V&V of M&S: Past, Present and Future

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ABSTRACT

Measures for Verification and Validation (V&V) of models, simulations and data (M&S) have been always important aspects and caused specific activities ensuring quality and utility of M&S results and their interpretation. Along with rapid innovations and increasing performance of computer systems, networks and software, capabilities as well as complexity of models and simulations are permanently increasing. Therefore, the major challenges of M&S nowadays are to master M&S complexity as well as quality demand.

To substantiate specific quality demands requires to keep track of evidences for correctness, validity and usefulness of models, simulations and data through verification and validation. This contribution presents an overview about importance and evolution of V&V processes and techniques established over the past, and it summarizes briefly current state-of-the-art as well as major challenges for future M&S projects.

1.0 INTRODUCTION

Besides application of fundamental natural laws, and besides processing of experiments in real world scenarios, modeling and simulation (M&S) is considered as the third pillar for enabling generation of new knowledge and of product innovations. Modeling and simulation (M&S) are receiving increasing importance as a technology which supports learning and training capabilities, serves for decision support as well as for systems analysis and evaluation. Rapid advancements of computer and communication technologies enable also rapid advancements in the field of modeling and simulation: Development and application of new modeling methods and simulation techniques, as well as a wide and increasing range of M&S application domains which result in increasing complexity of models, simulations and data.

Besides benefits of these innovations and advances, increasing risks with respect to quality of simulation model development and operation as well as regarding credibility and utility of simulation results and their interpretation have to be considered. As demonstrated by several cases, the use of erroneous models, invalid simulations or data can lead to severe safety-critical situations and can result in wrong decisions and economic damages. In June 1995, the cruise ship *Royal Majesty* grounded on Rose and Crown Shoal about 10 miles east of Nantucket Island, Massachusetts, due to a navigation model error which caused a severe safety problem. Though there were no deaths or injuries as a result of this accident but repair of the vessel and lost revenue were estimated at about US-$7 million ([6]). Other examples of modelling errors caused deficient designs of airport baggage handling and delivery systems leading to significant economic damages.

Especially in context of the increasing importance of manifold M&S application such as component-based modeling, parallel and distributed simulation, collaborative simulation or agent-based simulation, efficient quality control and credibility assurance mechanisms have to be applied to avoid safety-critical, expensive and other unwanted side effects. This requires the application of standardized engineering processes for M&S design, development and operation, including careful selection and application of M&S verification, Validation and Acceptance (VV&A) processes, methods and supporting tools.

This chapter presents a brief overview of terminology and of basic concepts applied in context of modelling and simulation, in general. It also includes a review of the evolution of VV&A methods and techniques applied to perform quality assurance, verification and validation.

1.1 Basic Terminology

Following J. Rothenberg's definition, **a model** can be defined as **a symbolic, abstract, cost-effective and safe referent of something else for some specific cognitive purpose** [1]. Most of human reasoning and decision making processes are based on mental modeling. Even in everyday life, mental models are being used for analysing situations or for making decisions. Understanding and analysis of real world problems require – at least in general – simplification and abstraction of reality as humans are only able to conclude interdependencies between about 5 – 7 parameters at the same time.

As mental models are built intuitively based on experiences, they belong to the category of **inductive models**. Inductive modelling approaches enable reasoning based on similar situations or cases. In contrast, the majority of computer-based models and simulations used nowadays for analyses, decision making or training are designed and applied as **deductive models** expressing qualitative or quantitative dependencies between goal, input and state parameters. Interdependencies between these parameters can be described mathematical formulas, numerical or logical algorithms. In the following, we will focus on design and application principles of those kinds of deductive models.

Along these lines, and in accordance with Maisel and Gnugnoli (in [3]), **simulation** can be defined as **a (numerical) technique for conducting experiments on a computer; this technique involves certain types of mathematical and logical models that describe real world behaviour or the behaviour of a system over periods of time.** This definition describes simulation explicitly as a technique for solving and using models by means of computers. This definition also indicates that (computer-based) simulation is a multi-stage process which differentiates between stages like conceptual model design, its formal description, technical solution and experimental applications.

For collecting evidences of correctness, validity and utility of models, simulations and data, some general principles and specific techniques for M&S verification and validation can be applied. An informal but clear distinction between these terms has been presented already long time ago by Balci: Application of verification techniques provides evidences for M&S correctness ("Is the **model right** ?") opposed to validation techniques which can provide evidences for validity and utility of an M&S regarding its specific application goals and constraints ("Is it **the right model**?"). Meanwhile, multiple and more precise definitions for verification and validation are provided by national and international standards, like in DoD- or IEEE-Standards.

In GM-VV-Volume 1 ([19]), the following definitions are established and are used by all contributions of this Lecture Series seminar:

- **Verification: The process of providing evidence justifying the M&S system's correctness.**
- **Validation: The process of providing evidence justifying the M&S system's validity. Validity is the property of an M&S system's representation of the simuland to correspond sufficiently enough with the referent for the intended use.** The simuland is the system or process that is simulated by a simulation while the referent is "… the codified body of knowledge about a thing being simulated (IEEEStd 1516.4; [12]).
- **Acceptance: The process that ascertains whether an M&S system is fit for its intended use.**
- Project demands like use risk, time schedules, limited resources or intellectual property rights can be constraints that have to be considered while planning M&S activities, Therefore, project-specific tailoring of M&S activities including V&V planning is required in general. In context of GM-VV,

> **Tailoring** is defined as "…**the modification of V&V processes V&V organization and V&V products to fit agreed risks, resources, and implementation constraints**." ([19])

These and some alternative but closely related definitions from other international M&S standards can be found in SISO-GUIDE-GM-VV-001.1-2012 (Volume 1 [19]).

2.0 BASIC PRINCIPLES AND TECHNIQUES FOR M&S DEVELOPMENT; VERIFICATION AND VALIDATION

In the first decades of computer-based M&S, modeling was considered more as creative art rather than an engineering discipline. Shannon described "....**the art of modeling** consists in an ability to analyse a problem, abstract from it its essential features, select and modify basic assumptions that characterize the system, and then enrich and elaborate the model until a useful approximation results." ([2]). Already in the same book – published in 1975 – Shannon and others also mention model building as "… an evolutionary multi-stage process where evolution is depending on factors like user requirements, requested model flexibility, available resources and skills." But he also mentions that a model building process also relays on the communication and collaboration between model builder and model user to ensure that the modelling results meet the relevant goals, objectives and criteria of a project defined by the project sponsor ([2]).

To assure a demanded level of M&S quality, utility and credibility of its results, this contribution promotes the application of the general "divide and conquer" engineering principle in threefold:

- Each M&S project has to be considered and should be processed like a typical engineering process: M&S development and application require strict separation between different M&S phases and activities. According to Figure 1, each M&S phase or activity has to result in a work product of (intermediate) M&S results along with some documentation. For each M&S phase, roles and responsibilities of team members have to be defined performing the activities and contributing to these work products;
- Verification and validation (V&V) of (intermediate) work products of each modeling phase should be performed stepwise by application of verification and validation processes and techniques. All results of applied V&V activities have to be documented by means of V&V reports (see Figure 2).
- Basically, V&V planning which includes the selection of V&V techniques and intensity of V&V activities should be tailored according project-specific requirements and constraints.

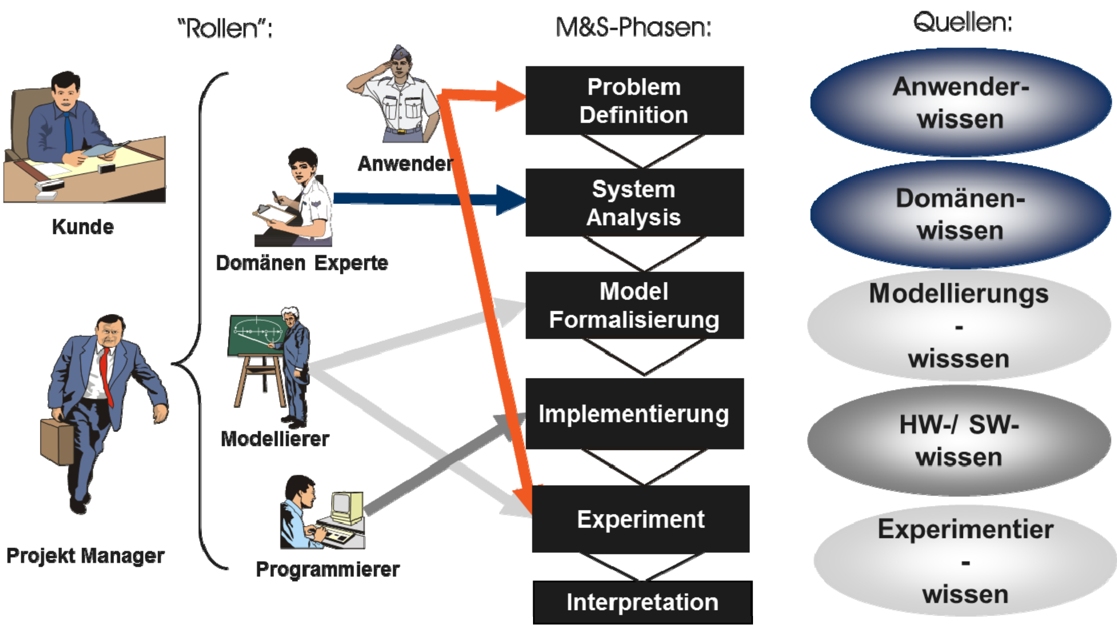

Figure 1: Typical multi-phase M&S design, development and application process ([5], [4]).

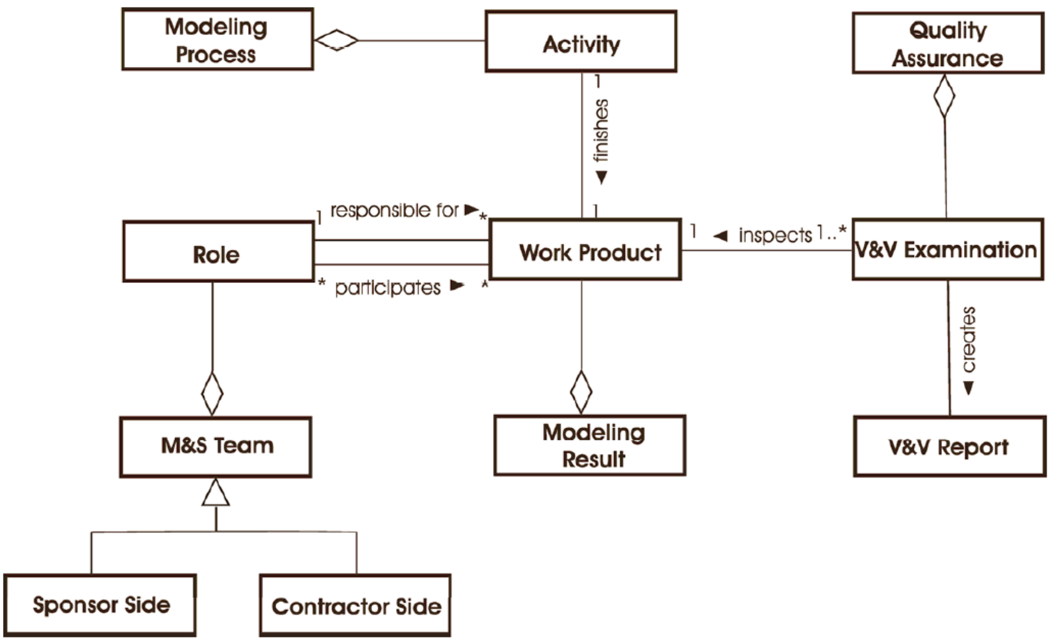

Figure 2: Meta model of an M&S Building and Application Process ([14], [17]).

In accordance with these definitions and as widely accepted by the M&S community, a model and simulation building and application process is basically a multi-stage process. As demonstrated in Figure 1, each stage, or phase, of this process requires generally input from domain experts and/or data, an execution of stage-specific activities by skilled persons, and each stage has to provide an (intermediate or final) work product with documentation as result of this working stage. The iterative, evolutionary character of a typical M&S building process can lead to optional solutions, work products as well as to different versions of a work product (as indicated by the tree-structured graph on the right hand side in Figure 3 which will be discussed in detail in Section 2.1).

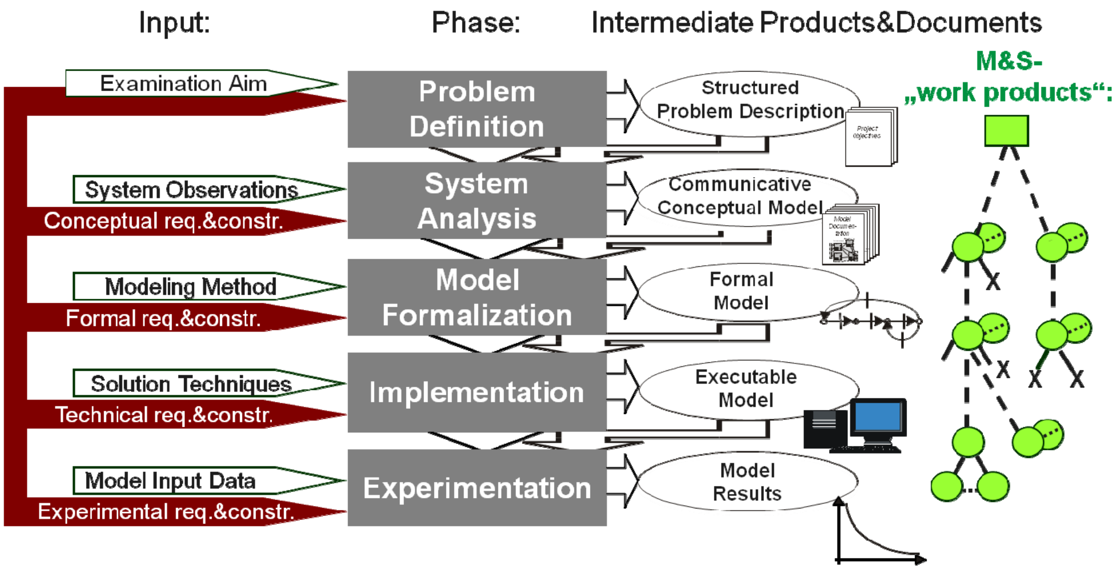

Figure 3: Typical Multi-Phase M&S Design, Development and Application Process (e.g. [4], [5], [17]).

2.1 A Systems Engineering Approach for M&S Development and Operation

As mentioned before, in the past computer-based modelling and simulation model building has been considered more like an art rather than a scientific or an engineering challenge (e.g. see Shannon [1]). Due to permanently increasing scope and complexity of models being built and applied nowadays, M&S projects can only be mastered if some general engineering principles are also applied for M&S design, development, maintenance, and quality assurance. One of those principles concerns guidelines or standards for well-structured and globally accepted M&S- and V&V processes. The meta model in Figure 2 describes the generic structure of a typical M&S building and application process, including activities, working products, roles and responsibilities of those contributing to an M&S project.

Permanent increasing performance and capabilities of ICT hardware and software, improved or novel modeling methods and a huge variety of powerful M&S tools enable the development and application of very complex models. On one side, basic engineering practices and standardized procedures are required to guarantee the demanded quality of development and operation processes of complex simulation applications as a whole.

Like in other engineering disciplines (e.g. [8], [10], [11] ,[12]), as well as already fixed in M&S standards like in IEEE 1516.4 for the FEDEP ([12]), or in “Generic Methodology for Verification and Validation of Models, Simulation and Data (GM-VV)” ([19]), a “divide and conquer” strategy is proposed according to which an M&S process consists of a fixed sequence of different modeling phases, or development levels, respectively. To process the activities of a modeling phase requires phase-specific knowledge and input data to transform the results – the work products – of the previous modeling phase. For example, according to Figure 2 and Figure 3, each M&S development process starts with a problem definition phase (development level 1) based on a project’s Sponsor Needs (SN) in which information about goals, requirements and constraints of a concrete M&S project are used as input to produce a Structured Problem Specification (SPD) as result documented in an intermediate work product. In the following development phase, this work product together with additional information (e.g. measured data or assumptions about a system under consideration) should be used as specification for transformation of the Structured Problem Description to a work product "Conceptual Model" (CM). The Conceptual Model in turn can be considered as specification for transforming the Conceptual model to a Formal Model (FM) by using a problem adequate modeling method or formalism, etc. ([4], [9], [17]).

As indicated by the green colored graphical example of a tree structure in Figure 3 (on the right hand side), nodes represent work products and arcs represent transformations between nodes. A Structured Problem Description (SPD) may result in different Conceptual Model (CM) options (in this example: 2 nodes on the next M&S development level). As a result of some modifications, each of those Conceptual Model work products might be modified again in different versions (as indicated by doted lines between the nodes on the same level). In general, transformation of an intermediate work product can result in different, optional solutions in the following modeling phase (work products), while each of those can be implemented in different (e.g. refined) versions again.

This approach leads to a tree-structured M&S development process with relations like "transformation" or "modification" between intermediate work products and final M&S experimentation results. Starting from the root node down to the leaves of a tree, each path describes all the intermediate work products of a possible solution or alternative solution approaches for a given problem. Vice versa, paths starting from leaves up to the root of a tree can be used for error detection, fault analysis and interpretation of experimentation results [13], [16].

Besides these benefits, this systems engineering approach offers additional opportunities for efficient reusability or further development of models or model components. These developments can start from or are based on already existing intermediate work products and links to those roles or individuals who have been in charge of these work product developments. To support effectively those additional kinds of M&S application and to keep track of a model's history as basis for further developments, tool support by a model management system is highly recommended. Major capabilities and services of such a model management system serving as platform for all those involved in the different phases of an M&S process should include:

- Versioning;
- Change management;
- Error and fault management;
- Configuration management;
- Role management;
- Workflow management; and
- Case studies and, experiences.

As an example, we have developed concept and demonstrator of a model management architecture according to Figure 4. Following the M&S development and operation process as discussed above, according to the proposed concept, all intermediate work products, documentation, data and information produced during the various M&S design, development, and application stages is collected in a single system. This approach allows efficient M&S development, maintenance and operation. It also facilitates cooperative M&S, collection of experiences and effective reuse of M&S intermediate and final results or work products.

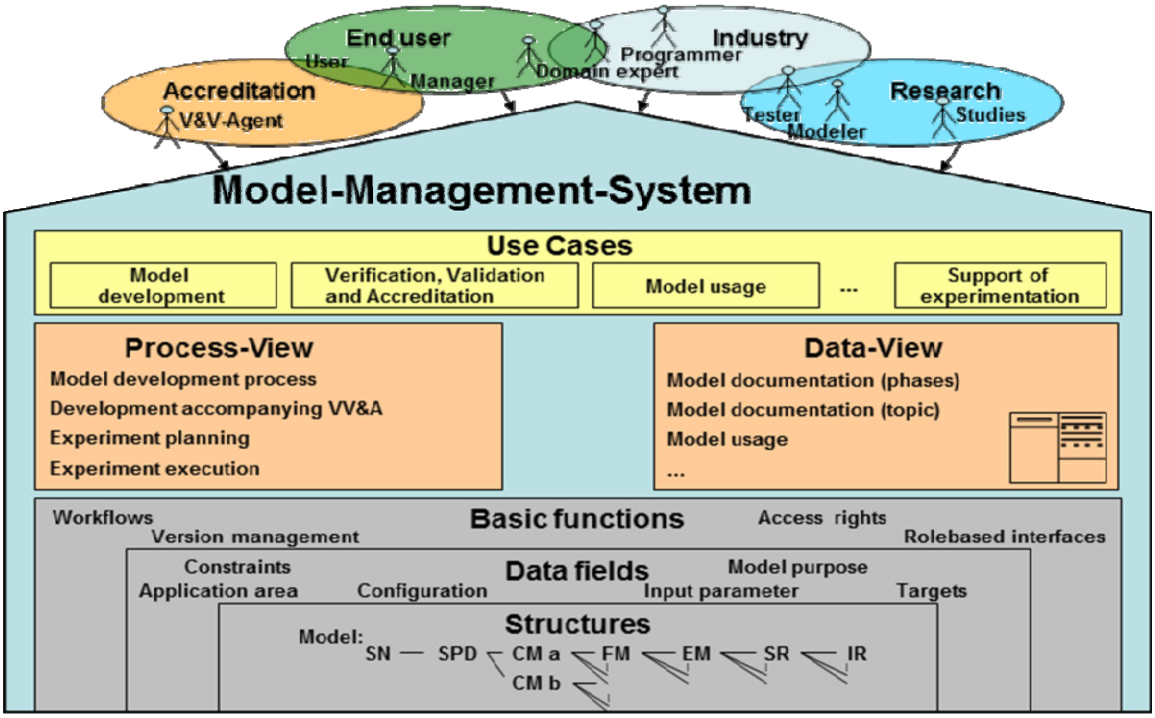

Figure 4: Example of a Model Management Architecture.

2.2 Verification and Validation for Improving M&S Correctness, Credibility and Utility

In addition to quality improvement measures by basic system engineering principles, specific activities have to be applied to assure correctness of a model, its validity with respect to the specified project goals and constraints, as well as utility of its final modeling. Following Balci's informal definitions of **correctness (“Is the <u>model right</u> ?”)** versus his informal definition of **validity / utility (“Is it the <u>right model</u> ?”)**, verification activities have to demonstrate error free implementation of a model and simulation applications while validation measures should check validity and usability of a model, its simulation and its data for a specific purpose as well as its effectiveness with respect to predefined resource constraints like time schedules, or availability of budget and experts (see e.g. [5], [7], [8]).

While in theory verification is being considered as proof of correctness of an implementation (work product), verification of an M&S work product requires at least to demonstrate completeness and consistency of a work product implementation according to its specification (which is in general the work product of the previous modeling phase). In contrast, validation measures have to check problem-specific, predefined project constraints regarding accuracy, fidelity or fitness of a model and its results (see Figure 5).

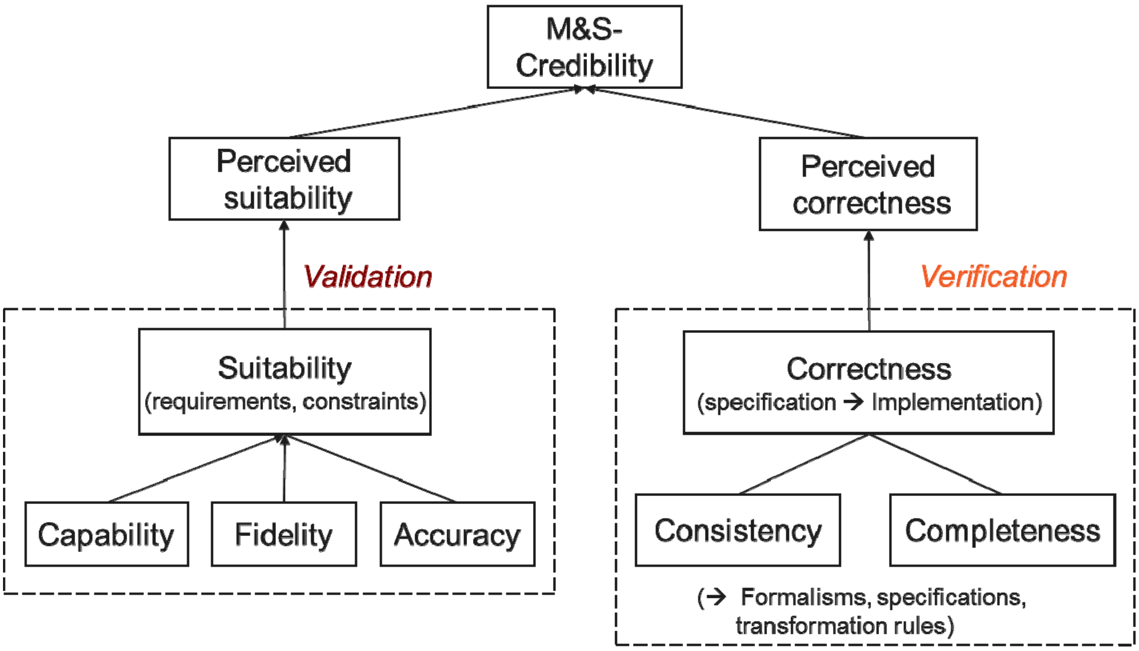

Figure 5: M&S Credibility Assurance by Verification versus Validation.

To achieve those verification and validation goals, which also depend on the availability of intermediate work products together with additional domain knowledge and documentation, a V&V plan has to be established including all V&V techniques that should be applied. In [7], Balci has listed more than 75 V&V techniques that should be considered for application of verification and validation activities. As shown in Figure 6, he classified those techniques into 4 major categories – static versus dynamic, formal versus informal V&V-techniques ([7]). The majority of techniques listed there are well-known from software and systems engineering (e.g. [10], [11]). There are no general rules available that can be applied for selection of V&V techniques in a project. For every project, project specific requirements and constraints as well as knowledge and expertise of those who have to perform V&V activities are decisive factors for preparation of the V&V plan including all V&V activities and techniques that have to be performed.

Figure 6: Classification of V&V-Techniques According to O. Balci (published in [7]).

Despite the fact that no general rules exist for the selection of V&V techniques, Balci has formulated fifteen general principles of VV&A that should be considered in any M&S project (see [7]). With respect to V&V planning, some major ones from this list are:

- V&V must be conducted throughout the entire M&S lifecycle;
- VV&A must be planned and documented;
- A well-formulated problem is essential to the acceptability … of M&S results;
- The outcome of VV&A should not be considered as a binary variable where the model or simulation is absolutely correct or absolutely incorrect;
- V&V requires independence to prevent developer's bias;
- Credibility can be claimed only for the prescribed conditions for which the model or simulation is verified, validated and accredited; and
- Simulation model validity does not guarantee the credibility and acceptability of simulation results.

Organizing an M&S design and development process as proposed in Figure 1 and Figure 3, and before selection of a specific V&V technique, two different principles of V&V of a work product have to be distinguished: **intrinsic V&V** versus **pairwise V&V**. While intrinsic V&V checks the internal consistency and completeness of a single work product, pairwise V&V checks the complete and consistent transformation between work products between two model stages (see Figure 7). For example, an intermediate work product A on development level i can be seen as implementation of the work product B on development level (i-1) which is linked by a transformation arc with work product A on level i. This allows to check if work product B is a complete and consistent implementation of work product A including additional input data required for the implementation of work product B. In addition and if applicable, validation checks can be also performed on each work product. According to the proposed V&V approach, results of every intrinsic or pairwise V&V activity should result in a V&V report. The collection of all those V&V reports have to be considered for final evaluation of correctness, validity and utility of a model, simulation and data (e.g. [4], [6], [7]).

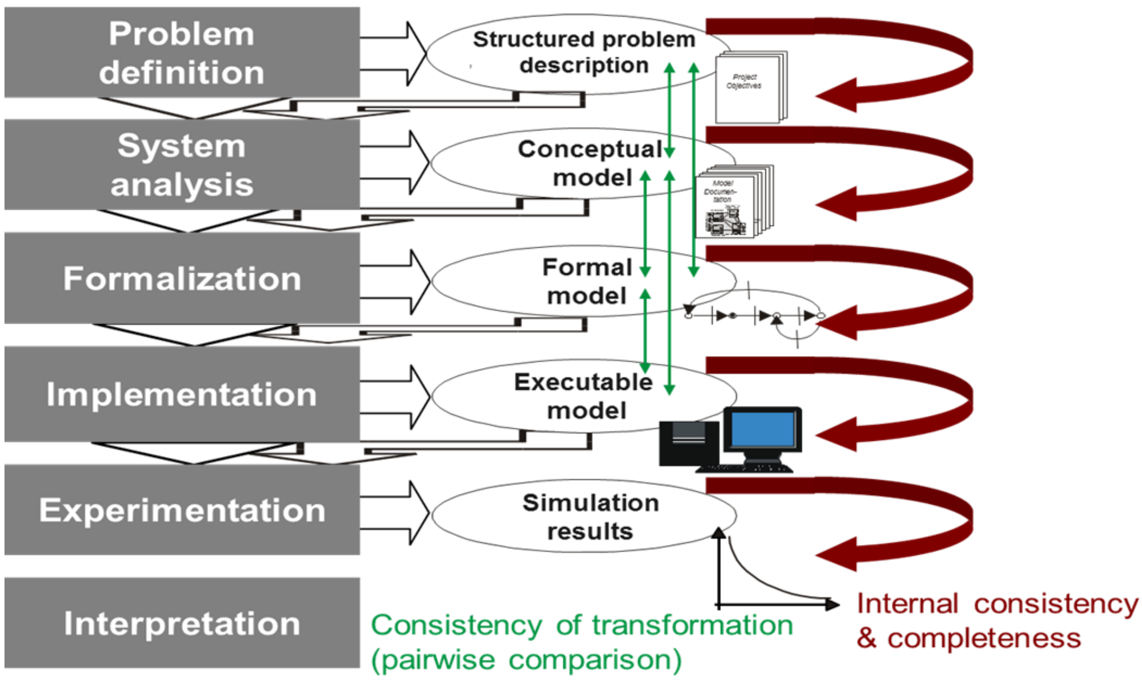

Figure 7: Pairwise Checking of Consistency and Completeness.

In addition to these V&V activities at each M&S development level, verification and validation activities can be performed between all work products on a path at different levels. For example, consistency and completeness of a work product on a level j can be tested in comparison with all work products on levels (j-1),(j-2), etc. That means, performing feasible V&V activities between two work products along a path should always result in a V&V report. Consequent application of these principles leads to an extensive amount of V&V activities and a large collection of V&V reports.

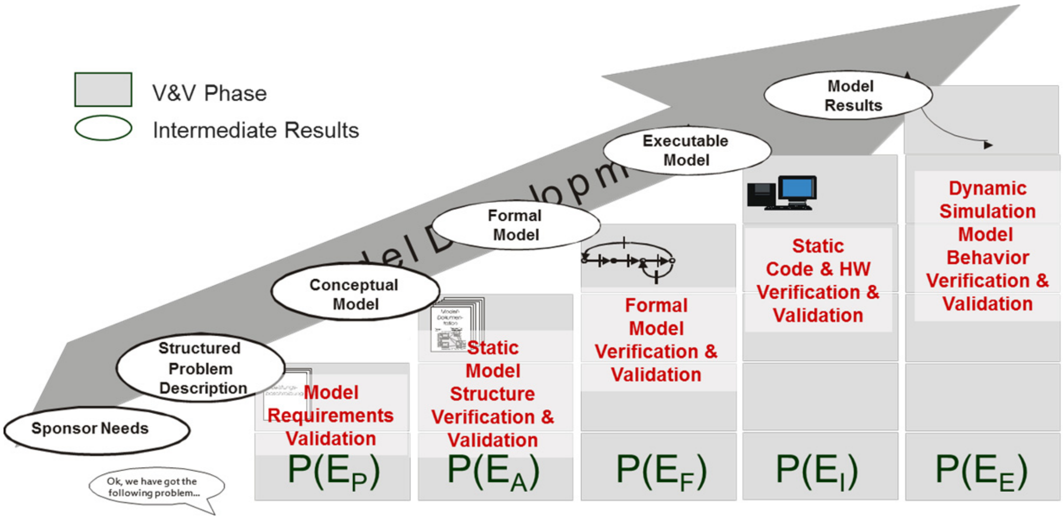

Figure 8: Stage-Wise Verification and Validation.

2.3 Tailoring of M&S Verification and Validation Activities

In general, M&S tailoring can lead to reduction, to extension, to specialization or to balancing of M&S activities and work products as a consequence of project requirements and constraints. According to Figure 9, tailoring actions are feasible at different M&S development levels: on process, product, subject and / or role level ([13], [14]). In the same way, but depending in addition on the availability and accessibility of M&S work products, V&V tailoring can be considered.

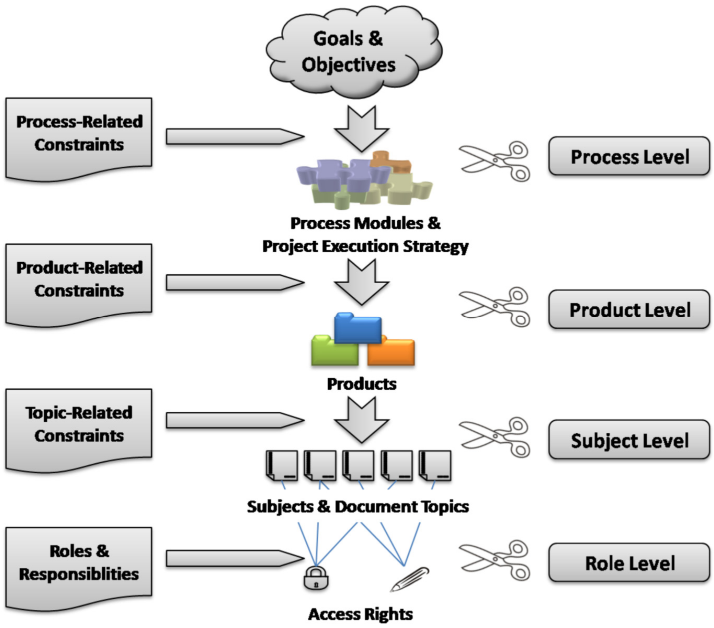

Figure 9: Tailoring Principles ([17], [14], [15]).

For example, regarding availability of M&S resources and use risk constraints specified for a concrete project or M&S application – those tailoring actions can consider a reduction of the amount of V&V activities.

Figure 10 demonstrates consequences of tailoring by reduction: If on the Product Level the work product "Formal Model" is not available or not accessible, this leads to a reduction of adequate V&V activities and missing V&V result reports 3.1, 3.2, 3.3, as well as to missing V&V reports 4.2, 5.3, in Figure 10). If – in addition – some data is not available on the Subject Level, this can also lead to a reduction of V&V activities and missing V&V reports 2.3 and 4.5. A reason for tailoring a Formal Model could be intellectual property rights held by a developer or his or her institution so that this work product is not accessible for external review. Those tailoring actions can result in significant reduction of V&V efforts and costs but also in an increase of use risks ([10], [11], [14]).

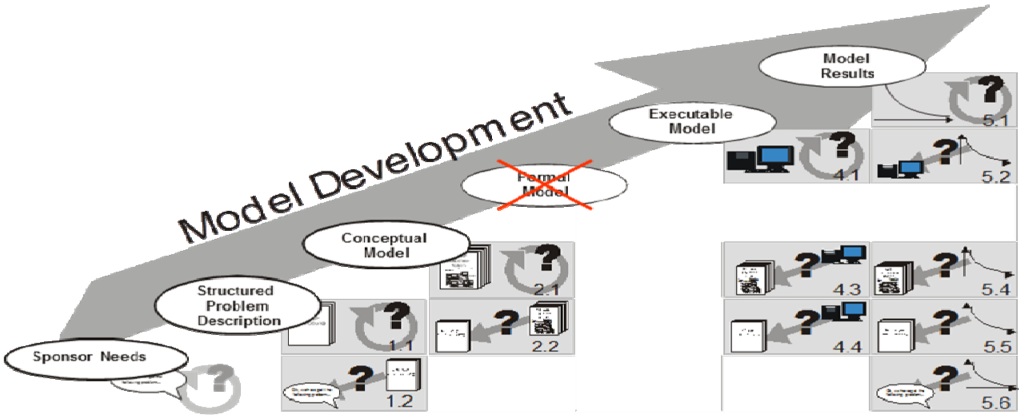

Figure 10: Tailoring Consequences (Tailoring on Product Level and Subject Level).

3.0 GUIDELINES AND STANDARDS FOR M&S-V&V

The issue of verification and validation as basis for acceptance decisions of models, simulations and data in respect of a specific M&S application has been addressed by various regional and international working groups. While there is a general consensus on the increasing importance of this topic, only a few international guidelines or standards on V&V exist. Most of current standards are targeted on interoperability within distributed simulation systems related to either DIS or HLA standards (IEEE 1278.4 and 1516.4) or to software tests. NATO has supported the IEEE HLA VV&A efforts under two Task Groups (MSG-019 and MSG-054).

V&V of models and simulations (M&S) are supported by national policies, methodologies, tools and techniques (like the US VV&A Recommended Practice Guidance, RPG). However there was a lack of **internationally recognized** standards that address V&V of models, simulations and data from a general perspective, independent of specific M&S technology, application domain and life-cycle paradigms.

As early as 2002, a European consortium was created to address this issue under the Western European Armament Group (WEAG) umbrella: the REVVA (Reference project for VV&A) project was born. In its final composition, this consortium included 5 NATO member/partner nations (Canada, Denmark, France, The Netherlands and Sweden) and began a standardization effort in the context of SISO (Simulation Interoperability Standards Organization). Results from and experiences with the REVVA project formed the basis for the development of generic V&V guidelines developed by GM-VV-PDG (The Generic Methodology for Verification and Validation Product Development Group of SISO) also adopted by MSG-073.

In 2006, RTO approved the formation of Task Group MSG-054/TG-037, "An Overlay Standard for Verification, Validation, and Accreditation (VV&A) of Federations". That group was established to formalize the draft recommended practice produced before by MSG-019 in vetting the documents through SISO and IEEE-SA standardization processes. As a result of this Task Group, IEEE Std. 1516.4-2007 was approved by the IEEE-SA Standards Board and published as an international industry standard in December 2007. In addition to the development of this IEEE standard, the Task Group also developed components for tailoring guidance in order to match project specific risk and resource constraints.

In parallel, other nations, like Australia or Germany, also had launched initiatives for the development of national V&V guidelines.

4.0 CASE STUDY EXPERIENCES

For analysis of efficiency and effectiveness of some of the quality assurance and V&V methods proposed in Section 2, three case studies sponsored by the German Armed Forces Procurement Office (BWB) have been performed. In each of these case studies, professional M&S developers had to follow a tailored M&S engineering process as described in Section 2, and had to provide stepwise their intermediate work products plus documentations for external verification and validation. One of the case studies concerned quality assurance and phase-oriented V&V of a simulation model for analysis of traffic flow, while the other two case studies concerned external reviewing of training simulator developments during the respective development processes.

Major lessons learned of these case studies indicate that:

- At the begin of an M&S project, developer guidance has to be provided regarding the multi-stage M&S development process, its phases, role identifications, work products and templates for documentation to enable an efficient M&S development and V&V processes.
- Furthermore, additional time is required for coaching during project phases, e.g. how to plan, to tailor and to perform V&V activities and to document V&V results. Especially required is the development of a use-risk-based V&V plan at the beginning of an M&S project which has to be accepted between project sponsor and M&S developer.
- It turned out that in following M&S projects all institutions involved get a return of their time and budget investments in quality assurance and rigid V&V. But still not enough experiences are available to calculate cost-benefit relations for application of these kinds of quality, correctness and credibility assurance measures.

5.0 CONCLUSIONS

This paper briefly summarizes evolution and increasing importance of M&S design, development and manifold application principles over past decades. It also demonstrates the increasing importance of introducing quality, credibility and utility methods, measures and standards in context of increasing complexity of models, simulations and their results.

Major purpose of this paper is to show how application of general systems engineering principles can improve the quality of M&S design, development processes and multiple application of those models. It demonstrates that the introduction of standardized multi-stage M&S- and V&V-development processes – like already existing guideline IEEE-1516.4 ([12]) or the SISO-standardized guideline "Generic Methodology for Verification and Validation of Models, Simulations, and Data (GM-VV)" ([19]) – are important prerequisites for application of verification, validation measures, and for final M&S acceptance.

With respect to use-risk and cost-benefit relations, this contribution also considers goal-dependent tailoring of modeling phases, intermediate work products, roles and responsibilities as well as of V&V activities. Tailoring activities can take into account project-specific requirements and constraints regarding correctness, validity and usability, but also available budget, resources and acceptable use risks. The article also includes a brief summary of major experiences and findings from application of those approaches obtained from several case studies in Germany.

Based on current experiences it can be concluded that future research efforts should be directed towards implementation of model management systems for efficient management of design, development, operation and maintenance of all kinds of M&S- and V&V-work products, -documentation and -experiences. In addition, as complexity of systems developments and M&S applications will be further increasing, effective methods and tools for use risk identification and use risk management are urgently required.

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V&V of M&S: Past, Present and Future

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ABSTRACT

Measures for Verification and Validation (V&V) of models, simulations and data (M&S) have been always important aspects and caused specific activities ensuring quality and utility of M&S results and their interpretation. Along with rapid innovations and increasing performance of computer systems, networks and software, capabilities as well as complexity of models and simulations are permanently increasing. Therefore, the major challenges of M&S nowadays are to master M&S complexity as well as quality demand.

To substantiate specific quality demands requires to keep track of evidences for correctness, validity and usefulness of models, simulations and data through verification and validation. This contribution presents an overview about importance and evolution of V&V processes and techniques established over the past, and it summarizes briefly current state-of-the-art as well as major challenges for future M&S projects.

1.0 INTRODUCTION

Besides application of fundamental natural laws, and besides processing of experiments in real world scenarios, modeling and simulation (M&S) is considered as the third pillar for enabling generation of new knowledge and of product innovations. Modeling and simulation (M&S) are receiving increasing importance as a technology which supports learning and training capabilities, serves for decision support as well as for systems analysis and evaluation. Rapid advancements of computer and communication technologies enable also rapid advancements in the field of modeling and simulation: Development and application of new modeling methods and simulation techniques, as well as a wide and increasing range of M&S application domains which result in increasing complexity of models, simulations and data.

Besides benefits of these innovations and advances, increasing risks with respect to quality of simulation model development and operation as well as regarding credibility and utility of simulation results and their interpretation have to be considered. As demonstrated by several cases, the use of erroneous models, invalid simulations or data can lead to severe safety-critical situations and can result in wrong decisions and economic damages. In June 1995, the cruise ship *Royal Majesty* grounded on Rose and Crown Shoal about 10 miles east of Nantucket Island, Massachusetts, due to a navigation model error which caused a severe safety problem. Though there were no deaths or injuries as a result of this accident but repair of the vessel and lost revenue were estimated at about US-$7 million ([6]). Other examples of modelling errors caused deficient designs of airport baggage handling and delivery systems leading to significant economic damages.

Especially in context of the increasing importance of manifold M&S application such as component-based modeling, parallel and distributed simulation, collaborative simulation or agent-based simulation, efficient quality control and credibility assurance mechanisms have to be applied to avoid safety-critical, expensive and other unwanted side effects. This requires the application of standardized engineering processes for M&S design, development and operation, including careful selection and application of M&S verification, Validation and Acceptance (VV&A) processes, methods and supporting tools.

This chapter presents a brief overview of terminology and of basic concepts applied in context of modelling and simulation, in general. It also includes a review of the evolution of VV&A methods and techniques applied to perform quality assurance, verification and validation.

1.1 Basic Terminology

Following J. Rothenberg's definition, **a model** can be defined as **a symbolic, abstract, cost-effective and safe referent of something else for some specific cognitive purpose** [1]. Most of human reasoning and decision making processes are based on mental modeling. Even in everyday life, mental models are being used for analysing situations or for making decisions. Understanding and analysis of real world problems require – at least in general – simplification and abstraction of reality as humans are only able to conclude interdependencies between about 5 – 7 parameters at the same time.

As mental models are built intuitively based on experiences, they belong to the category of **inductive models**. Inductive modelling approaches enable reasoning based on similar situations or cases. In contrast, the majority of computer-based models and simulations used nowadays for analyses, decision making or training are designed and applied as **deductive models** expressing qualitative or quantitative dependencies between goal, input and state parameters. Interdependencies between these parameters can be described mathematical formulas, numerical or logical algorithms. In the following, we will focus on design and application principles of those kinds of deductive models.

Along these lines, and in accordance with Maisel and Gnugnoli (in [3]), **simulation** can be defined as **a (numerical) technique for conducting experiments on a computer; this technique involves certain types of mathematical and logical models that describe real world behaviour or the behaviour of a system over periods of time.** This definition describes simulation explicitly as a technique for solving and using models by means of computers. This definition also indicates that (computer-based) simulation is a multi-stage process which differentiates between stages like conceptual model design, its formal description, technical solution and experimental applications.

For collecting evidences of correctness, validity and utility of models, simulations and data, some general principles and specific techniques for M&S verification and validation can be applied. An informal but clear distinction between these terms has been presented already long time ago by Balci: Application of verification techniques provides evidences for M&S correctness ("Is the **model right** ?") opposed to validation techniques which can provide evidences for validity and utility of an M&S regarding its specific application goals and constraints ("Is it **the right model**?"). Meanwhile, multiple and more precise definitions for verification and validation are provided by national and international standards, like in DoD- or IEEE-Standards.

In GM-VV-Volume 1 ([22]), the following definitions are established and are used by all contributions of this Lecture Series seminar:

- **Verification: The process of providing evidence justifying the M&S system's correctness.**
- **Validation: The process of providing evidence justifying the M&S system's validity. Validity is the property of an M&S system's representation of the simuland to correspond sufficiently enough with the referent for the intended use.** The simuland is the system or process that is simulated by a simulation while the referent is "… the codified body of knowledge about a thing being simulated (IEEEStd 1516.4; [12]).
- **Acceptance: The process that ascertains whether an M&S system is fit for its intended use.**
- Project demands like use risk, time schedules, limited resources or intellectual property rights can be constraints that have to be considered while planning M&S activities, Therefore, project-specific tailoring of M&S activities including V&V planning is required in general. In context of GM-VV,

Tailoring is defined as "…**the modification of V&V processes V&V organization and V&V products to fit agreed risks, resources, and implementation constraints**." ([22])

These and some alternative but closely related definitions from other international M&S standards can be found in SISO-GUIDE-GM-VV-001.1-2012 (Volume 1 [22]).

2.0 BASIC PRINCIPLES AND TECHNIQUES FOR M&S DEVELOPMENT; VERIFICATION AND VALIDATION

In the first decades of computer-based M&S, modeling was considered more as creative art rather than an engineering discipline. Shannon described "....**the art of modeling** consists in an ability to analyse a problem, abstract from it its essential features, select and modify basic assumptions that characterize the system, and then enrich and elaborate the model until a useful approximation results." ([2]). Already in the same book – published in 1975 – Shannon and others also mention model building as "… an evolutionary multi-stage process where evolution is depending on factors like user requirements, requested model flexibility, available resources and skills." But he also mentions that a model building process also relays on the communication and collaboration between model builder and model user to ensure that the modelling results meet the relevant goals, objectives and criteria of a project defined by the project sponsor ([2]).

To assure a demanded level of M&S quality, utility and credibility of its results, this contribution promotes the application of the general "divide and conquer" engineering principle in threefold:

- Each M&S project has to be considered and should be processed like a typical engineering process: M&S development and application require strict separation between different M&S phases and activities. According to Figure 1, each M&S phase or activity has to result in a work product of (intermediate) M&S results along with some documentation. For each M&S phase, roles and responsibilities of team members have to be defined performing the activities and contributing to these work products;
- Verification and validation (V&V) of (intermediate) work products of each modeling phase should be performed stepwise by application of verification and validation processes and techniques. All results of applied V&V activities have to be documented by means of V&V reports (see Figure 2).
- Basically, V&V planning which includes the selection of V&V techniques and intensity of V&V activities should be tailored according project-specific requirements and constraints.

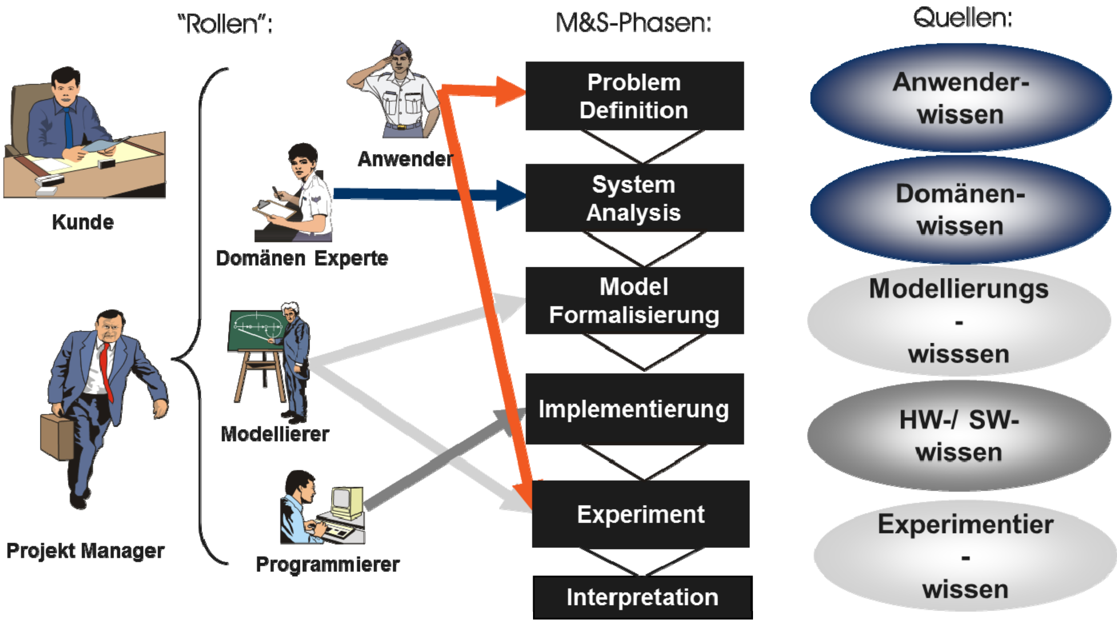

Figure 1: Typical multi-phase M&S design, development and application process ([5], [4]).

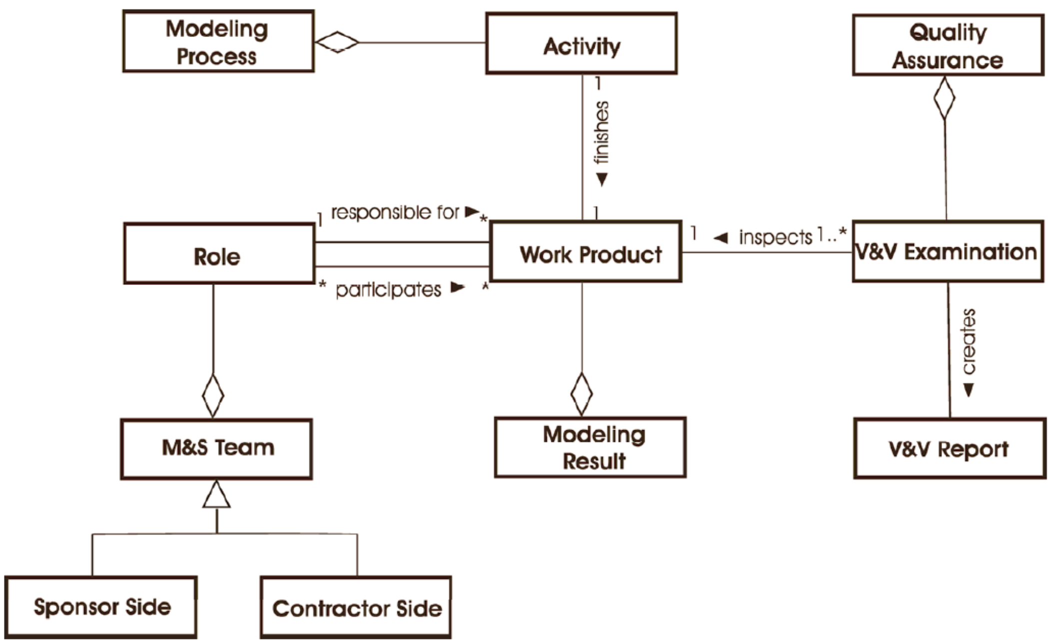

Figure 2: Meta model of an M&S Building and Application Process ([14], [17]).

In accordance with these definitions and as widely accepted by the M&S community, a model and simulation building and application process is basically a multi-stage process. As demonstrated in Figure 1, each stage, or phase, of this process requires generally input from domain experts and/or data, an execution of stage-specific activities by skilled persons, and each stage has to provide an (intermediate or final) work product with documentation as result of this working stage. The iterative, evolutionary character of a typical M&S building process can lead to optional solutions, work products as well as to different versions of a work product (as indicated by the tree-structured graph on the right hand side in Figure 3 which will be discussed in detail in Section 2.1).

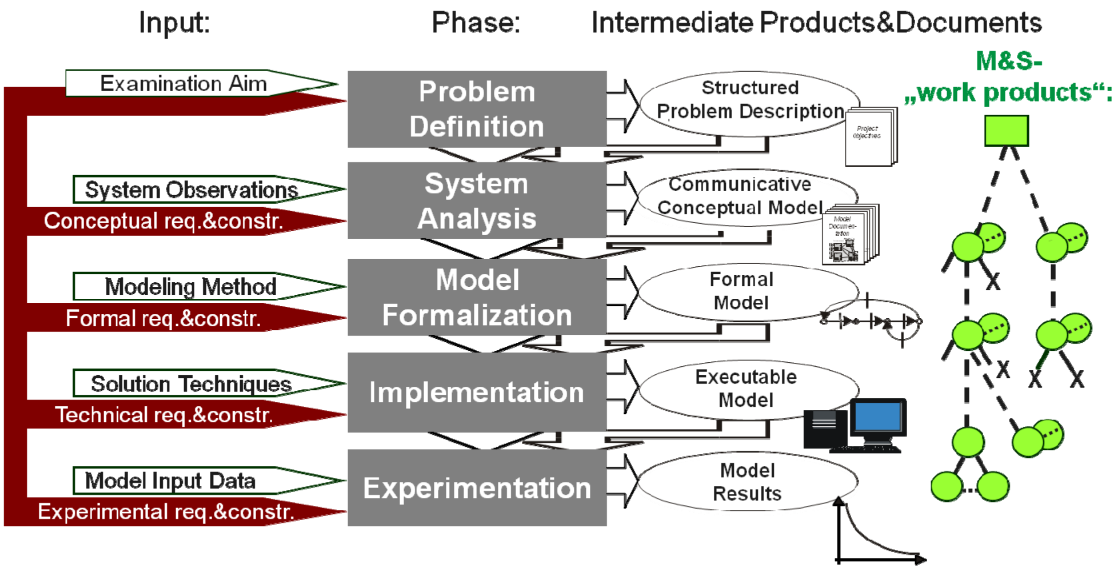

Figure 3: Typical Multi-Phase M&S Design, Development and Application Process (e.g. [4], [5], [17]).

2.1 A Systems Engineering Approach for M&S Development and Operation

As mentioned before, in the past computer-based modelling and simulation model building has been considered more like an art rather than a scientific or an engineering challenge (e.g. see Shannon [1]). Due to permanently increasing scope and complexity of models being built and applied nowadays, M&S projects can only be mastered if some general engineering principles are also applied for M&S design, development, maintenance, and quality assurance. One of those principles concerns guidelines or standards for well-structured and globally accepted M&S- and V&V processes. The meta model in Figure 2 describes the generic structure of a typical M&S building and application process, including activities, working products, roles and responsibilities of those contributing to an M&S project.

Permanent increasing performance and capabilities of ICT hardware and software, improved or novel modeling methods and a huge variety of powerful M&S tools enable the development and application of very complex models. On one side, basic engineering practices and standardized procedures are required to guarantee the demanded quality of development and operation processes of complex simulation applications as a whole.

Like in other engineering disciplines (e.g. [8], [10], [11] ,[12]), as well as already fixed in M&S standards like in IEEE 1516.4 for the FEDEP ([12]), or in “Generic Methodology for Verification and Validation of Models, Simulation and Data (GM-VV)” ([22]), a “divide and conquer” strategy is proposed according to which an M&S process consists of a fixed sequence of different modeling phases, or development levels, respectively. To process the activities of a modeling phase requires phase-specific knowledge and input data to transform the results – the work products – of the previous modeling phase. For example, according to Figure 2 and Figure 3, each M&S development process starts with a problem definition phase (development level 1) based on a project’s Sponsor Needs (SN) in which information about goals, requirements and constraints of a concrete M&S project are used as input to produce a Structured Problem Specification (SPD) as result documented in an intermediate work product. In the following development phase, this work product together with additional information (e.g. measured data or assumptions about a system under consideration) should be used as specification for transformation of the Structured Problem Description to a work product "Conceptual Model" (CM). The Conceptual Model in turn can be considered as specification for transforming the Conceptual model to a Formal Model (FM) by using a problem adequate modeling method or formalism, etc. ([4], [9], [17]).

As indicated by the green colored graphical example of a tree structure in Figure 3 (on the right hand side), nodes represent work products and arcs represent transformations between nodes. A Structured Problem Description (SPD) may result in different Conceptual Model (CM) options (in this example: 2 nodes on the next M&S development level). As a result of some modifications, each of those Conceptual Model work products might be modified again in different versions (as indicated by doted lines between the nodes on the same level). In general, transformation of an intermediate work product can result in different, optional solutions in the following modeling phase (work products), while each of those can be implemented in different (e.g. refined) versions again.

This approach leads to a tree-structured M&S development process with relations like "transformation" or "modification" between intermediate work products and final M&S experimentation results. Starting from the root node down to the leaves of a tree, each path describes all the intermediate work products of a possible solution or alternative solution approaches for a given problem. Vice versa, paths starting from leaves up to the root of a tree can be used for error detection, fault analysis and interpretation of experimentation results [13], [16].

Besides these benefits, this systems engineering approach offers additional opportunities for efficient reusability or further development of models or model components. These developments can start from or are based on already existing intermediate work products and links to those roles or individuals who have been in charge of these work product developments. To support effectively those additional kinds of M&S application and to keep track of a model's history as basis for further developments, tool support by a model management system is highly recommended. Major capabilities and services of such a model management system serving as platform for all those involved in the different phases of an M&S process should include:

- Versioning;
- Change management;
- Error and fault management;
- Configuration management;
- Role management;
- Workflow management; and
- Case studies and, experiences.

As an example, we have developed concept and demonstrator of a model management architecture according to Figure 4. Following the M&S development and operation process as discussed above, according to the proposed concept, all intermediate work products, documentation, data and information produced during the various M&S design, development, and application stages is collected in a single system. This approach allows efficient M&S development, maintenance and operation. It also facilitates cooperative M&S, collection of experiences and effective reuse of M&S intermediate and final results or work products.

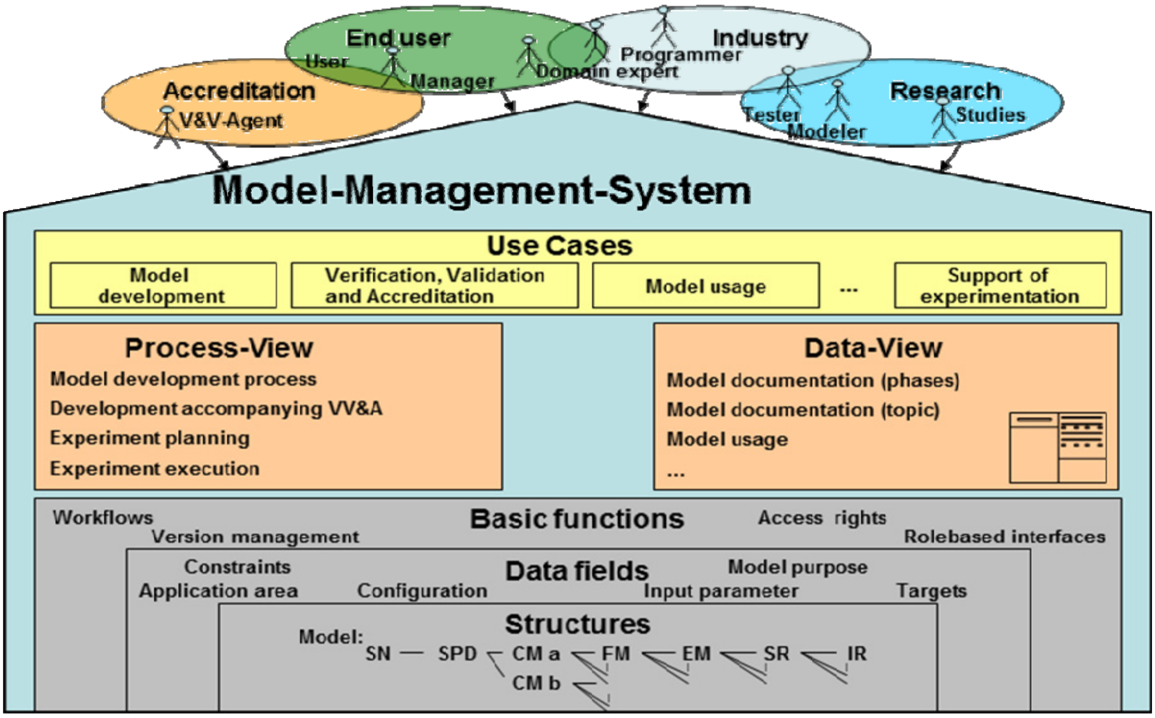

Figure 4: Example of a Model Management Architecture.

2.2 Verification and Validation for Improving M&S Correctness, Credibility and Utility

In addition to quality improvement measures by basic system engineering principles, specific activities have to be applied to assure correctness of a model, its validity with respect to the specified project goals and constraints, as well as utility of its final modeling. Following Balci's informal definitions of **correctness (“Is the model right ?”)** versus his informal definition of **validity / utility (“Is it the right model ?”)**, verification activities have to demonstrate error free implementation of a model and simulation applications while validation measures should check validity and usability of a model, its simulation and its data for a specific purpose as well as its effectiveness with respect to predefined resource constraints like time schedules, or availability of budget and experts (see e.g. [5], [7], [8]).

While in theory verification is being considered as proof of correctness of an implementation (work product), verification of an M&S work product requires at least to demonstrate completeness and consistency of a work product implementation according to its specification (which is in general the work product of the previous modeling phase). In contrast, validation measures have to check problem-specific, predefined project constraints regarding accuracy, fidelity or fitness of a model and its results (see Figure 5).

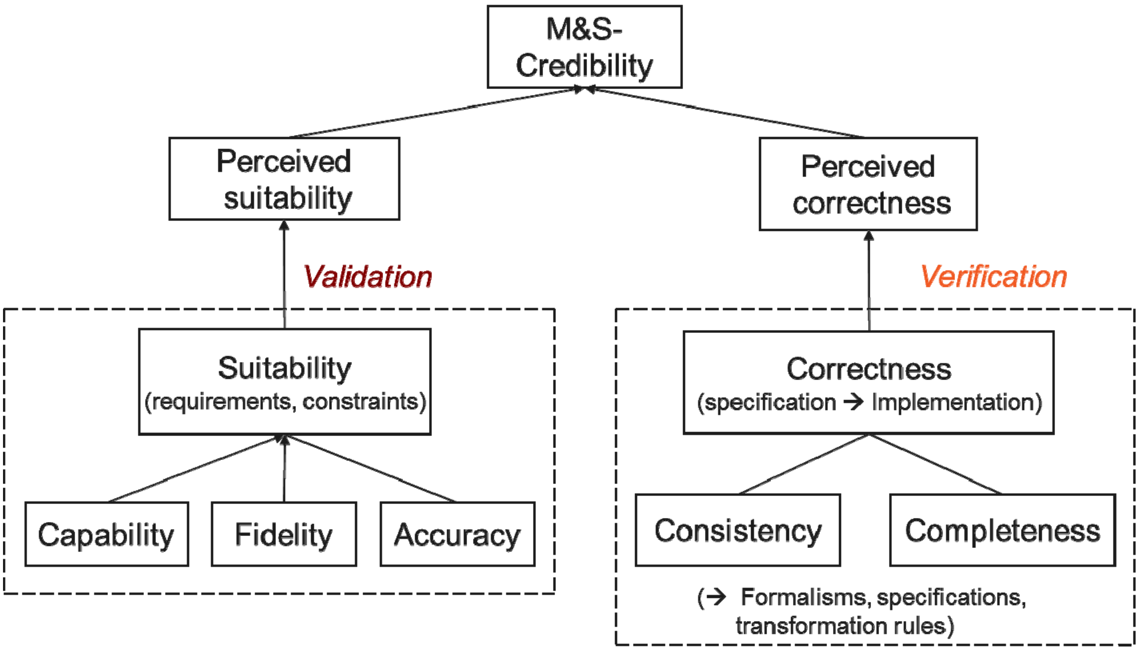

Figure 5: M&S Credibility Assurance by Verification versus Validation.

To achieve those verification and validation goals, which also depend on the availability of intermediate work products together with additional domain knowledge and documentation, a V&V plan has to be established including all V&V techniques that should be applied. In [7], Balci has listed more than 75 V&V techniques that should be considered for application of verification and validation activities. As shown in Figure 6, he classified those techniques into 4 major categories – static versus dynamic, formal versus informal V&V-techniques ([7]). The majority of techniques listed there are well-known from software and systems engineering (e.g. [10], [11]). There are no general rules available that can be applied for selection of V&V techniques in a project. For every project, project specific requirements and constraints as well as knowledge and expertise of those who have to perform V&V activities are decisive factors for preparation of the V&V plan including all V&V activities and techniques that have to be performed.

Figure 6: Classification of V&V-Techniques According to O. Balci (published in [7]).

Despite the fact that no general rules exist for the selection of V&V techniques, Balci has formulated fifteen general principles of VV&A that should be considered in any M&S project (see [7]). With respect to V&V planning, some major ones from this list are:

- V&V must be conducted throughout the entire M&S lifecycle;
- VV&A must be planned and documented;
- A well-formulated problem is essential to the acceptability … of M&S results;
- The outcome of VV&A should not be considered as a binary variable where the model or simulation is absolutely correct or absolutely incorrect;
- V&V requires independence to prevent developer's bias;
- Credibility can be claimed only for the prescribed conditions for which the model or simulation is verified, validated and accredited; and
- Simulation model validity does not guarantee the credibility and acceptability of simulation results.

Organizing an M&S design and development process as proposed in Figure 1 and Figure 3, and before selection of a specific V&V technique, two different principles of V&V of a work product have to be distinguished: **intrinsic V&V** versus **pairwise V&V**. While intrinsic V&V checks the internal consistency and completeness of a single work product, pairwise V&V checks the complete and consistent transformation between work products between two model stages (see Figure 7). For example, an intermediate work product A on development level i can be seen as implementation of the work product B on development level (i-1) which is linked by a transformation arc with work product A on level i. This allows to check if work product B is a complete and consistent implementation of work product A including additional input data required for the implementation of work product B. In addition and if applicable, validation checks can be also performed on each work product. According to the proposed V&V approach, results of every intrinsic or pairwise V&V activity should result in a V&V report. The collection of all those V&V reports have to be considered for final evaluation of correctness, validity and utility of a model, simulation and data (e.g. [4], [6], [7]).

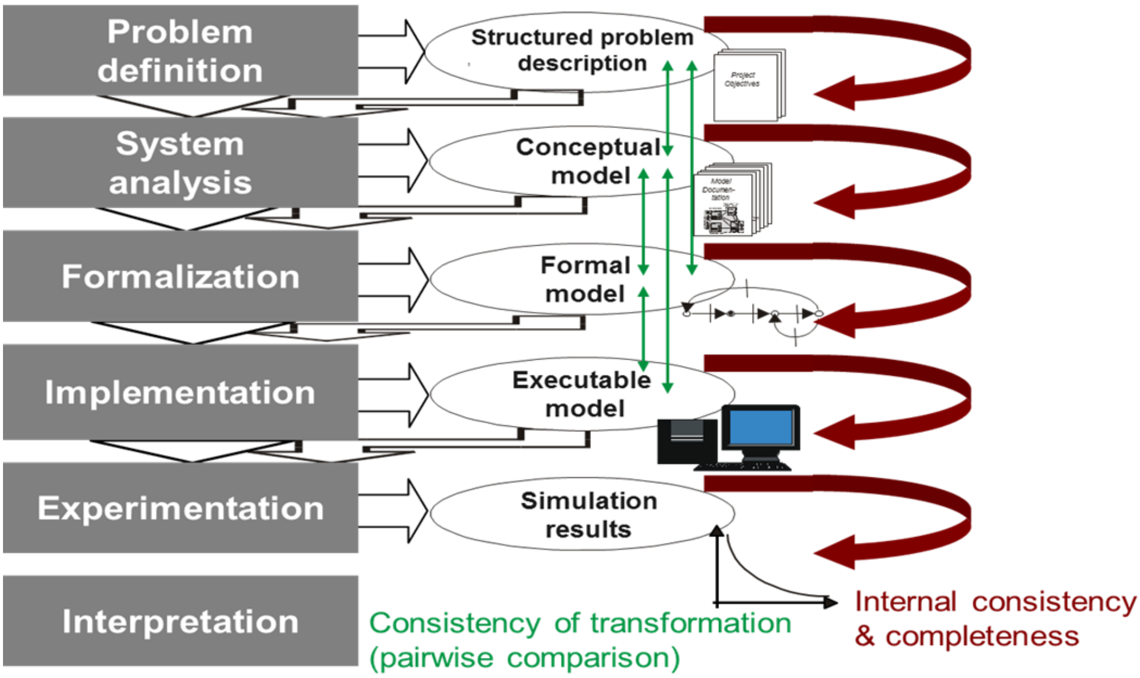

Figure 7: Pairwise Checking of Consistency and Completeness.

In addition to these V&V activities at each M&S development level, verification and validation activities can be performed between all work products on a path at different levels. For example, consistency and completeness of a work product on a level j can be tested in comparison with all work products on levels (j-1),(j-2), etc. That means, performing feasible V&V activities between two work products along a path should always result in a V&V report. Consequent application of these principles leads to an extensive amount of V&V activities and a large collection of V&V reports.

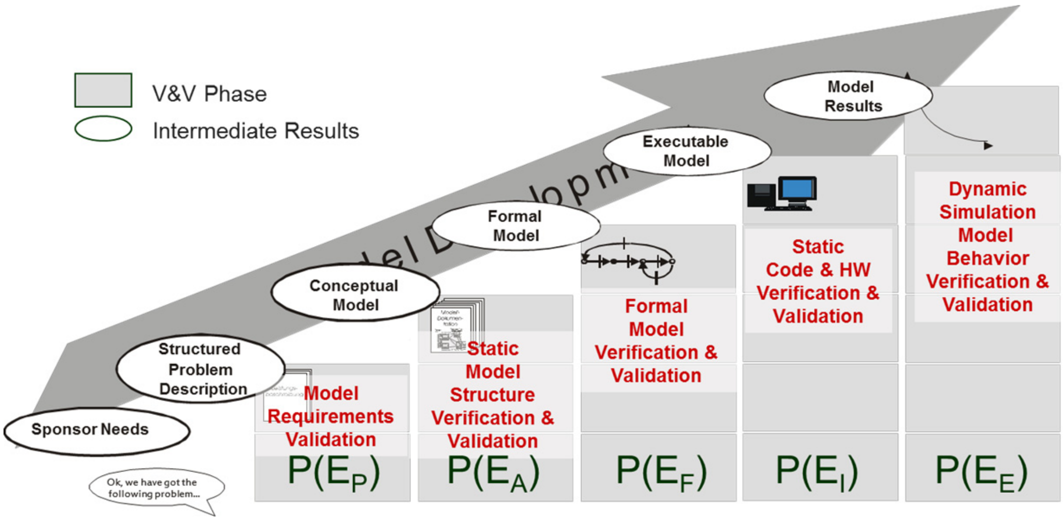

Figure 8: Stage-Wise Verification and Validation.

2.3 Tailoring of M&S Verification and Validation Activities

In general, M&S tailoring can lead to reduction, to extension, to specialization or to balancing of M&S activities and work products as a consequence of project requirements and constraints. According to Figure 9, tailoring actions are feasible at different M&S development levels: on process, product, subject and / or role level ([13], [14]). In the same way, but depending in addition on the availability and accessibility of M&S work products, V&V tailoring can be considered.

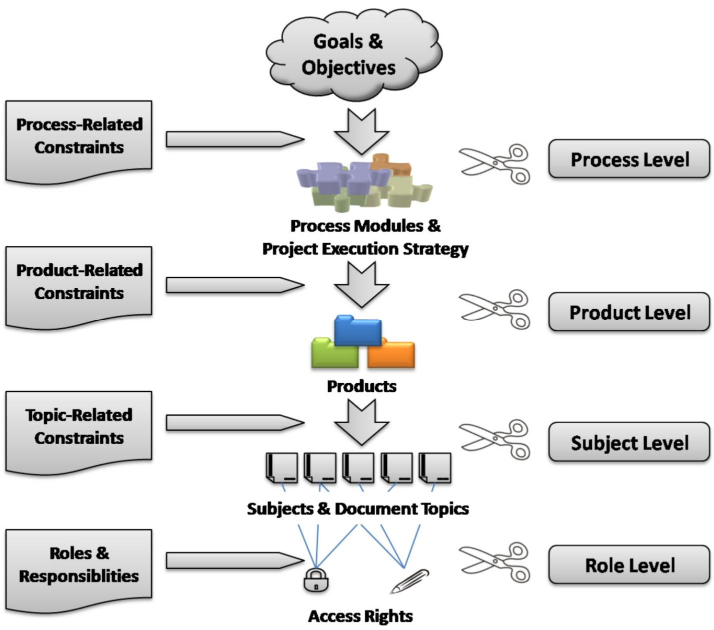

Figure 9: Tailoring Principles ([17], [14], [15]).

For example, regarding availability of M&S resources and use risk constraints specified for a concrete project or M&S application – those tailoring actions can consider a reduction of the amount of V&V activities.

Figure 10 demonstrates consequences of tailoring by reduction: If on the Product Level the work product “Formal Model” is not available or not accessible, this leads to a reduction of adequate V&V activities and missing V&V result reports 3.1, 3.2, 3.3, as well as to missing V&V reports 4.2, 5.3, in Figure 10). If – in addition – some data is not available on the Subject Level, this can also lead to a reduction of V&V activities and missing V&V reports 2.3 and 4.5. A reason for tailoring a Formal Model could be intellectual property rights held by a developer or his or her institution so that this work product is not accessible for external review. Those tailoring actions can result in significant reduction of V&V efforts and costs but also in an increase of use risks ([10], [11], [14]).

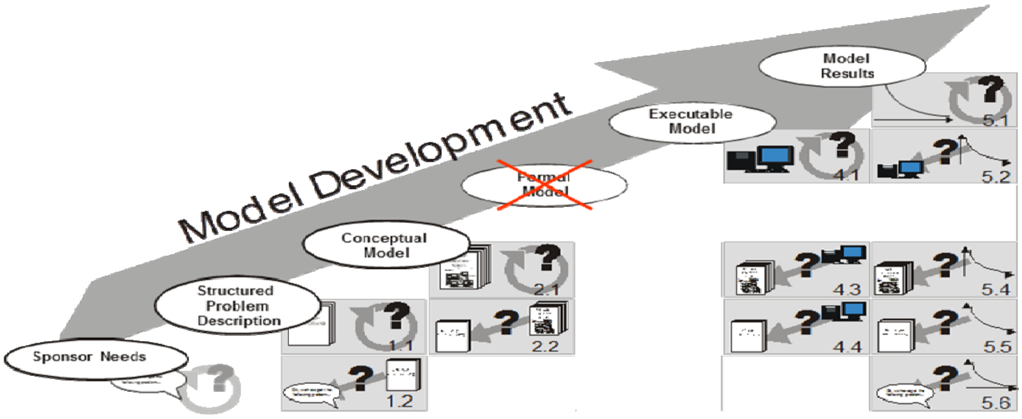

Figure 10: Tailoring Consequences (Tailoring on Product Level and Subject Level).

3.0 GUIDELINES AND STANDARDS FOR M&S-V&V

The issue of verification and validation as basis for acceptance decisions of models, simulations and data in respect of a specific M&S application has been addressed by various regional and international working groups. While there is a general consensus on the increasing importance of this topic, only a few international guidelines or standards on V&V exist. Most of current standards are targeted on interoperability within distributed simulation systems related to either DIS or HLA standards (IEEE 1278.4 and 1516.4) or to software tests. NATO has supported the IEEE HLA VV&A efforts under two Task Groups (MSG-019 and MSG-054).

V&V of models and simulations (M&S) are supported by national policies, methodologies, tools and techniques (like the US VV&A Recommended Practice Guidance, RPG). However there was a lack of **internationally recognized** standards that address V&V of models, simulations and data from a general perspective, independent of specific M&S technology, application domain and life-cycle paradigms.

As early as 2002, a European consortium was created to address this issue under the Western European Armament Group (WEAG) umbrella: the REVVA (Reference project for VV&A) project was born. In its final composition, this consortium included 5 NATO member/partner nations (Canada, Denmark, France, The Netherlands and Sweden) and began a standardization effort in the context of SISO (Simulation Interoperability Standards Organization). Results from and experiences with the REVVA project formed the basis for the development of generic V&V guidelines developed by GM-VV-PDG (The Generic Methodology for Verification and Validation Product Development Group of SISO) also adopted by MSG-073.

In 2006, RTO approved the formation of Task Group MSG-054/TG-037, "An Overlay Standard for Verification, Validation, and Accreditation (VV&A) of Federations". That group was established to formalize the draft recommended practice produced before by MSG-019 in vetting the documents through SISO and IEEE-SA standardization processes. As a result of this Task Group, IEEE Std. 1516.4-2007 was approved by the IEEE-SA Standards Board and published as an international industry standard in December 2007. In addition to the development of this IEEE standard, the Task Group also developed components for tailoring guidance in order to match project specific risk and resource constraints.

In parallel, other nations, like Australia or Germany, also had launched initiatives for the development of national V&V guidelines.

4.0 CASE STUDY EXPERIENCES

For analysis of efficiency and effectiveness of some of the quality assurance and V&V methods proposed in Section 2, three case studies sponsored by the German Armed Forces Procurement Office (BWB) have been performed. In each of these case studies, professional M&S developers had to follow a tailored M&S engineering process as described in Section 2, and had to provide stepwise their intermediate work products plus documentations for external verification and validation. One of the case studies concerned quality assurance and phase-oriented V&V of a simulation model for analysis of traffic flow, while the other two case studies concerned external reviewing of training simulator developments during the respective development processes.

Major lessons learned of these case studies indicate that:

- At the begin of an M&S project, developer guidance has to be provided regarding the multi-stage M&S development process, its phases, role identifications, work products and templates for documentation to enable an efficient M&S development and V&V processes.
- Furthermore, additional time is required for coaching during project phases, e.g. how to plan, to tailor and to perform V&V activities and to document V&V results. Especially required is the development of a use-risk-based V&V plan at the beginning of an M&S project which has to be accepted between project sponsor and M&S developer.
- It turned out that in following M&S projects all institutions involved get a return of their time and budget investments in quality assurance and rigid V&V. But still not enough experiences are available to calculate cost-benefit relations for application of these kinds of quality, correctness and credibility assurance measures.

5.0 CONCLUSIONS

This paper briefly summarizes evolution and increasing importance of M&S design, development and manifold application principles over past decades. It also demonstrates the increasing importance of introducing quality, credibility and utility methods, measures and standards in context of increasing complexity of models, simulations and their results.

Major purpose of this paper is to show how application of general systems engineering principles can improve the quality of M&S design, development processes and multiple application of those models. It demonstrates that the introduction of standardized multi-stage M&S- and V&V-development processes – like already existing guideline IEEE-1516.4 ([12]) or the SISO-standardized guideline "Generic Methodology for Verification and Validation of Models, Simulations, and Data (GM-VV)" ([22]) – are important prerequisites for application of verification, validation measures, and for final M&S acceptance.

With respect to use-risk and cost-benefit relations, this contribution also considers goal-dependent tailoring of modeling phases, intermediate work products, roles and responsibilities as well as of V&V activities. Tailoring activities can take into account project-specific requirements and constraints regarding correctness, validity and usability, but also available budget, resources and acceptable use risks. The article also includes a brief summary of major experiences and findings from application of those approaches obtained from several case studies in Germany.

Based on current experiences it can be concluded that future research efforts should be directed towards implementation of model management systems for efficient management of design, development, operation and maintenance of all kinds of M&S- and V&V-work products, -documentation and -experiences. In addition, as complexity of systems developments and M&S applications will be further increasing, effective methods and tools for use risk identification and use risk management are urgently required.

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