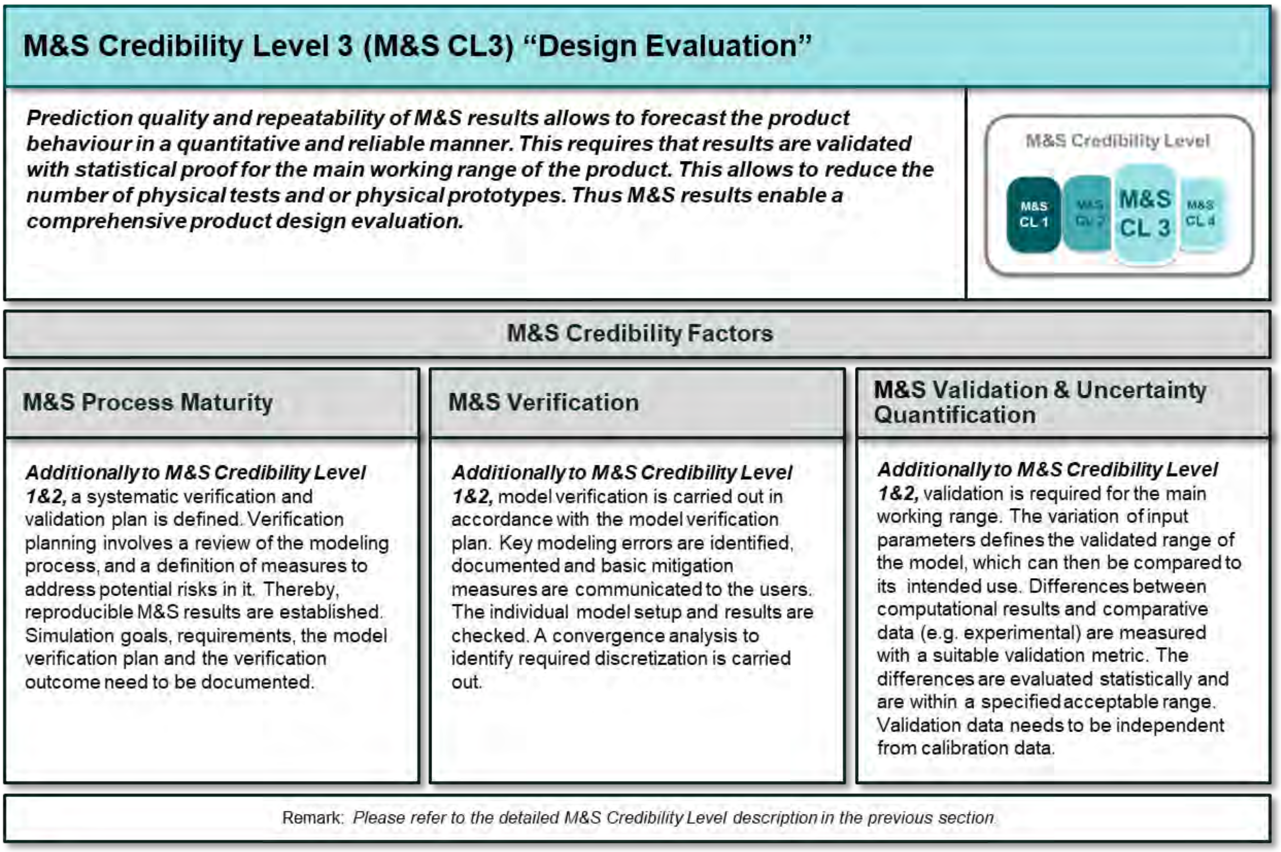


Figure 16: M&S Credibility Level 3 (M&S CL3) “Design Evaluation”

5.2.5 M&S Credibility Level 4 (M&S CL4) “Virtual Product Verification & Validation”

The M&S Credibility Level 4 is sufficient or fulfills the simulation purpose: ***“Virtual Product Verification & Validation” -*** *Without additional physical test of corresponding requirements*

Detailed description M&S CL4 “Virtual Product Verification & Validation”:

In addition to the design evaluation, the M&S results allow the prediction of product behaviour for full working range analyzing the effect of uncertainties for most relevant parameters and inputs. This implies additional requirements on data management for reproducibility and traceability of M&S data and results.

Such M&S results are comparable with physical tests for product verification and validation and can replace them.

The associated “M&S Credibility Factors” of “M&S Credibility Level 4 (Virtual Product Verification & Validation)” are described in detail in Figure 17.

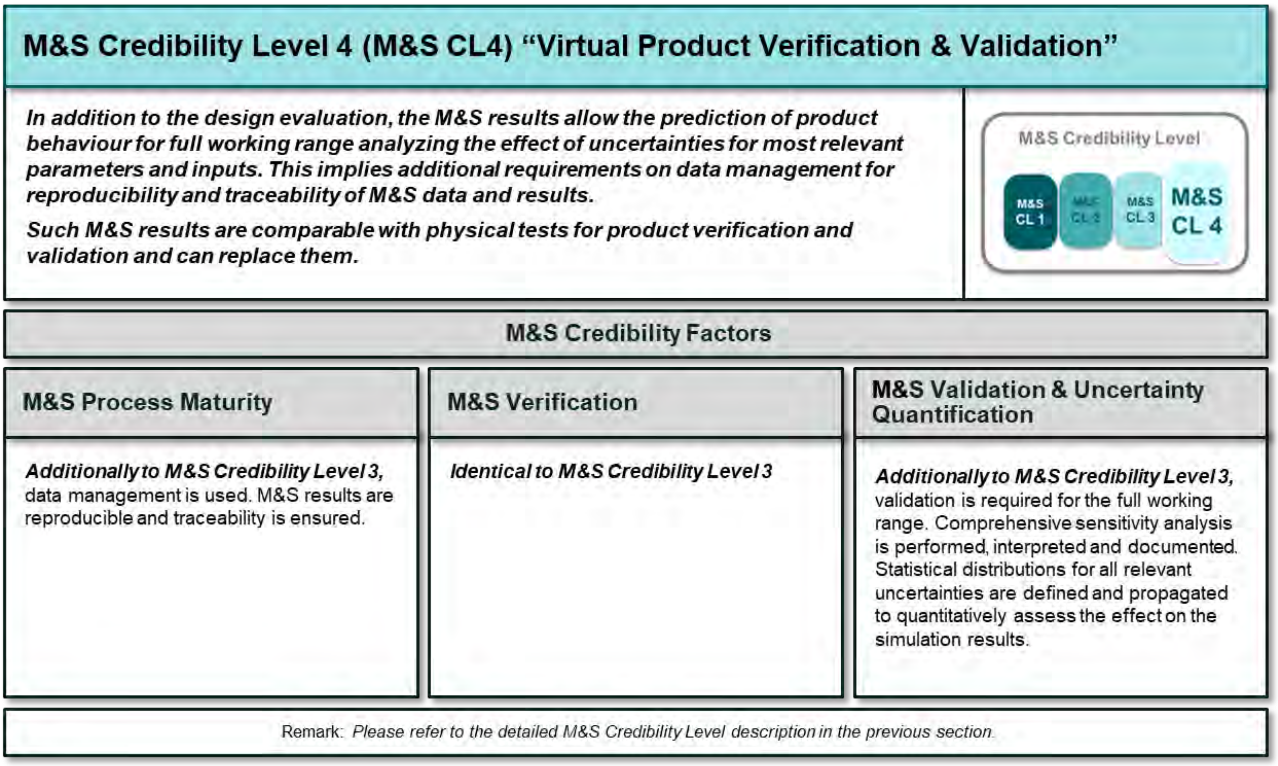


Figure 17: M&S Credibility Level 4 (M&S CL4) “Virtual Product Verification & Validation”

5.3 Relationship between Decision, Risk Assessment, and the Credibility of a Simulation

The relationship between the decision to be made at the product level and its criticality - whether for a product, subsystem, or component - and the assessment of the associated technical risk and analysis of its impact on the overall system (in terms of accepted residual risk) is explained below. It also shows how the necessary “credibility” is derived from this as a requirement for the simulation to be performed.

Risk analysis at the product level forms the basis for all validation and verification measures - both in real-world testing and in simulation. Only when the risks and their effects have been fully identified, understood, and evaluated can a decision be made as to what level of credibility is required for simulation results to serve as a basis for decision-making and approval by those responsible for the product.

> *The “**Simulation Credibility Assessment”** focuses on mapping the risk classification of a decision to be made, as determined by the risk assessment, to a corresponding “M&S Credibility Level” and on defining the minimum requirements for the simulation (“M&S Credibility Factors”).*

This relationship is illustrated in following Figure 18..

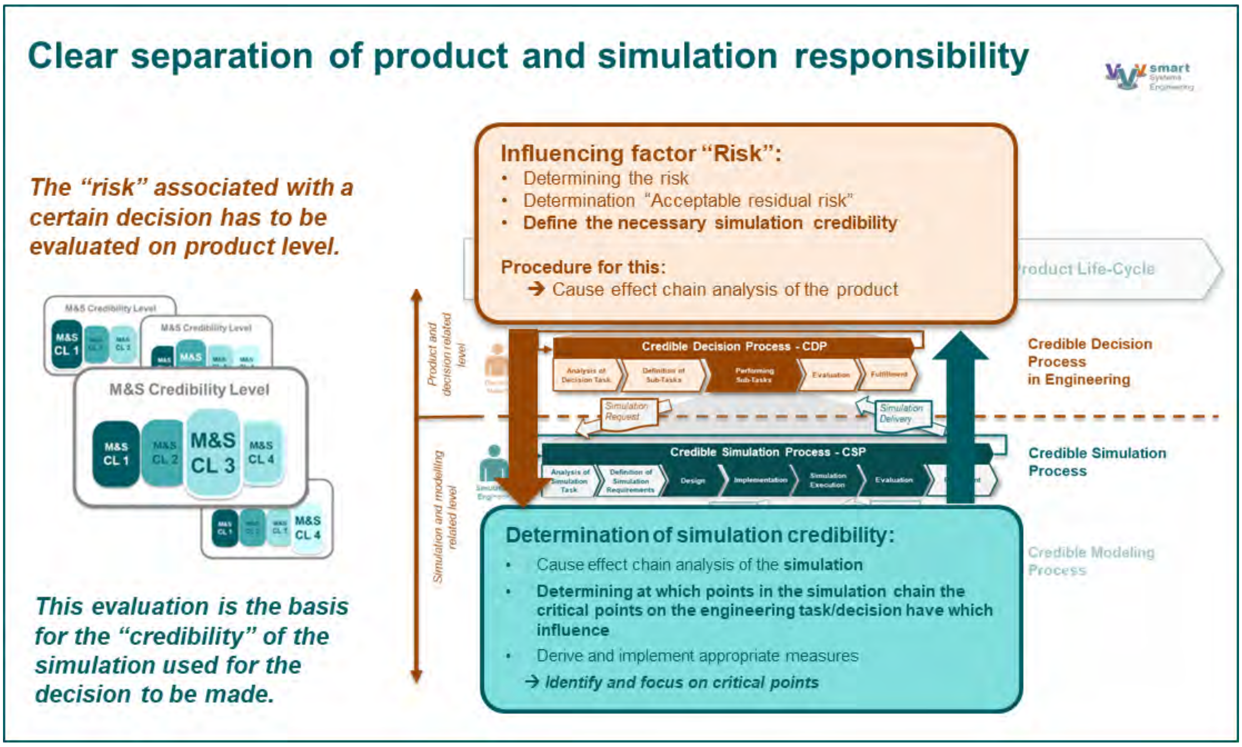


Figure 18: Clear separation of product and simulation responsibility

When **assessing risk**, it is important to determine the criticality of the decision, the subsystem or component to be simulated, and thus its impact on the overall system or product.

After analyzing the task, the **potential risk** and consequences of an incorrect decision must be determined. The individual sub-processes (see section 4.3 “Credible Process Framework for Simulations”) must then be created with the requirements for the necessary specific credibility. Clear requirements are assigned to the sub-processes. These then return their partial results to the higher-level process.

Influencing factor *“risk” associated with a certain decision on product level:*

- Determining the risk
- Determination “Acceptable residual risk”
- **Define the necessary simulation credibility**

Proposed procedure: *Cause effect chain analysis of the product*

This assessment is the basis for the “credibility” of the simulation used to make the decision.

Determination of the “Simulation Credibility” for performing a specific simulation:

- Cause effect chain analysis of the simulation
  - **Determining at which points in the simulation chain the critical points on the engineering task/decision have which influence**
- Derive and implement appropriate measures

Proposed procedure: *Identify and focus on critical points*

The derivation of **“Simulation Credibility”** based on risk analysis at the product level and the criticality of a decision to be made is shown schematically in Figure 18.

After all subtasks have been completed, their results are evaluated. This evaluation includes confirmation that the required subtasks are credible and that the probable identified M&S risks are acceptable in relation to the technical decision.

Upon completion, the decision is made based on the sufficiently credible, approved sub-task results. This step confirms that all requirements for the task have been met and that the identified risks are acceptable.

5.3.1 Notes on Implementation and Application of Risk Assessments in Companies

As described in the previous chapter 5.3 “Relationship between Decision, Risk Assessment, and the Credibility of a Simulation,” the risk and the acceptable residual risk are determined and defined at the product level. This is done on a company-specific basis. Appropriate procedures are usually established within companies. This white paper therefore does not provide any further guidelines or recommendations for determining risks.

5.4 Concretization of the Procedure for Determining the “M&S Credibility Level” using Examples

Using two systems to be developed, a steering system (system A) and a windshield wiper system (system B), as well as related development tasks (A1, B2, A2 and B2), we will illustrate how requirements, risks, and the handling of M&S-specific risks can differ, even though the same “M&S credibility level” is formally required.

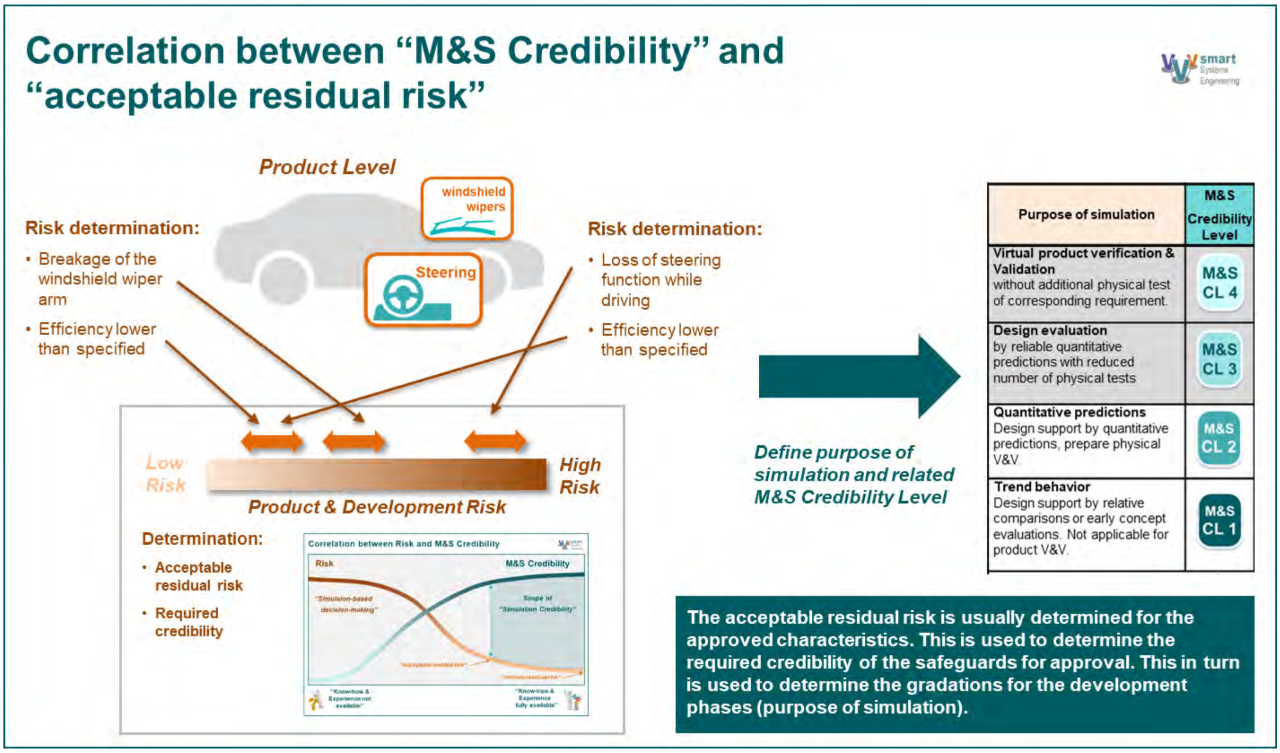


Figure 19: Correlation between “M&S Credibility” and “acceptable residual risk”

Development task A1

Development and validation of the breaking strength of the steering system's steering rod. A break in the steering rod during operation leads to failure of the steering function and thus has safety-critical consequences (danger to life and limb).

Development task B1

The windshield wiper system must function reliably under a variety of environmental conditions. Overload situations, e.g., when there is a heavy snow load or the windshield wiper is frozen, should not lead to breakage of the windshield wiper arm or failure due to mechanical overload of the mechanism or an overheated drive. However, such conditions can usually be detected and controlled by suitable monitoring functions. Even in the event of a fault or inadequate monitoring, these do not pose a direct danger to vehicle occupants and other potential road users. The development task here is to design and verify the breakage resistance of the windshield wiper arm.

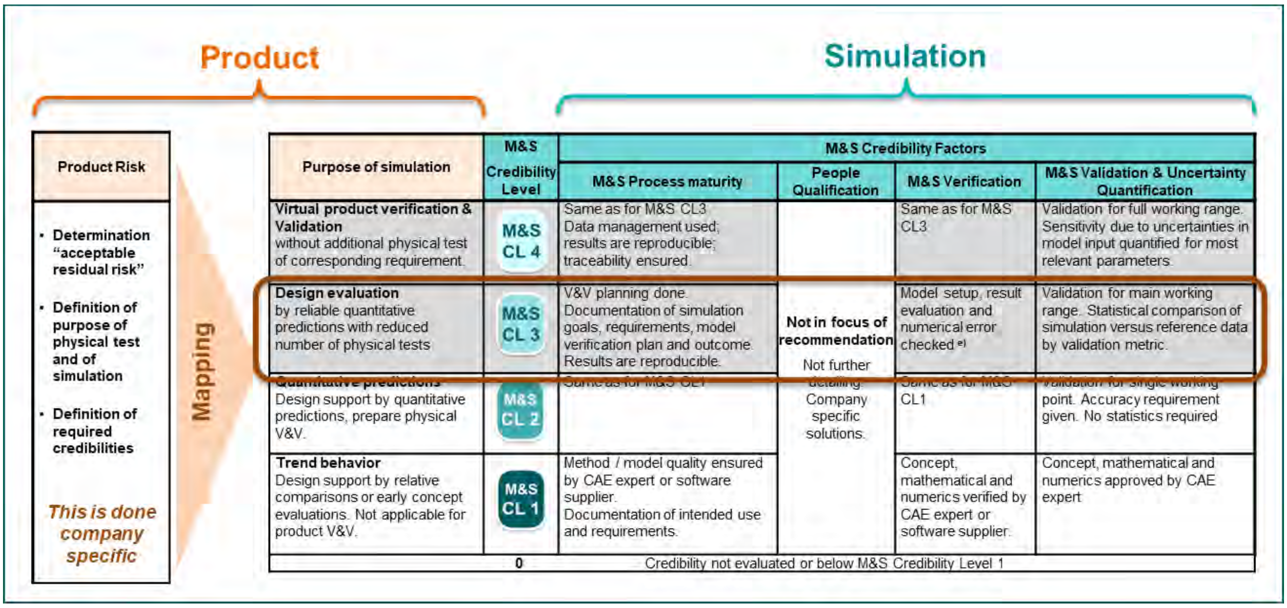


Figure 20: Specific implementation of M&S Credibility Factors

The purpose of the simulation or the simulation task is identical for both development tasks: Simulation is used for "design evaluation," i.e., to assess and validate the design. Consequently, "M&S Credibility Level 3" is the goal in both cases. This M&S credibility level requires that all M&S credibility factors - M&S process maturity, M&S verification, M&S validation, and quantification of uncertainties - meet well-defined requirements. In both simulation tasks, the requirements of the credibility factors are identical, but there are differences in the implementation and the effort required.

M&S Process Maturity requires the existence and implementation of a V&V plan at M&S Credibility Level 3. However, this is significantly more extensive for A1 than for B1. In the development task of verifying the breaking strength of the steering system's steering rod (A1), the determination of load collectives and simulations based on them are complex. Possible errors or inaccuracies in the simulation results have a direct impact on the predicted reliability characteristics and thus the safety of the product. The resulting M&S risks are therefore directly related to the product and development risks. When verifying the breaking strength of the windshield wiper arm, the load collectives and simulation studies can be considered in much less detail because possible overloads can be compensated for by suitable simple monitoring measures. Therefore, errors or inaccuracies in the simulation results have no direct or a significantly lower impact on the safety of the product than in the case of A1.

Development tasks A2 and B2

For both development tasks, simulation should be used to ensure that the specified efficiencies are achieved. As a development risk, insufficient efficiency can lead to increased costs and delays due to additional iterations. Excessive efficiency can lead to increased product costs and conflicts with product requirements in terms of size and weight. However, an efficiency that deviates from the specification does not lead to any safety-critical product risk.

In both development tasks, simulation is also used for "design evaluation," i.e., for assessing and validating the design. Consequently, "M&S Credibility Level 3" is the goal in both cases. This M&S credibility level requires that all M&S credibility factors – M&S process maturity, M&S verification, M&S validation, and quantification of uncertainties – meet well-defined requirements. Differences in the implementation of the requirements are rather minor, as the systems under consideration are comparable and the operating conditions for the efficiency considerations are also comparable, meaning that the simulations will have a comparable level of detail and scope. M&S risks due to simulation errors have a comparable impact on development risks, primarily development/product costs and development time.

5.5 Application of the Credibility Assessment for Simulation Task „DC Motor“

The following chapter uses the simple example of preselecting a DC motor for a window lifter to demonstrate the application of credibility assessment.

> *The task is to select a suitable DC motor for a side window lifter application based on the available data sheets.*
>
> *A qualitative statement is required as to whether a specific DC motor can reach the required speed within the specified time.*

The potential damage, and thus the risk associated with selecting an unsuitable DC motor, would amount to approximately €20,000 due to a time loss of about three weeks until detection (through subsequent investigation or verification).

Therefore, this constitutes a requirement for the simulation or verification to be conducted according to “M&S Credibility Level 2 – Quantitative Predictions.”

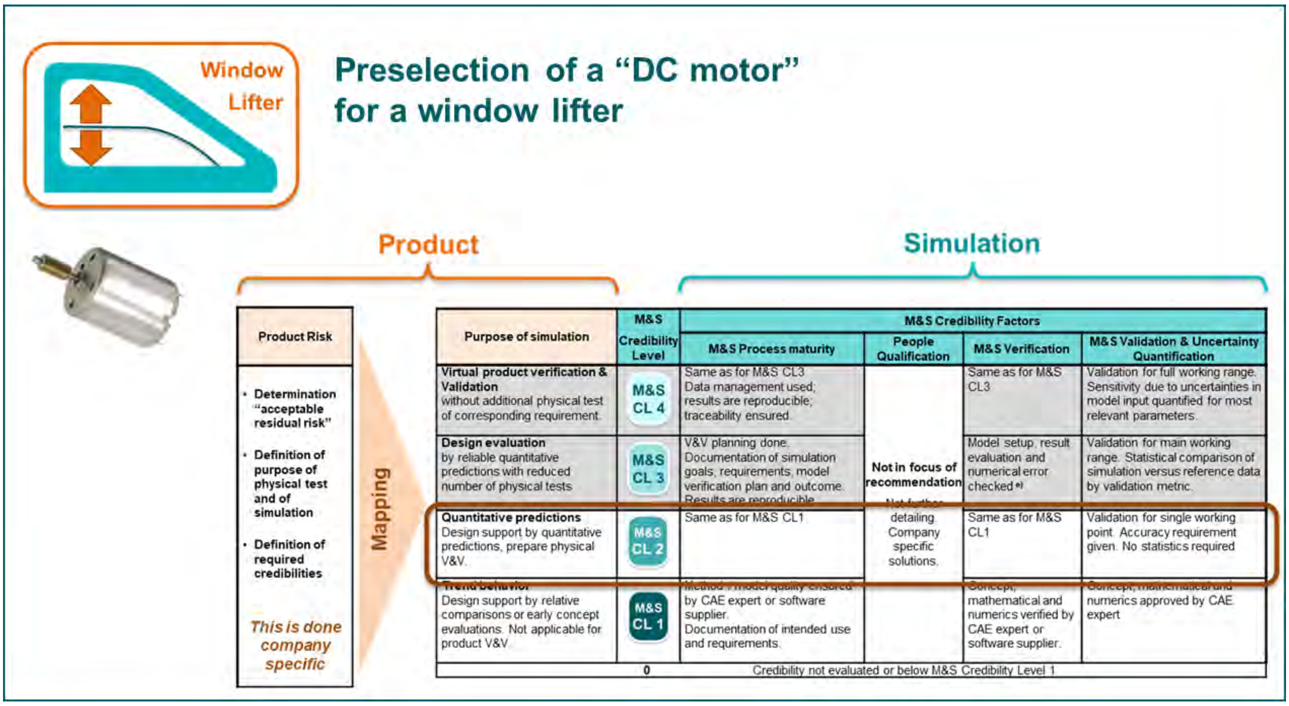
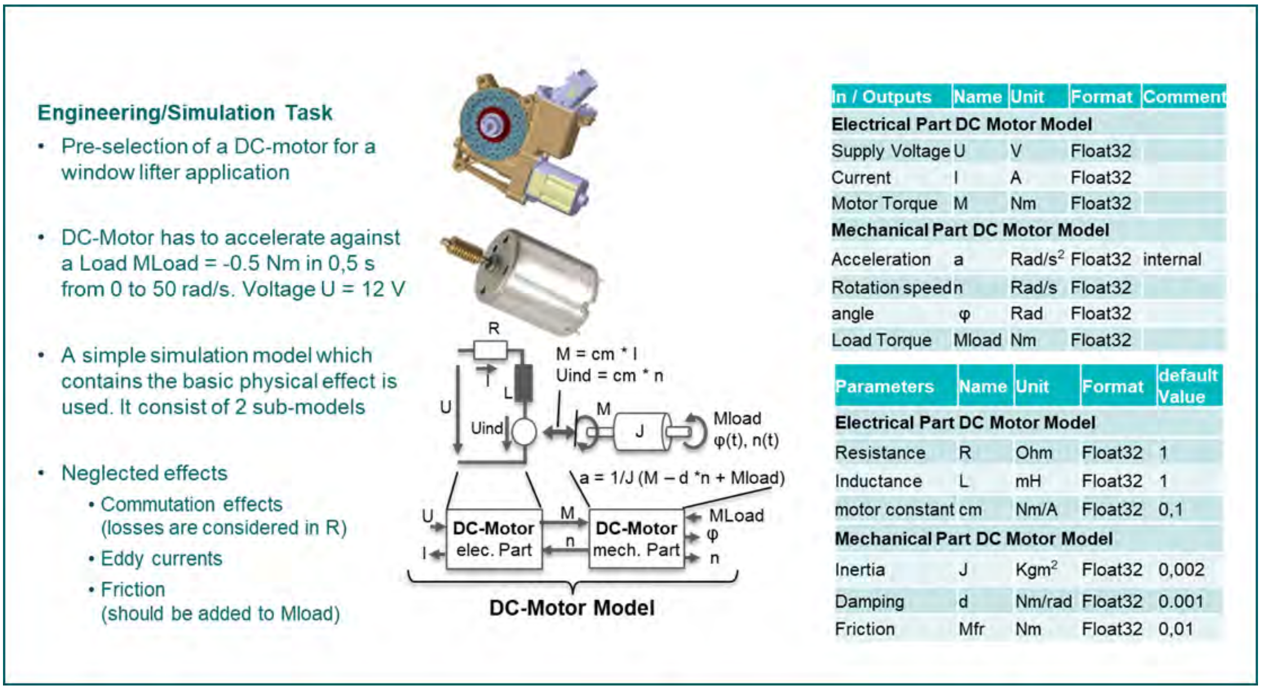


Figure 21: Preselection of a “DC motor” with corresponding “M&S Credibility Level 2”

This type of simulation or verification is proven and well established for this kind of task. The credibility factors for “M&S Credibility Level 2 – Quantitative Predictions” are therefore fulfilled. The statement derived from the simulation (in this case, the selection of a DC motor) still needs to be verified and documented.

This example of DC motor selection demonstrates that even with very simple simulations, an M&S Credibility Level 2 or higher can be achieved.

The advantage of using simple models for specific tasks lies in the reduced effort required for verification.



In / Outputs	Name	Unit	Format	Comment
Electrical Part DC Motor Model				
Supply Voltage	U	V	Float32	
Current	I	A	Float32	
Motor Torque	M	Nm	Float32	
Mechanical Part DC Motor Model				
Acceleration	a	Rad/s²	Float32	internal
Rotation speed	n	Rad/s	Float32	
angle	φ	Rad	Float32	
Load Torque	Mload	Nm	Float32	

Parameters	Name	Unit	Format	default Value
Electrical Part DC Motor Model				
Resistance	R	Ohm	Float32	1
Inductance	L	mH	Float32	1
motor constant	cm	Nm/A	Float32	0,1
Mechanical Part DC Motor Model				
Inertia	J	Kgm²	Float32	0,002
Damping	d	Nm/rad	Float32	0.001
Friction	Mfr	Nm	Float32	0,01

Figure 22: Simple example of the simulation task "DC motor"

6 Industrial Application Examples of "Simulation Credibility Assessments"

This chapter presents the practical application of a "Simulation Credibility Assessment" using two industry examples. The aim is to illustrate how different companies have integrated the principles and methods for assessing simulation credibility into their development processes. It shows which adjustments to company-specific conditions were necessary and how implementation in practice contributes to improving decision-making processes and increasing efficiency in product development.

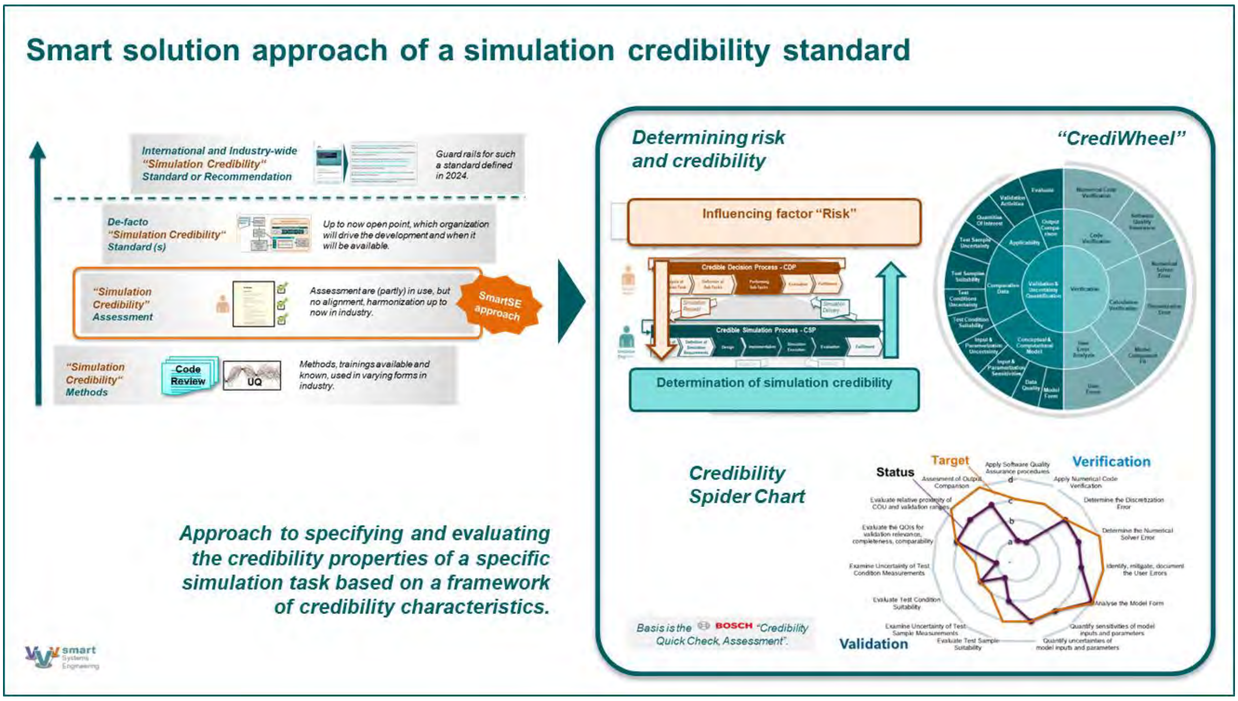


Figure 23: Smart solution approach of a simulation credibility standard

6.1 Industrial Application Example "Bosch"

The SmartSE proposed Credible Process Framework for Simulation is implemented in Bosch as RB Credibility of Simulation Framework. Its procedure is a rather simplified view that merges CDP and CSP into a rather linear but iterative manner (see Figure 24). The strict hierarchical levels of the Credible Process Framework for Simulation are resolved; also, the level of CMP is not explicitly shown. However, this simplified and reduced procedural perspective is consistent with CDP, CSP and CMP and its steps, as illustrated in Figure 7.

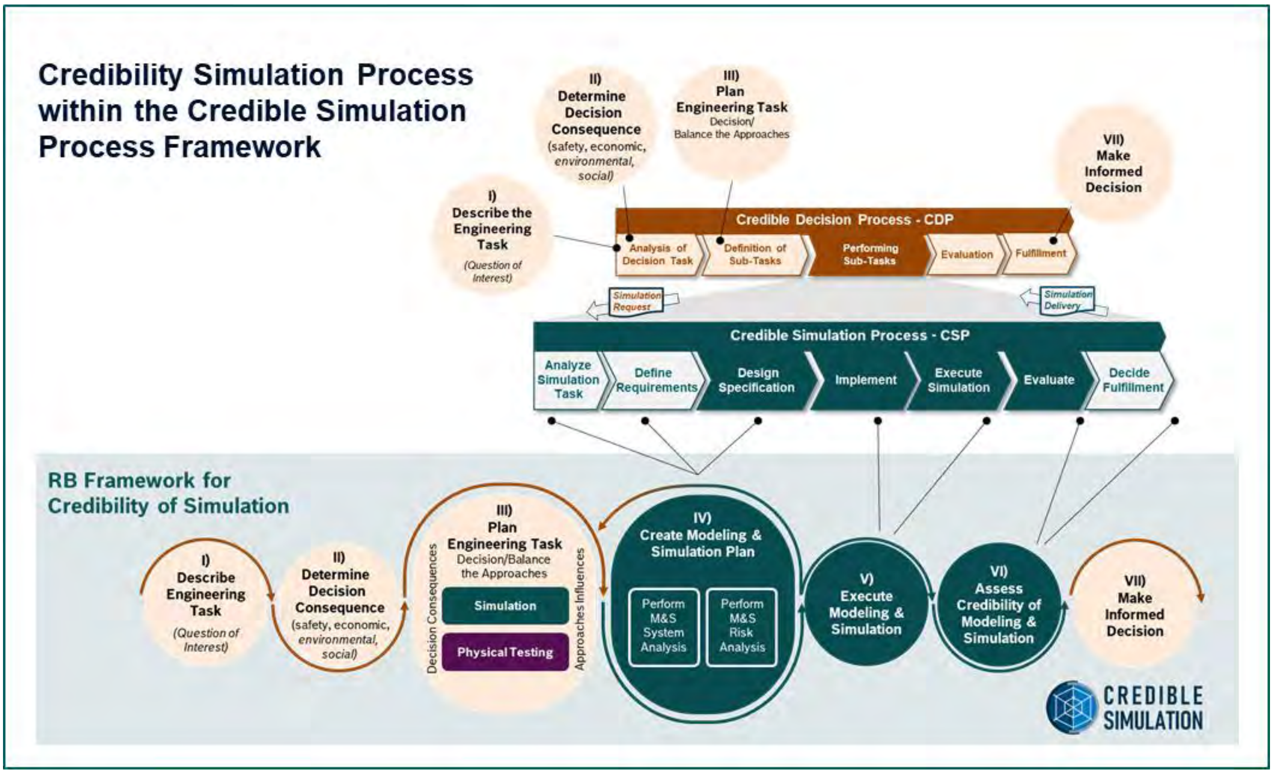


Figure 24: Mapping of Credible Simulation Process Framework with RB Framework for Credibility of Simulation

In the RB Credibility of Simulation Framework, in phase II), the decision consequence is determined, which corresponds to the determination of risk & consequences on product level in CDP as described in section 4.2. In phase III) the impact of simulation is regarded as the relation between decision consequences and related risks and the required credibility of M&S according to the M&S purpose. In RB Credibility of Simulation Framework, we use the following schematic description, see Figure 25.

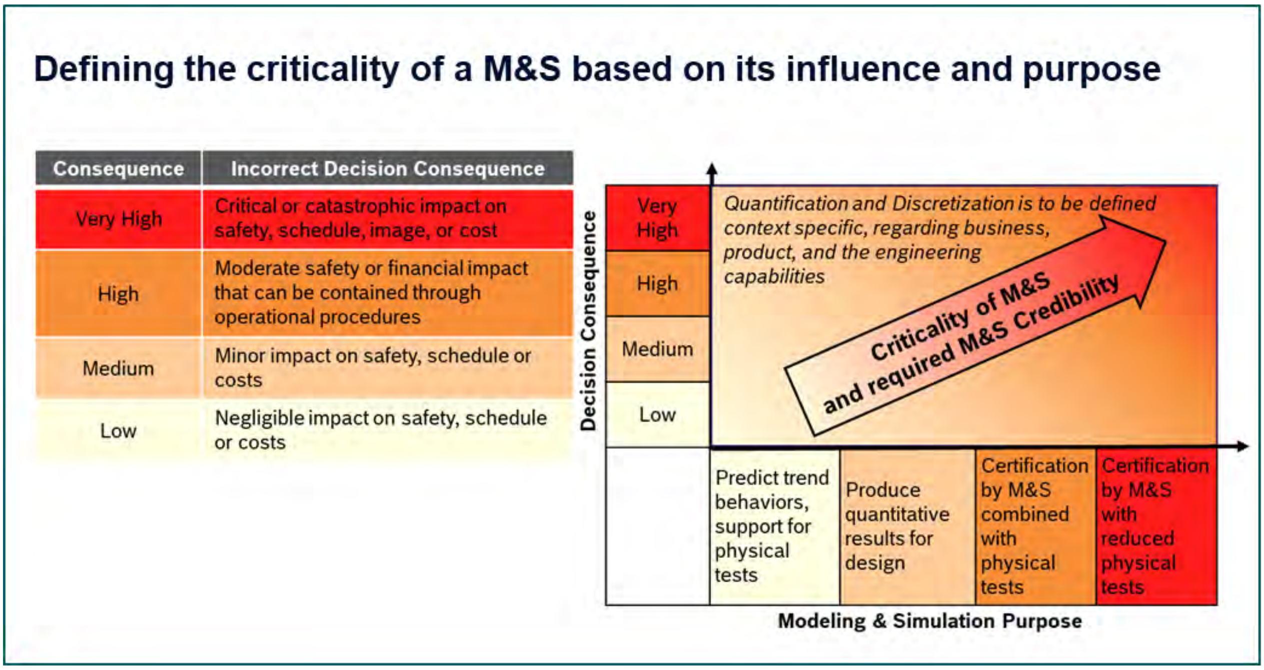


Figure 25: Defining the criticality of a M&S based on its influence, purpose and the decision consequence

The more challenging the M&S purpose and the higher the decision consequence, the higher the criticality of M&S and thus the required M&S credibility. This is consistent to the described approaches in section 5, but so far without naming M&S CL1-4, which is to be introduced in Bosch as well.

6.1.1 Relation between M&S Credibility Levels and the Bosch M&S Credibility Assessment

In section 4.1 the aspects of simulation credibility are methodological and procedural aspects as well as the people qualification aspects. The methodological aspects regards verification, validation and uncertainty quantification of M&S.

Within the RB Credibility of Simulation Framework we use a very similar systematic talking about four credibility attributes (see figure 26). However, these credibility attributes and here regarded credibility aspects cover the same:

- Verification and Validation & Uncertainty Quantification – corresponding to the methodological aspects.
- Organizational Capabilities – that contains the procedural aspects as well as people qualification aspects.
- M&S Error Management – that is in the RB Credibility of Simulation Framework its own credibility attribute that has specific methodological as well as procedural aspects.

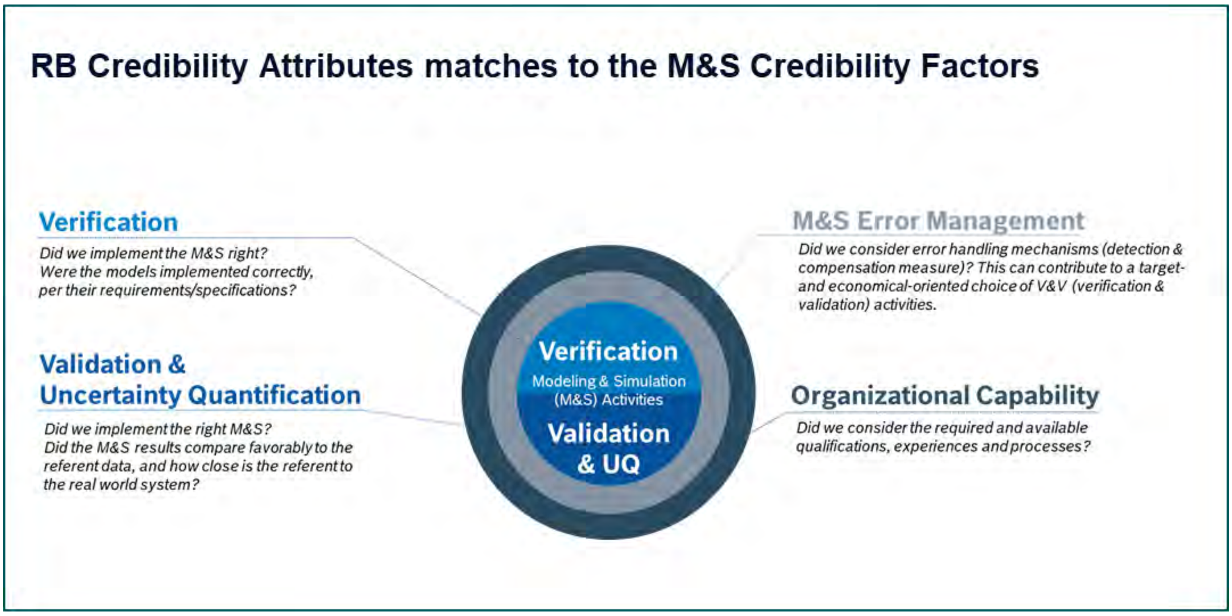


Figure 26: The Credibility Attributes in Bosch

In this White Paper the proposed M&S Credibility Levels 1-4 describe for the related simulation purposes the requirements on methodological and procedural aspects, namely on M&S Verification, M&S Validation & Uncertainty Quantification and on M&S Process Maturity, see section 5.3. about Credibility Factors.

The requirements for these three Credibility Factors are described in a quite compact manner.

At Bosch we focus for M&S Credibility Assessment mainly on the M&S verification, M&S validation and uncertainty quantification with a more detailed and systematic view on the related 15 VVUQ credibility activities. These 15 VVUQ credibility activities are shown in what we also call the “Credibility Wheel”, see Fig 27, the inner part,

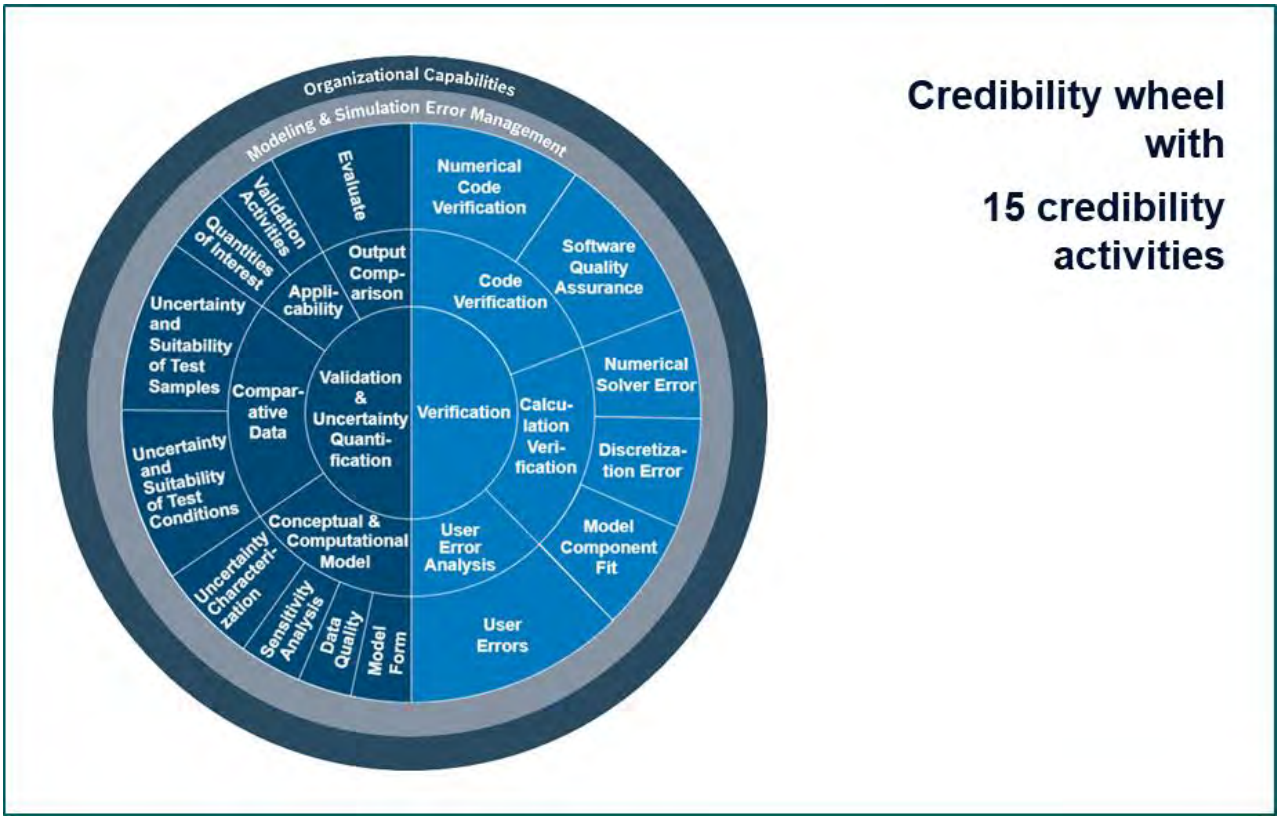


Figure 27: Credibility wheel with 15 credibility activities within the Verification, Validation and Uncertainty Quantification attributes

For each VVUQ credibility activity, there are up to four VVUQ-Credibility Levels a-d defined, that describe reasonable staged measures to demonstrate credibility. Lowest level “a” means “nothing done here” and highest level d describe recommended reasonable measures to demonstrate maximum of credibility for the regarded VVUQ credibility activity.

The 15 M&S activities are in our understanding a complete set of VVUQ credibility activities that allows to evaluate the credibility of M&S. Important is, that it is not mandatory to assess and perform all 15 VVUQ credibility activities. Depending on the simulation and engineering tasks, some may be not applicable and can be omitted.

During a credibility assessment the appropriate credibility level for all relevant VVUQ credibility activities are to be defined. We furthermore propagate to analyse for each VVUQ credibility activity probable M&S risks w.r.t. the engineering task. These M&S risks depend of course on the measures according to the VVUQ credibility levels a-d.

Finally, M&S results are regarded as credible if the M&S risks are evaluated as acceptable. This evaluation lies at the end by the decision-maker for the engineering task.

Different to the proposed approach in this white paper is that at Bosch currently there is no aggregated M&S Credibility Level. The definition of the credibility profile over all VVUQ credibility activities is done depending on the context for each application or set of similar applications. A clear orientation based on simulation purpose like proposed in section 5.3. and the M&S Credibility Levels 1-4 are currently missing. We plan to integrate that in Bosch as well.

However, both approaches supplement each other. Furthermore, the more detailed approach for M&S Credibility Assessment at Bosch can be mapped to the here shown M&S Credibility Levels and their requirements in the sense of minimum requirements.

6.1.2 Summary of VVUQ Credibility Activities in RB Credibility Assessment

This summary contains the VVUQ credibility activities formulated as questions without the measures of credibility levels a-d.

Verification: the process of determining how much a M&S meets its requirements and assessing the correctness of its mathematical model and numerical implementation [7] [9]. Three main aspects, along with their underlying activities, are considered for this attribute. For each we have included a short question to provide users of the framework with a quick understanding of what each activity entails:

- **Code Verification:** Are there errors in code or in algorithms?
  - *Numerical Code Verification (NCV): Are the algorithms correctly implemented?*
  - *Software Quality Assurance (SQA): Is the Software good enough?*
- **Calculation Verification:** Are there numerical errors in the calculation?
  - *Numerical Solver Error: Are the solver and its parameters well chosen?*
  - *Discretization Error: Is the discretization appropriate?*
  - *Model Component Fit: Are the right sub-models and scripts used?*
- **User Error Analysis:** What user error management measures are implemented?

Validation and Uncertainty Quantification: aim to ensure the appropriate credibility of the model's prediction accuracy considering all possible uncertainties that influence the M&S results. This attribute ensures that the validated model predictions remain accurate and credible under different model boundary conditions. Four main aspects, along with their underlying activities, are considered for this attribute:

- **Conceptual and Computational Model:** Is the model good enough?
  - *Model Form: Is everything relevant implemented? Data Quality: How good is the data used for simulation?*
  - *Sensitivity Analysis: How robust is the result to input variances?*
  - *Uncertainty Characterization: What influence do uncertainties have? Are they Propagated?*
- **Comparative Data:** How good is the reference data?
  - *Uncertainty and Suitability of Test Conditions: Are the test conditions representative and their uncertainties characterized and propagated?*
  - *Uncertainty and Suitability of Test Samples: Are the test samples representative and their uncertainties characterized and propagated?*
- **Applicability:** How suitable are the validation activities?
  - *Relevance of the Quantities of Interest: Is the full model scope validated?*
  - *Relevance of the validation conditions: Do the validation conditions cover the CoU?*
- **Output Comparison:** How good is the result?

Example for summary diagram of M&S Credibility Assessment: M&S risk assessment example based on an assessment of the VVUQ credibility activities. Green: risk accepted, Red: risk not accepted, black: risk not assessed, red arrows: required level to get an accepted risk

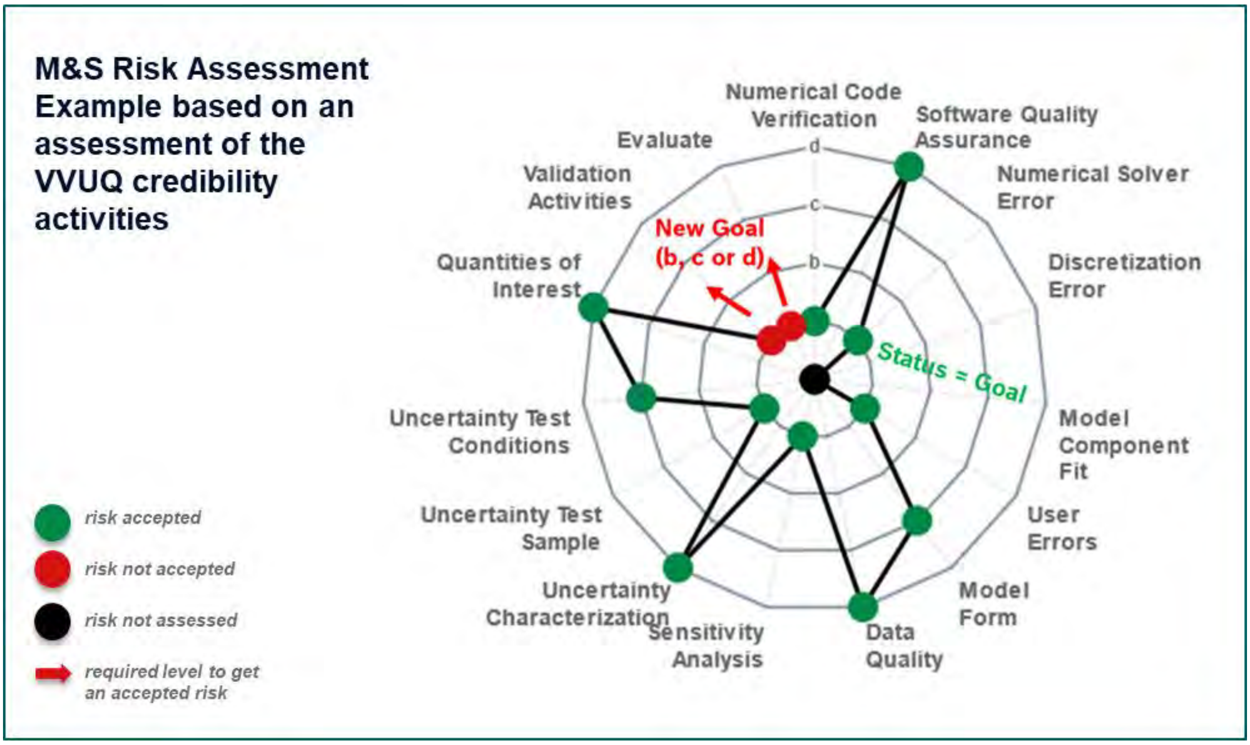


Figure 28: M&S Risk Assessment Example

Some more details are described in "Advances in Credibility of Modeling and Simulation: A Generic Framework Approach at Bosch" [10].

6.2 Industrial Application Examples "ZF"

ZF applies the Simulation Credibility Assessment framework within its product development process to systematically assess and document the credibility of simulation results. The following sections illustrate how simulation is integrated into ZF's verification strategy and how the required M&S Credibility Level is determined.

6.2.1 Simulation-Based Verification Strategy in ZF's Product Development

ZF's product development process defines the necessary activities to transform an idea into a product ready for series production. While traditionally based on physical testing, this process now formally integrates simulation as an equivalent method for product verification. The validation manager is responsible for planning the verification strategy and may now choose the most suitable and efficient approach - whether test-based, simulation-based, or hybrid - depending on the product risks and failure modes to be addressed.

Reliability analysis ensures that all three approaches deliver the same level of product quality.

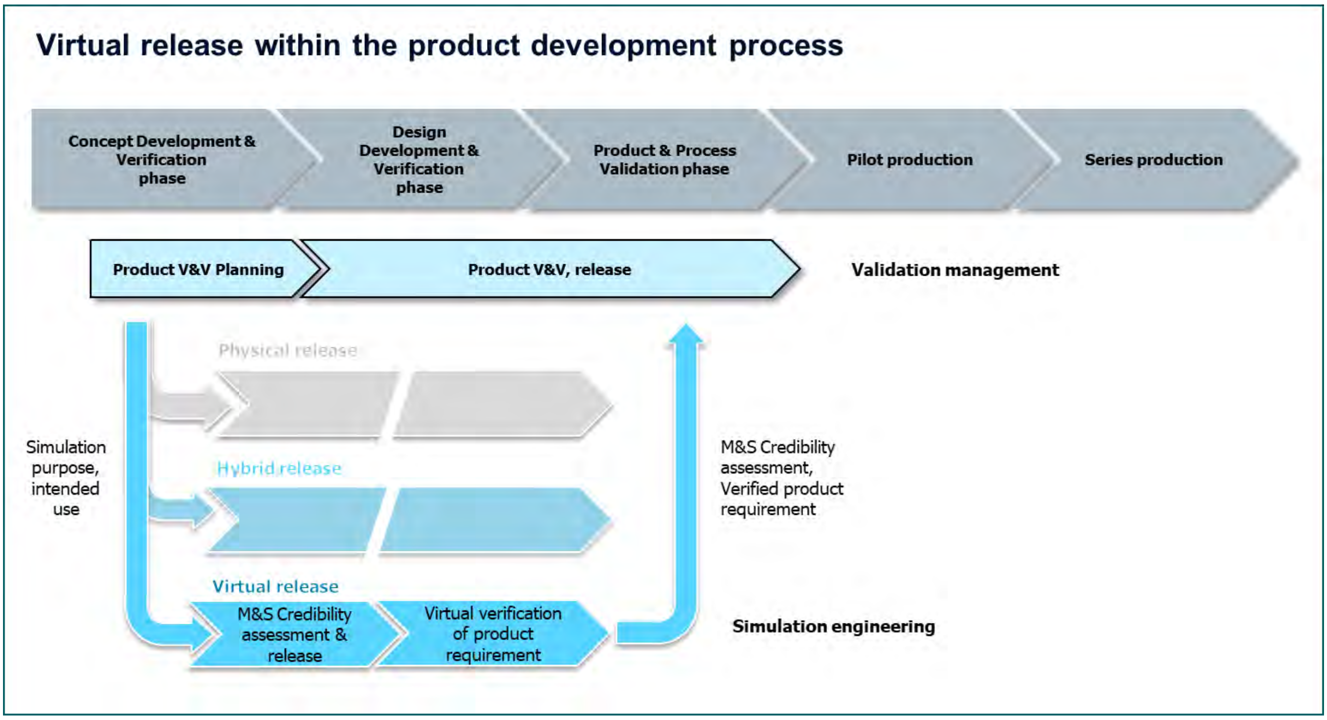


Figure 29: Virtual release within the product development process

In ZF's terminology:

- Virtual Release: *Individual product requirements are verified entirely through simulation.*
- Hybrid Release: *Individual product requirements are verified by a combination of simulation and physical testing.*

Releasing a product requirement virtually requires assessing the credibility of the simulation method and applying it to verify the requirement.

Simulation models typically focus on specific system response quantities, such as the fatigue failure of a shaft. In contrast, physical tests often cover multiple potential failure modes. Therefore, at ZF, replacing a physical test (partially or fully) with a simulation-based approach involves identifying the critical failure modes and requirements previously covered by testing and ensuring they are adequately addressed. Moreover, obtaining a system response via M&S often requires multiple simulation models. For example, predicting fatigue failure may require a stress simulation model feeding into a fatigue life model. Consequently, several simulation models are typically needed to verify the equivalent scope of a physical test.

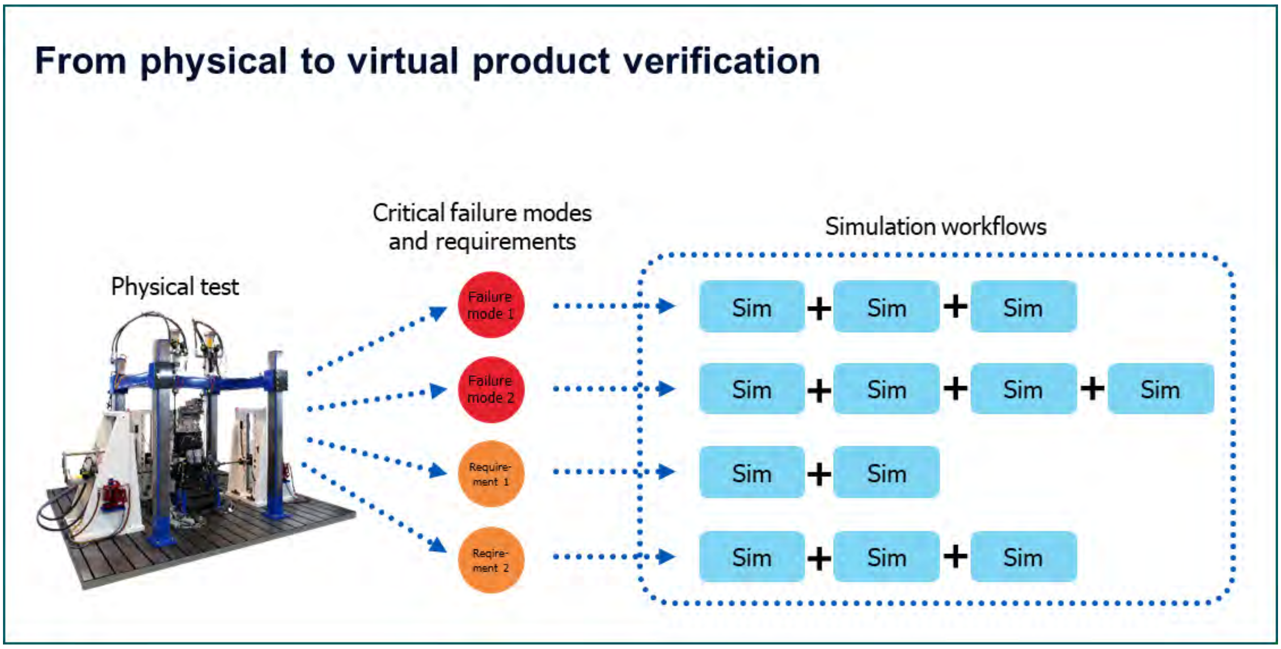


Figure 30: From physical to virtual product verification

ZF has established an internal standard for assessing the credibility of simulation models. This standard ensures a consistent approach across different simulation disciplines, teams and locations. It also clarifies the responsibilities in the use of simulations in product release. Simulation engineers simply need to make sure their simulation models comply with the requirements defined in the standard, providing a documented credibility assessment. Often this can be done once for a class of simulation models. This approach enables efficient reuse, ensures traceability, and supports reproducibility across projects.

A board composed by test, simulation and product experts verifies the credibility assessment made by the simulation engineer and releases the credibility assessment for the respective product. After this release, assessed models are made available to validation managers for use in product V&V planning. The description of the intended use of simulation models adds to the communication between product and simulation level, specifying their scope of application.

6.2.2 ZF’s M&S Credibility Level assessment

Similarly to the concept presented in chapter 5, ZF has defined distinct M&S Credibility Levels, specifying both the purpose for which a simulation can be used in the product verification process and the requirements the simulation must meet to fulfill that purpose.

Thus, M&S credibility levels serve as a central interface between product-level validation planning and simulation execution.

Within ZF, model credibility is assessed based on four main factors which are:

- Process maturity
- Verification
- Calibration
- Validation.

An overview of the Credibility levels, the main influence factors and required activities for numerical simulation models is presented in the following Figure 31.

M&S CL	Purpose	Process maturity	Verification	Calibration (if needed)	Validation
4	**Virtual verification** without additional physical verification of corresponding requirement	Same as for CL3; Data management used; Results are reproducible; Traceability ensured	Same as for M&S CL3	Calibration done for all relevant components or effects	Validation for full working range; Sensitivity due to uncertainties in model input quantified for most relevant parameters
3	**Design evaluation** by reliable quantitative predictions; Physical verification with reduced number of samples	V&V planning done; Documentation of simulation goals, requirements, model verification plan and outcome; Results are reproducible	Model setup, result evaluation and numerical error checked	Calibration done for some components or effects	Validation for main working range; Statistical comparison of simulation versus reference data by validation metric
2	**Quantitative predictions** Design support by quantitative predictions; Prepare physical verification	Same as for M&S CL1	Same as for M&S CL1	Calibration done on datasheet level	Validation for single working point; Accuracy requirement given; No statistics required
1	**Trend behavior** Design support by relative comparisons or early concept evaluations; Not applicable for product verification	Method / model quality ensured by CAE expert or software supplier; Documentation of intended use and requirements	Concept, mathematical and numerical models verified by CAE expert or software supplier	No calibration required	No validation needed
0	M&S Credibility Level not evaluated or below CL1.				

Figure 31: Minimum requirements for M&S Credibility Levels within ZF

The assessment of the M&S Credibility Level follows a structured process. In this process, the simulation model is considered as a system of interest. Based on the simulation requirements - including the intended Credibility Level - necessary activities are derived.

These activities follow the V-model and ensure that the simulation is internally consistent (verification) and sufficiently accurate in representing physical phenomena (validation).

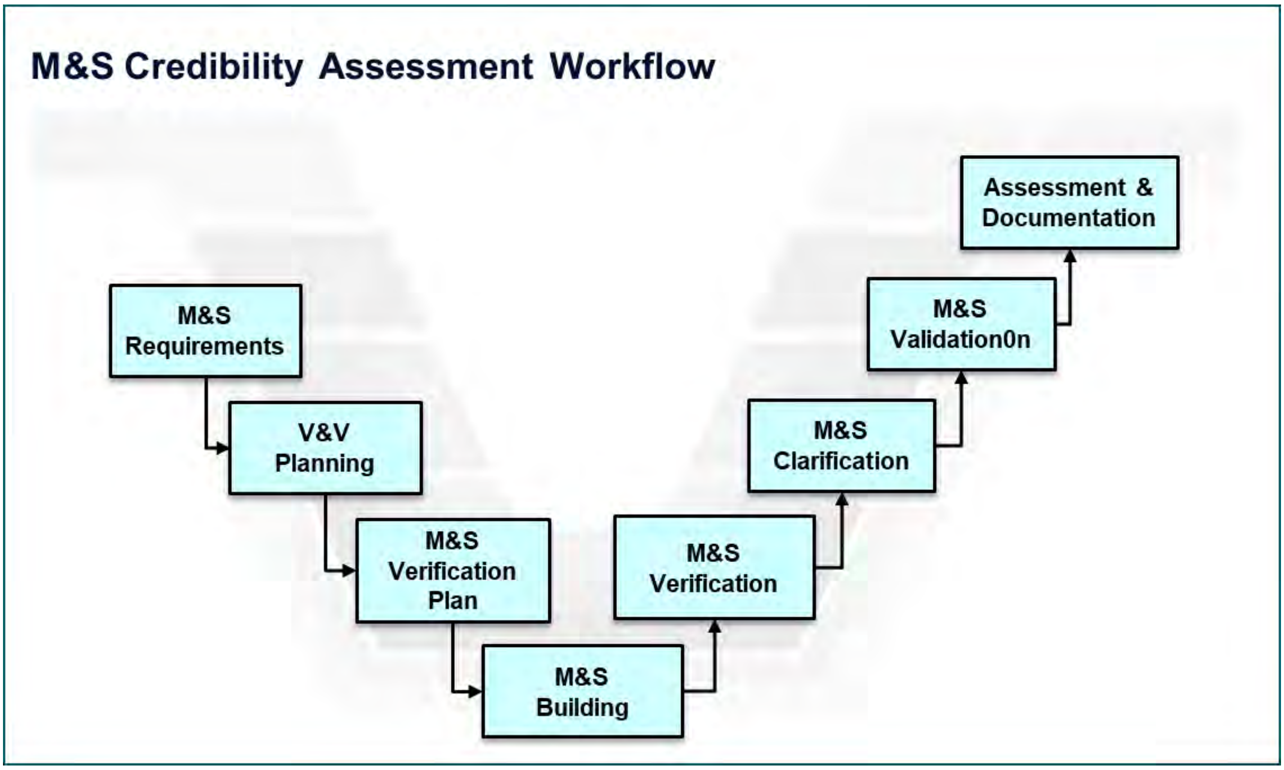


Figure 32: M&S Credibility Assessment Workflow based on the V-Model

M&S requirements

The reality of interest is defined to specify which aspects of the real system are represented in the model. The intended use of the model is described, including the scope, input ranges, and expected system responses.

V&V Planning

For lower M&S Credibility Level, the verification of the concept, mathematical and physical model is done individually by the simulation expert. For higher M&S Credibility Level, a more formal V&V planning is required.

- Verification Planning involves identifying risks in the modeling process and creating a plan to mitigate each of them. The outcome is a model verification plan.
- Validation Planning defines a set of test cases for which the model should have to demonstrate predictive capability. These cases reflect the range of input parameters specified in the intended use.

Model Verification Plan

The plan is created during Verification Planning, and contains a list of identified risks, as well as measures to prevent them.

Model building

Actual realization of the model. Models can be constructed from scratch, as an assembly of sub-models (e.g. from a library of elements in system simulation) or be based on a template. The result of model build-up is the individual model, e.g. an input file for a solver to be executed. All relevant aspects such as inputs, boundaries, model setup, assumptions, and limitations are documented.

Model verification

The model is verified (for higher M&S Credibility Level, against the criteria defined in the Model Verification Plan), ensuring correctness in conceptual, mathematical-physical, numerical model, and its implementation. Also, the software implementation is checked (code verification). This can be outsourced to the vendor.

Model calibration

In some simulation domains, it is required to tune model parameters to meet the results of corresponding measurements. Model calibration is typically done on the lowest level of hierarchical models.

Model validation

The model accuracy is demonstrated by comparing simulation outcomes to reference data, according to the Validation Plan. The reference data are usually taken from validation experiments but can also be taken from already validated simulation models. Validation is specific to a model and intended use.

For M&S Credibility Level 4, the uncertainty of the model output is quantified with respect to the most influential input parameters.

Assessment of M&S Credibility Level and documentation

The model's M&S Credibility Level is assessed based on the individual credibility factors, and all relevant steps of M&S Credibility Level demonstration are documented.

All process steps are documented to ensure traceability and reproducibility.

7 Conclusion and Outlook

Simulations enable the virtual analysis and optimization of products, making development processes more efficient and cost-effective while supporting well-founded engineering decisions**.** Despite these advantages, the acceptance and practical use of numerical simulations remain limited in many companies. This is often due to a **lack of clear evaluation criteria and transparent benchmarks for assessing the credibility of simulation** results. As consequence, many decision-makers continue to rely on physical testing, even when reliable numerical simulation results would be available.

To close this gap and systematically strengthen trust in simulation results, the SmartSE project group has developed the approach of **“Simulation Credibility Assessments.”** The goal of this white paper is to present practical and adaptable methodological approaches for assessing the credibility of numerical simulations, as already applied in the automotive industry.

The **requirements for simulation credibility are derived from the purpose of the simulation** within the development task. This forms the basis of the proposed four **“M&S Credibility Levels”** (M&S CL 1–4) as a clear, qualitative assessment framework.

Nevertheless, when implementing identical requirements for the credibility of a simulation, differences will occur. These differences are primarily determined by the criticality of the decision to be made and how identified remaining M&S risks affect product and development risks despite the simulation credibility requirements being met.

Each development task is associated with the criticality of the decision to be made at the product level and the corresponding potential risk of a wrong decision. **M&S risks** refer to risks arising from faulty simulations.

Only when the risks, both at the product and decision level as well as M&S risks, and their effects on the product and development level have been understood and evaluated, is it possible to make a sufficiently informed decision. The **Simulation Credibility Assessment classifies the purpose of the simulation for the development task and specifies clear and understandable requirements for the credibility assessment of simulations, which ideally avoid or minimize remaining M&S risks.**

The methodology contributes significantly to establishing numerical simulations as an equivalent, reliable basis for decisions alongside real-world tests and ensures transparency and comparability. However, the specific design and effort required to achieve an M&S credibility level depend heavily on the type of development task and its safety relevance.

Outlook

Credibility assessments serve as an adaptable methodological framework on the path toward a comprehensive **standard or recommendation for simulation credibility**. The overarching goal of the SmartSE project group is to initiate a general, cross-industry, and adaptable standard for numerical simulations. Since SmartSE does not have the resources to fully develop such a standard, the group is focusing on establishing guidelines and guard rails for it. Until an international, cross-industry credibility standard or recommendation is adopted, SmartSE aims to create an applicable de facto credibility standard by providing methodological approaches and practical building blocks. The harmonization of the currently very different organizational credibility assessments is crucial to enable consistent and comparable M&S credibility levels, especially in cross-company development and at certification bodies. Industrial application examples (such as at Bosch and ZF) show that the basic principles of risk-based decision-making and the Credible Process Framework are already being implemented. In the future, there are plans to integrate the proposed aggregated M&S credibility levels (M&S CL 1–4) more closely into these detailed, company-specific frameworks (such as the 15 VVUQ credibility activities at Bosch) in order to create clear guidance based on the simulation purpose.

With the ongoing transition to software-defined systems (SDS), software validation is rapidly gaining importance in assessing the credibility of simulations. SDS pose additional challenges for ensuring the credibility of simulation results due to their high degree of software integration and continuous functional updates. In particular, the complexity and criticality of embedded software in areas such as driver assistance systems and autonomous vehicle systems of the automotive industry require robust and transparent validation and verification strategies. As part of its future activities, the SmartSE project group intends to further investigate the influence of software validation on the assessment of simulation credibility. This includes the development of methodological approaches and best practices for integrating software V&V into the overall credibility framework, with a focus on software-intensive systems.

The **Simulations Credibility Assessment**s approach thus lays the foundation for **modern, fully virtual, and efficient product development** by creating the necessary basis of trust for the widespread use of numerical simulations in decision-making and approval processes.

8 References

[1] Project group "Smart Systems Engineering (SmartSE"), prostep ivip association, https://www.prostep.org/en/projects/smart-systems-engineering-smartse

[2] Recommendation "Smart Systems Engineering – SmartSE, V4", prostep ivip association, 2025,https://www.prostep.org/en/medialibrary/translate-to-english-detail?ai%5Baction%5D=detail&ai%5Bcontroller%5D=Catalog&ai%5Bd_name%5D=wp_smartse_sdmr&ai%5Bd_pos%5D=1

[3] White Paper "Guard Rails for Simulation Credibility Standards and Recommendations", prostep ivip association, 2021, https://www.prostep.org/en/medialibrary/translate-to-english-detail?ai%5Baction%5D=detail&ai%5Bcontroller%5D=Catalog&ai%5Bd_name%5D=wp_smartse_sdmr&ai%5Bd_pos%5D=1

[4] White Paper "SmartSE - Simulation-based Decision Making and Release", prostep ivip association, 2021, https://www.prostep.org/en/medialibrary/translate-to-english-detail?ai%5Baction%5D=detail&ai%5Bcontroller%5D=Catalog&ai%5Bd_name%5D=wp_smartse_sdmr&ai%5Bd_pos%5D=1

[7] NASA, Standard for Models and Simulations NASA-STD-7009, Office of the NASA Chief Engineer, 2024.

[9] Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer, ASME, 2009.

[10] M. B. Baradi, R. Koehler, M. Atak, A. Karl, A. Kerst, L. Kocsan, S. Fricke, U. Schulmeister „Advances in Credibility of Modeling and Simulation: A Generic Framework Approach at Bosch" NAFEMS World Congress Salzburg 2025

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