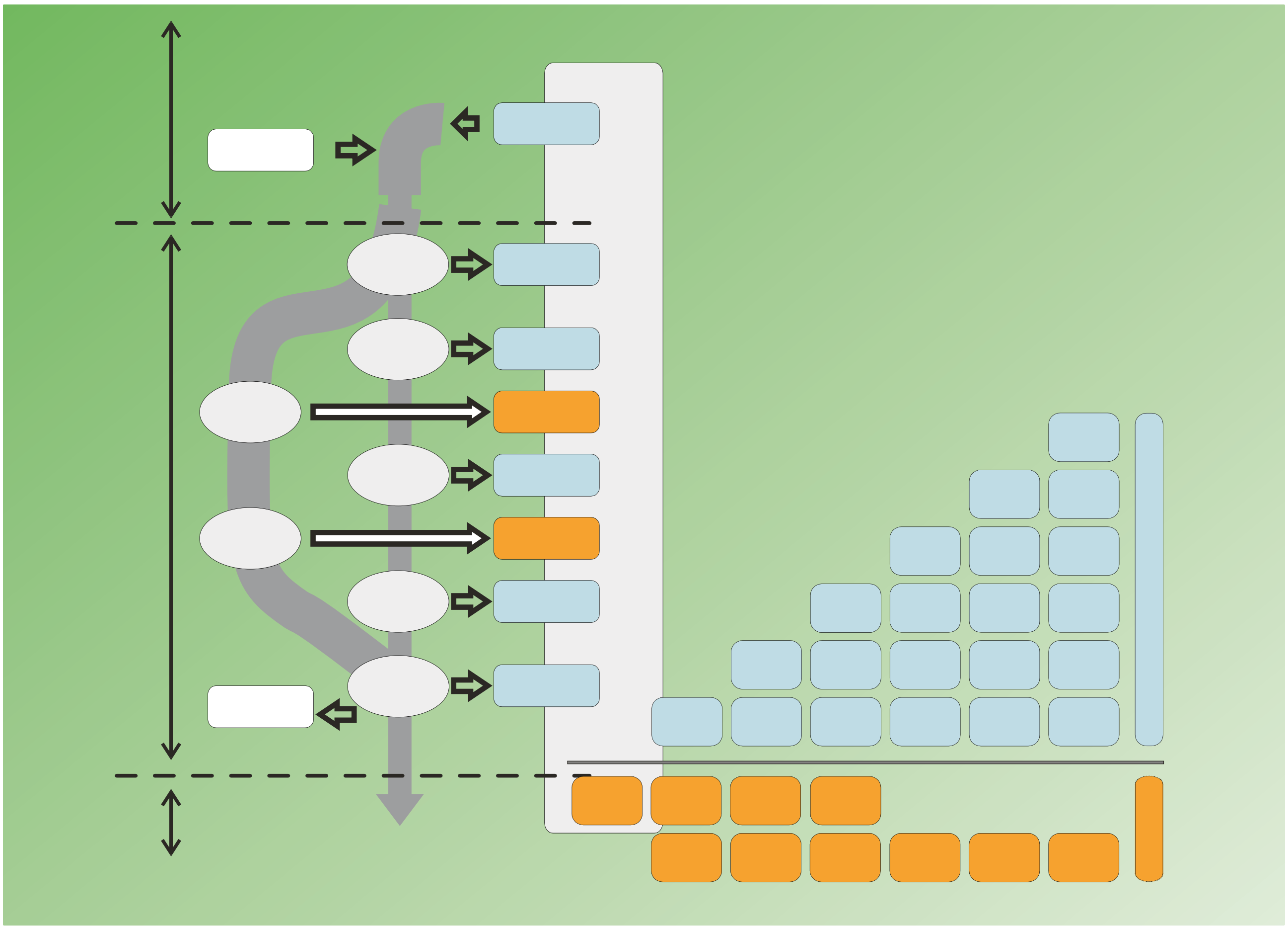
SNE SIMULATION NEWS EUROPE

Special Issue:

Quality Aspects in Modelling and Simulation



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Special Issue

ARGESIM

Dear readers,

We are glad to continue the SNE Special Issue Series with this special issue SNE 19/2 on 'Quality Aspects in Modelling and Simulation'. The editorial policy of SNE Special Issues is to publish high quality scientific and technical papers concentrating on state-of-the-art and state-of-research in specific modelling and simulation oriented topics in Europe, and interesting papers from the world wide modelling and simulation community. The subject 'Quality Aspects in Modelling and Simulation' fulfils all prerequisites for a special issue, and we are glad, that the ASIM Working Group 'Simulation in Production and Logistics' took over the task to edit this special issue, which underlines the significance of quality aspects in simulation studies and points out recent developments to achieve efficient and high-quality simulation studies.

I would like to thank all authors and all people who helped in managing this SNE Special Issue, especially Mrs. Sigrid Wenzel (University of Kassel, Germany), Head of the ASIM Working Group'Simulation in Production and Logistics' and Managing Guest Editor of this special issue, and her accompanying Guest Editors Markus Rabe (Fraunhofer IPK, Berlin, Germany) and Sven Spieckermann (SIMPLAN AG, Maintal, Germany).

For SNE Volume 20 (2010), we are planning a special issue SNE 20/2 on Simulation & Education.

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EDITORIAL SNE SPECIAL ISSUE

Quality Aspects in Modelling and Simulation

Simulation is an important method which helps to take right decisions in system planning and operation. Building high-quality simulation models and using the right input data are preconditions for achieving significant and usable simulation results. For this purpose, a simulation model has to be well-defined, consistent, accurate, comprehensive and applicable.

The SNE special issue on Quality Aspects in Modelling and Simulation (M&S) emphasizes the significance of quality aspects in simulation studies and points out recent developments to achieve efficient and high-quality simulation studies. This issue is structured into six contributions ranged from generic quality aspects for discrete event simulation (DES), different procedure models for verification and validation (V&V), specific validation techniques, ensuring input data quality in simulation studies to quality for continuous system dynamic models for product engineering. Two contributions (the first and third one) base on the discussions of special interest groups of the ASIM working group Simulation in Production and Logistics and aim to summarize some of the key ideas of simulation experts from industry and academia working in a large variety of application domains of discrete event simulation.

The first contribution Quality Aspects in Simulation Studies for Production and Logistics by Holger Pitsch, Oliver Rose and Sigrid Wenzel provides the simulation practitioner with an easy-to-use procedure to guide him through all phases of a simulation project. The authors outline five quality criteria, provide an extended procedure model for the different project phases, and explain how checklists can be applied for quality improvements.

The contribution A Multistage Approach for Quality- and Efficiency-Related Tailoring of Modelling and Simulation Processes by Zhongshi Wang, Axel Lehmann and Alexandros Karagkasidis describes a multistage approach for tailoring of an M&S project in compliance with the principles of the V-Modell XT, which is considered as the German standard IT development process mandatory for federal engineering projects.

The third paper Verification and Validation for Simulation in Production and Logistics by Markus Rabe, Sven Spieckermann and Sigrid Wenzel proposes a procedure model for V&V that is applicable for simulation studies in production and logistics and illustrates the elements of this procedure model on selected examples.

Falko Bause, Jan Kriege and Sebastian Vastag present some techniques for the validation of process-based simulation models in their contribution Efficient Validation of Process-based Simulation Models. These techniques used in the Collaborative Research Center 559 “Modelling of Large Logistics Networks” are based on efficient algorithms from the Petri net area, but details are completely hidden from the end user by means of a corresponding toolset.

The fifth contribution Mapping of Time-Consumption During Input Data Management Activities by Anders Skoogh and Björn Johansson presents a distribution of the time-consumption for the activities in the input data phase during DES projects. The results show where efforts need to be focused to reduce time-consumption and improve quality of input data management.

The sixth contribution Simulation Model Quality Issues in Product Engineering: A Review by David J. Murray-Smith considers the link between model quality and the quantitative testing of continuous system simulation models in product engineering and reviews techniques available for the verification and validation of such models. The paper also takes into account some of the problems inherent in applying rigorous testing and validation procedures.

The editors would like to thank Oliver Rose for assisting the reviewing process. Furthermore the editors would like to express their gratitude to all authors for their co-operation and efforts, e.g. for sending revised versions. We hope that the selected papers present a good overview and state-of-the-art in procedure models, methods and techniques for ensuring quality in M&S.

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TECHNICAL NOTES

Quality Aspects in Simulation Studies for Production and Logistics

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Quality aspects in simulation studies are addressed in a variety of papers and books. In our paper, we intend to provide the simulation practitioner in the field of production and logistics with an easy-to-use procedure to guide him through all phases of a simulation project, from the specification of his needs through the simulation study as such to the potential re-use of models and results. We outline five fundamental quality criteria, provide an extended procedure model for the different project phases, and explain how checklists can be applied for quality improvements. This work is based on the discussions over several years of a special interest group of the ASIM working group "Simulation in Production and Logistics" (Arbeitsgemeinschaft Simulation) and targets to summarise some of the key ideas of simulation experts from industry and academia working in a large variety of application domains of discrete event simulation (DES).

Introduction

Nowadays, a wide range of high-quality discrete event simulation (DES) tools for production and logistics applications are on the market. Simulation is a well-established tool in many industrial application domains (e. g. automotive, aircraft and shipbuilding industry, semiconductor industry, plant engineering and construction, supply chain management, health-care logistics or call centre). These aspects seem sometimes to result in using simulation as a problem solving method like a duck takes to water (see [1]): On the one hand the acceptance of simulation in industrial applications will increase also by new end-users who were put off in the past by statements like "Simulation is an innovative method only used by experts." On the other hand this development obviously provokes certain carelessness using simulation theory and the demand that modelling and simulation is easy, quick and low-cost. Unfortunately, the matter of course in using simulation methods leads to underestimate the time and manpower requirements for a simulation study. Neither statistical verification of the simulation results which is needed for a high-quality planning nor the relevance of the simulation results for the planning task is considered sufficiently. Sometimes a 3-D model of the system which had to be analysed will be sold as *the* result of the simulation study.

In addition, the matter of course in using simulation methods and the standardisation of using simulation on the part of the simulation experts may lead to a non-comprehensible project implementation for clients who do not know anything about simulation (for example: missing transparency with respect to the granularity and quantity of data to be acquired or the modelling level of detail to be chosen). Sometimes new users being non-familiar with the simulation methods adamantly refuse simulation applications.

Therefore the ASIM Working Group "Simulation in Production and Logistics" intends to recollect quality aspects in simulation project implementation. The discussed and published topics "Quality aspects" [2] and "Verification and Validation" [3] are essential for high-quality simulation projects and credible simulation results. In the next section, we briefly discuss some quality criteria in simulation projects and define five fundamental quality criteria. In Section 2, we present a simulation procedure model recommended by ASIM followed by a description of available checklists for a systematic project implementation (Section 3). Finally, a summary concludes the paper.

1 Quality criteria in simulation projects

To ensure a quality-oriented and professional project implementation, the involved project partners have to understand the meaning of the term *quality* in the same manner. "Quality is the totality of features and characteristics of a product or service that bears on its ability to satisfy given needs." "Quality is meeting or exceeding customer expectations." [4], pp. 15. Eppler

([5], pp. 20) discusses the twofold nature of quality defined by subjective (e.g., meeting expectations) and objective indicators (e.g., meeting requirements). The subjective indicators comprehend aspects like “fitness for use” or “satisfy needs” (relative dimension); the objective indicators includes aspects like “error free” or “meeting specification” (absolute dimension).

The definitions above directly show that there are no generic rules to define quality or to measure the degree of fulfilment. The quality of a project in general as well as of a simulation project (simulation study) is defined by different business, company and project-specific requirements. But it also takes into account the opinion of all project partners. Additionally, the definition clarifies that quality in simulation projects includes not only the *quality of the outcomes of the simulation projects* (in terms of correctness, validity, transparency, purpose-orientation, re-usability, acceptability) but also the *process quality* of the project itself. This implies that the results of each project step have to meet these quality requirements.

In the literature there are a lot of information and instructions about how to manage simulation projects successfully [6, 7]. Liebl [8] (pp. 222) describes seven deadly sins of simulation studies:

1. Wrong definition of the study goal
2. Deficient involvement of the sponsor
3. Unbalanced mixture of core competences
4. Inadequate level of detail
5. Selection of the wrong simulation tool
6. Insufficient validation
7. Poor result presentation.

In contrast to Liebl [8], Robinson and Pidd [9] point out 19 dimensions for simulation project quality. These dimensions include (in an updated version in accordance with [10], pp. 206) model, data, and software-specific criteria as well as characteristics of the model builder himself as credibility, professionalism, expertises and soft skills. Additionally, the client and his organisation (“the commitment of the client´s organization to the simulation project”, [10], pp. 206) and the relationship between the involved project partners are taken into account. However, the quality criteria do not have to be fulfilled to the same degree. First of all the project-specific expectations of the customer concerning the organisation of the project, the implementation with of content and technique as well as the usability of the results have to be met. In this context, Robinson [11] developed a simulation quality trilogy concerning the content, the process, and the outcomes of a simulation study.

In a nutshell, the quality in simulation projects is defined by the accuracy and systematic of the project preparation and implementation, adequate participation of the customer, and the consideration of his specific requirements (e.g. number of meetings, scope of presentation, outcomes). From the authors´ point of view, five basic quality criteria are identified which have to be fulfilled within a simulation project for production and logistics tasks:

1. Accurate project preparation
2. Consistent documentation
3. Integrated verification und validation
4. Continuous participation of the client
5. Systematic project implementation

An approach for a consistent documentation and an integrated verification and validation within simulation studies in production and logistics is discussed in more detail in [3] and [12]; the approach of an integrated verification and validation also in [12].

The first, the fourth and the fifth criterion are supported by different checklists on the basis of the simulation procedure model described in the following section. A short description of the checklists as developed by the authors of [2] as well as a list of the available checklists is given in Section 4. More details on the checklists can be found in [2].

2 The extended procedure model

The authors propose an extended procedure model for simulation including Verification & Validation (V&V, see Figure 1), based on a guideline of the German engineers’ association VDI [13].

Our procedure model extends the model published in [12]. In particular, we added references to the checklists (depicted as circles in Figure 1) which are discussed in Section 4. These checklists support the work of the project team in all phases of the simulation project and are a fundamental part of our quality improvement philosophy.

In contrast to most other publications on procedure models for simulation projects, we consider the pre-project phase (Project Definition) and the post-project phase (Re-Use) explicitly. Starting from the Sponsor Needs (like, e.g., initial situation, scope of the project, and constraints) the extended procedure model considers only tasks that normally occur after the project

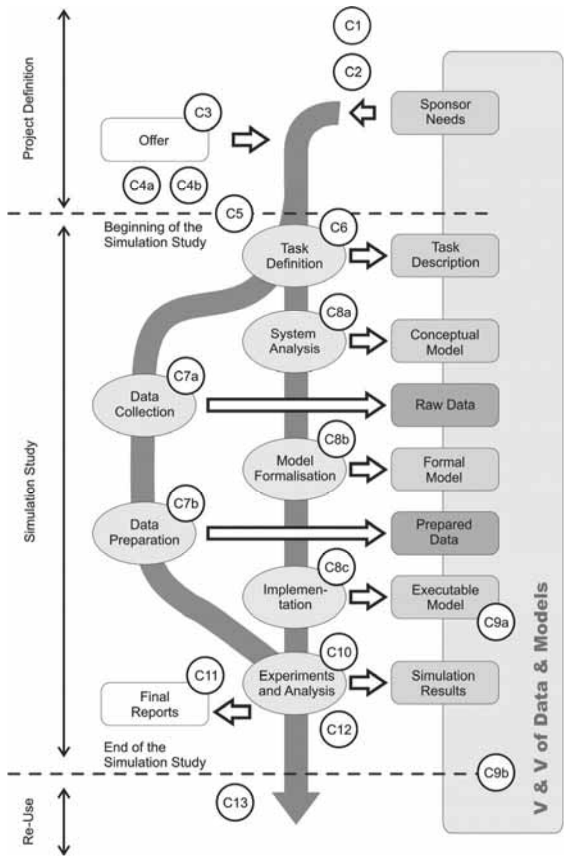

Figure 1. Extended Procedure Model (compare [2]).

sponsor had accepted the task and cost plan in the form of an offer for the simulation study from a simulation provider. We do not distinguish here between external and internal service providers. Therefore, the proposed procedure model starts with the Task Definition, which is considered to be the first analysis step within a simulation study. The Task Definition can be rather coarse in the beginning of the project definition phase and has to be updated with more and more details until a concrete offer finalises this step. This offer will set the frame for the whole simulation project.

The phases Data Collection and Data Preparation are intentionally defined in a second path, as they can be handled in parallel with respect to content, time, and involved persons. Therefore, the arrangement of Raw Data in Figure 1 does not indicate that they can only become available after the conceptual model. Raw Data does not need to be completely collected before the elaboration of the Formal Model. The same applies to the Prepared Data, analogously. The procedure model just defines that Data Preparation requires Data Collection to be done, and that for the use of the Executable Model the Prepared Data have to be available.

V&V has to be conducted *during all phases of the modelling process* [14]. Therefore, the procedure model does not contain a special phase “V&V”. But, V&V – both of the data and the models – is an *essential part of the whole simulation study* (see the rectangle on the right of Figure 1). More details about V&V can be found in [15]

The proposed procedure model is characterised by a clear definition of intermediate results, and separate paths for models and data. These phases are depicted as ellipses in Figure 1. A *Phase Result* is assigned to each phase (rectangles in Fig. 1). Phase results can be models, documents, or a combination of both. Only the document “Sponsor Needs” is not really a Phase Result, but the base for starting the simulation study. A detailed description of the procedure model and the necessary documentation is given in [3] and [12].

In addition to the documentation of the phase results, we consider the following documents:

Sponsor Needs

- Definition of the goal of the study
- Due date of the study
- Criteria to judge the successful completion of the study
- Initial situation, expected results, constraints

Offer

- Description of the initial situation
- Description of the goal of the study
- Contents of the study (work packages)
- Scope of the study
- Project management details (teams, meetings, etc.)
- Expected hardware and software environment
- Costs
- Due dates
- Legal issues (terms of payment, nondisclosure agreements, etc.)

Final Reports

- Goal of the simulation study
- Input data
- Modelling assumptions
- Structure of the simulation model
- Control strategies
- Model variants
- Design of experiments

- Simulation results including analysis and interpretation
- Measures of V&V
- Comments about model re-use

It is important to note that not all documents listed above will be required in every simulation study. In addition, the documents will provide the information at different levels of detail. The main purpose is not to generate as much pages as possible but to make transparent all decisions which had to be made during the course of the study.

3 Support utilities for quality criteria compliance

In order to obtain a high quality of all outcomes, intermediate and final, it is essential to consider the aspect of quality during the whole course of a project. This approach is especially expressed by the fifth quality criteria *Systematic Project Implementation* as described in Section 1. Since a consistent and systematic implementation is sometimes difficult to achieve - in particular for companies which use simulation for the first time - assistance has to be provided, e. g., by checklists like the ones developed by the authors of [2]. These checklists cover each phase of a simulation project and are particularly designed for daily and simple use.

The checklists support both customers and simulation experts with a collection of predefined recommendations of activities in each single project phase.

The given recommendations of activities are consciously expressed in an application-independent manner so that they can be used in any industrial branch. This means that the project manager has to decide which recommendation is applicable for the project under consideration when taking into account specific characteristics of the project definition and the given project environment. On the other hand, this means that the given collection of recommendations as published in [11] cannot be exhaustive.

Although it is basically possible to support the systematic project implementation by using simple ticklists, it was the aim of the authors of [2] to provide a dynamic tool which even allows keeping record of organisational data like appointments, responsibilities and remarks. Hence, consistently used checklists can even be used as part of the project documentation. Furthermore, this allows performing a transparent and comprehensible project implementation throughout all phases. Even in case of problems, causes of faults as well as the corresponding responsibilities can easily be tracked.

The tailor-made checklist form (cf. Fig. 2) supports the completion of the five basic quality criteria (see Section 1). The form offers a structured overview of all recommendations of activities for a specific project phase and allows to plan, to implement and to trace each single activity and its potential outcomes in a structured way.

The form consists of several parts for storing different kinds of information:

Header This part of the form contains general information about the project, the specific phase (name of the list; see list of available checklists below), the involved partners and the responsible project manager. He has to take care of a consistent use of all checklists and has to sign each list when closed.

Work Area This major part of each checklist contains all recommended activities for each project phase as well as the corresponding organisational

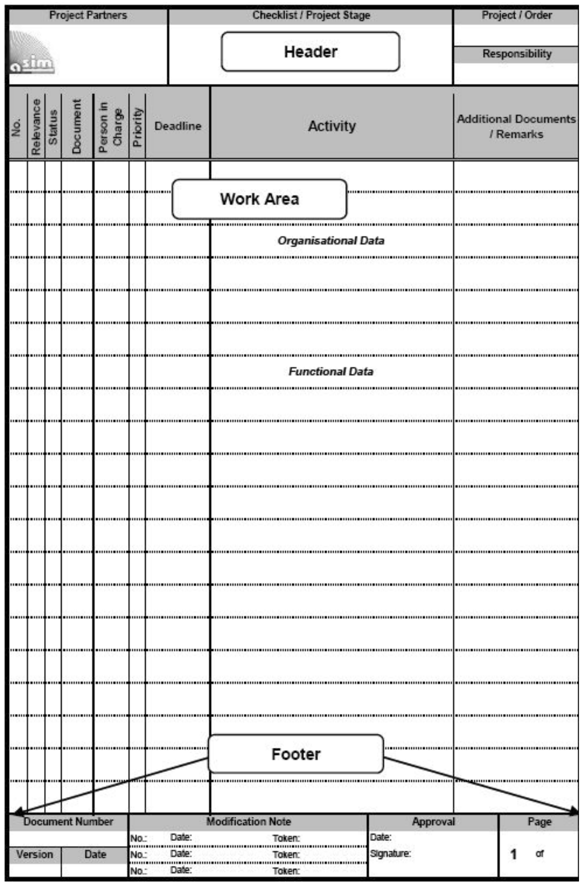

Figure 2. Checklist form – total view (see [2]).

information (see example in Figure 3). The activities are grouped into organisational and functional items in order to provide a guideline for the specific project phase. Each given recommendation has to be rated as relevant for the project or not. If relevant, a responsible person for the activity has to be assigned and a priority indicator as well as a deadline has to be specified. During the project the current status of each activity has to be tracked in the checklist. Relevance, status and priority should be depicted by symbols easy to understand. A reference to a part of the documentation which has to be prepared during the project should be given in the column *Document*. These documents should be written according to the proposed documentation structure for simulation projects in [2]. The proposed document identifier *Dx,y* indicates the document number *x* and the chapter number *y*. Documents that extent the recommended standard documentation should be referenced by an acronym (see example "*oD*" in Figure 3). Of course, the list of recommendations can be enhanced with project specific items by the project team.

Footer The lower part contains organisational data regarding the checklist itself. Besides the document and the page number, the version and the date of publishing have to be given here in order to fulfill the requirement of traceability. It is obvious that any change to a recommended activity has to be noted down together with an identification code of the initiator. Finally, when all activities have been done and the project phase is completed, the checklist has to be closed by the signature of the project leader. In case that a certain project phase has to be passed through

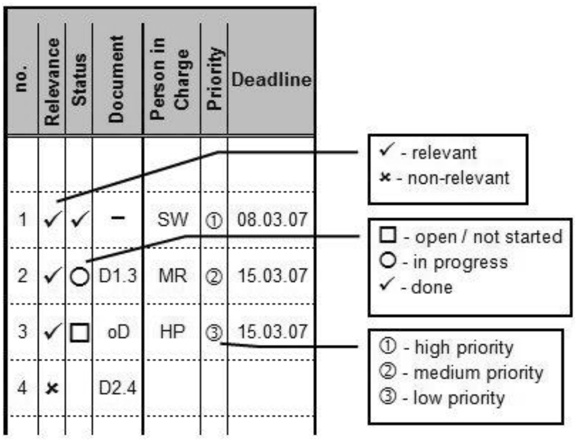

Figure 3. Organisational information in the work area of a checklist (see [2]).

another time because an iteration is necessary a new form of the same corresponding checklist shall be used.

The following 18 checklists are available in [2]. Each checklist can be identified either by a name or by an acronym built of a "*C*" plus a number and potentially a further attribute. Figure 1 in Section 2 illustrates how the checklists relate to the activities in the Extended Procedure Model:

- C1 Contractor's Project Preparation
- C2 First Meeting
- C3 Proposal Preparation
- C4a Proposal Selection
- C4b Tool Selection
- C5 Kick-off-Meeting
- C6 Problem Definition
- C7a Data Collection
- C7b Data Preparation
- C8a System Analysis
- C8b Model Formalisation
- C8c Implementation
- C9a Model Approval
- C9b Project Approval
- C10 Experimentation
- C11 Final Documentation
- C12 Final Presentation
- C13 Subsequent Use

A representative example of a checklist for an early project phase is given in Figure 4. Checklist *C2 – First Meeting* contains recommendations for organisational and functional activities which should be performed by the project participants – contractors and potential simulation experts – when they meet for the first time to discuss the intended simulation project in detail.

An example of an organisational recommended activity is "*Define date, location and group of participants; invite in time*"; no. 1 in checklist *C2 – First Meeting* (cf. Fig. 4). Although it is a very simple advice and seems to be obvious, it is even more important to note it down in a checklist so that it cannot be forgotten.

A very important example of a functional recommended activity for the first meeting between contractor and simulation expert is "*Clarify and define budget allowances*", No. 18 in Figure 4. Although not technical, this activity impacts the next steps of the simulation expert in case he is requested to prepare a

Project Partners	Checklist / Project Phase
asim	C2 – First Meeting

No.	Relevance	Status	Document	Person in Charge	Priority	Deadline	Activity
							Organizational Data
1			–				Define date, location, and participants; invite in time
2			oD				Distribute documents for preparation of meeting
3			oD				Determine person for minutes; write minutes in time
4			–				Approve minutes, determine recipients, distribute minutes
5			–				Plan for second meeting, update/extend list of participants
6			–				Define next steps, e.g., write offer, plan on-site visit
							Functional Data
7			D1.1				Ask for approval for problem description; add details (if necessary)
8			D1.2				Define system limits (plan on-site visit, if necessary)
9			D1.2				Define goals / research questions for study
10			D1.2				Ask for approval for outline of expected results and for form of presentation
11			D1.2				Discuss potential solution approaches and determine appropriate approach
12			D1.2				Outline project milestones and ask for approval
13			D1.2				Discuss intended application of results and models
14			D1.3				Define work packages and discuss whether additional partners are needed
15			D1.3				Determine third party reporting requirements
16			D1.3				Determine non-disclosure agreement requirements
17			D1.3				Clarify / determine time restrictions for the project
18			D1.3				Clarify / determine budget restrictions
19			D1.3				Define modeling and project approval criteria
20			D1.3				Define form and amount of documentation, define form of results
21			D1.3				Check / define hardware and software constraints

Document Number	Modification Note	Approval

Figure 4. Extract of Checklist C2 – First Meeting (see [2]).

quotation for the simulation project. The example in Figure 4 shows that the recommended activities are ordered logically within the two groups. The users of the checklist just have to follow the list deciding which recommendations are relevant for the specific project. In the next step, they have to decide about the persons in charge, the priorities and the deadlines for the relevant activities. Of course, it is possible to add further activities individually based on the project and its characteristics. While the decisions for relevance, persons in charge, priorities and deadlines for organisational items can mostly be taken by one party before the project phase starts, most of the decisions regarding the functional items have to be taken by all involved parties during the project phase – here: during the first meeting.

For a further support of contractors and simulation experts in order to achieve high quality level simulation projects, the authors of [2] advise to use methods which allow, e. g. a systematic selection of proposals or simulation tools based on assessment criteria and procedures. These methods were adopted from design methodology and support objective results in decision processes; see also [16].

4 Summary

Simulation is a well-established decision and analysis tool in industry and academia. Nevertheless, it is still important to foster a high-quality attitude of all partners in simulation projects.

In our paper, we provided several methods to achieve this goal, namely fundamental quality criteria, an extended procedure model, and problem-specific checklists. Based on our experience, these methods can be practically applied and they are helpful to initiate and implement simulation projects at a high quality level.

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A Multistage Approach for Quality- and Efficiency-Related Tailoring of Modelling and Simulation Processes

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For reasons of increasing productivity, efficiency, and decreasing time and cost for complex system innovations, modelling and simulation (M&S) becomes a standard "tool" for a huge variety of applications. The demand for controlling and demonstrating the quality of a model and its applications by introducing appropriate quality measures, techniques, and tools is obvious. Consequently, a variety of structured and even standardized processes for development of modelling and simulation (M&S) applications as well as for verification and validation (V&V) has been proposed. All of them require, however, due to different characteristics of organisation structures and project environments, some kind of adaptation or tailoring prior to application. This paper describes a multistage approach for tailoring of an M&S project in compliance with the principles of the V-Modell XT, which is considered as the German standard IT development process obligatory for federal engineering projects. Along with the integration of the M&S-specific components into the V-Modell, this tailoring approach enables the project-specific selection of essential products, documents and activities for developing M&S applications and conducting their V&V according to specified cost, time and application constraints.

Introduction

Enabled by rapid advances of computer and network technologies, the development and application of increasingly complex simulation models and applications (M&S) in various domains is inevitable. Accompanied by increasingly powerful visualisation and simulation infrastructures and tools, quality assurance, especially correctness and validity of models and of simulation results becomes an urgent requirement.

As a consequence, a large number of well-structured and even standardized processes [1, 2, 3, 4, 5, 6] for development of M&S applications and also for their verification and validation (V&V) have been introduced. However, since there exist no two organisations with the same structural properties, and furthermore, every M&S project differs in terms of objectives, scale, scope, technical challenges etc., none of these processes is well suited for all possible circumstances. Therefore, the potential of an M&S process to be adapted to various application domains and different project environments is a crucial issue for its acceptance in practical application [7, 8].

Instead of proposing new standard processes, this work investigates the opportunity to use the V-Modell XT [9, 10, 11, 12] for conducting an M&S project, and introduces a multistage approach to adaptation of model development and V&V to the actual project context in accordance with the principles of the V-Modell. As the official German standard development process for IT systems, the V-Modell describes detailed requirements and guidelines necessary for system development throughout the entire life cycle, integrating various essential management processes, such as quality assurance, project management, and configuration management. It is based on a modular structure, and can be flexibly extended. A considerable amount of benefits can be directly achieved by using the V-Modell for M&S development, since:

- the V-Modell covers all relevant aspects for software and hardware development;
- the V-Modell XT can be flexibly adapted to project-specific constraints due to its advanced tailoring concept;
- documentation, templates, training material, and open source tools are publicly available;
- supporting tools developed for the V-Modell could be also applied to model development;
- comprehensive experiences collected from V-Modell applications in practice are also meaningful for model development;
- the V-Modell XT obtains growing (national as well as international) acceptance.

As already discussed in [13, 14], since some essential elements for conducting a simulation study are not available in the V-Modell XT, the M&S-specific components have to be additionally defined and integrated. Therefore, the scope of adaptation addressed in the context of this paper is twofold: (1) enabling the V-Modell XT to conduct an M&S project; (2) tailoring of an M&S project with respect to specified time, cost and application constraints.

The remainder of this paper begins with a brief introduction to the V-Modell XT. Section 2 points out the required M&S-specific aspects to be integrated in the V-Modell. In Section 3, the adaptations of the V-Modell for conducting an M&S project and a multi-stage tailoring approach are introduced. Section 4 presents an application example of the tailoring process. Finally, Section 5 concludes the work.

1 Overview of the V-Modell XT

The V-Modell XT defines detailed requirements and guidelines necessary for developing a successful software and hardware system throughout the entire project life cycle from the project planning up to the acceptance of end products. The following description provides a general outline of the basic concepts included in the V-Modell [9, 12], particularly the concepts of Project Types, Process Modules, Project Execution Strategies and Tailoring.

1.1 Project Types and Project Type Variants

The success of a system development depends on whether the user requirements are fulfilled to the full extent. Therefore, clients should be involved in the entire project life cycle and work closely with other project participants. According to the particular perspectives of clients and contractors on the development process, the V-Modell XT distinguishes different project types, each of which defines a set of specific tasks from the viewpoint of a client (acquirer) or a contractor (supplier), concerning the different project execution. To describe project characteristics in more detail, different project type variants are defined for each project type. A project type variant specifies the basic requirements for a possible project execution regarding contents and time, and thus, determines an ordered development life cycle.

1.2 Process Modules

The essential structure of the V-Modell is represented by various process modules. Each process module focuses on a particular task to be accomplished within the scope of a V-Modell project, and defines a set of products, activities and roles required to complete the intended task in the context of a certain process area, such as project management, software development, quality assurance, etc.

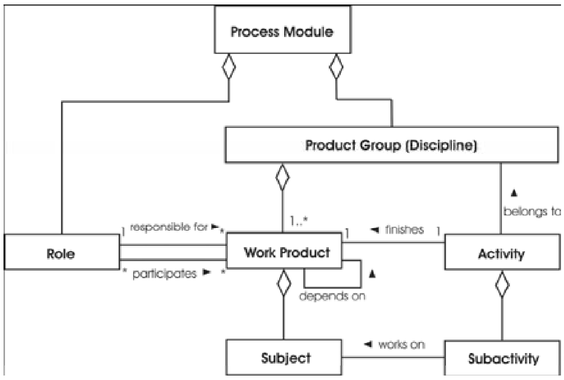

Figure 1. Structure of a process module.

Figure 1 shows the structure of a process module defined in the V-Modell. Products stand in the central point and represent the main project results. Each work product being developed is completed exactly by one activity. To define the responsibility of product creation, a well-structured role concept is introduced. During a project execution, a person or an organisational unit can be assigned to a role, according to the competency. Several roles may contribute to a product's creation concurrently, but only one of them carries the responsibility. A product can be subdivided further into several subjects. In addition, products can be also integrated into a product group (or a discipline) with regard to contents, and the associated activities belong to the same discipline.

The concept of process modules is a typical component-based approach [10]. Each process module contained in the V-Modell is an independent unit, and can be changed and extended for different project situations. The four process modules: *Project Management*, *Quality Assurance*, *Configuration Management*, and *Problem and Change Management* specified in the V-Modell XT, are mandatory to be used for each software development project, and therefore, are also designated as the core process modules or the V-Modell Core.

1.3 Project Execution Strategies and Decision Gates

Since a process module does not contain any information about the order of preparing certain products, project execution strategies are introduced to specify the possible sequence of product development. With respect to time aspect, each project execution strategy represents an ordered development life cycle for a certain project type, and defines in detail the different project progress stages to be achieved, which are designated as decision gates. A decision gate is comparable with a milestone in a project, and indicates which products have to be finished in which order [10]. To achieve the decision whether the defined products have been completed correctly and accurately, diverse verification and validation (V&V) methods must be applied to evaluate the quality of products. The relationship between project types, project type variants, process modules, and project execution strategies is illustrated in Figure 2.

1.4 Tailoring

According to specified cost, time and application constraints, the V-Modell XT can be adapted to different project constellations. This project-specific adaptation is called tailoring. The tailoring process of the V-Modell begins with the selection of a project type. Since a set of process modules is predefined for each project type, this step determines mandatory process modules preliminarily. After that, a possible project type variant of the selected project type is to be determined, by means of which not only the project execution strategy but also further process modules can be selected.

Moreover, different project characteristics describing the project in more detail are assigned to the selected project type and the associated project type variant. During the Tailoring process, one value that has to be selected from a number of possible values must be determined for each project characteristic. This step could add additional process modules and modify the project execution strategy. As a result, besides the V-Modell Core only relevant process modules and a suitable project execution strategy with well-defined decision gates are determined exactly in consideration of the actual project conditions. The work process for further tailoring of products and activities within a process module is, however, not defined in the standard V-Modell XT.

2 Modelling and Simulation in the Context of the V-Modell XT

Modelling and Simulation (M&S) requires a specific development process, which can not be completely specified by the V-Modell XT [13, 14]. This section investigates the essential features of an M&S project, and points out the M&S-specific elements which have to be additionally defined and integrated in the V-Modell for conducting a simulation study. The resultant new variant of the V-Modell is referred to as the V-Modell XT-M&S.

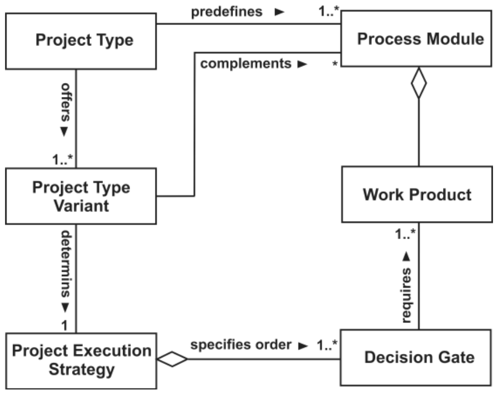

Figure 2. Relationship between the basic concepts.

2.1 Adding the M&S-specific Aspects: towards the V-Modell XT-M&S

Commonly, regardless of how a concrete modelling process looks like, a simulation model is developed through the progress stages of Model Initialisation, Model Design, Model Realisation and Model Application in the course of any M&S project. For each progress stage, one or more (intermediate) work products are to be prepared, and the quality of them is also to be estimated as part of the model development. For example as shown in Figure 3, the progress stage *Model Initialisation* includes the work product *Sponsor Needs* (SN), in *Model Design* the products *Structured Problem Description* (SPD), *Conceptual Model* (CM) and *Formal Model* (FM) are defined, *Executable Model* (EM) is prepared in *Model Reali-*

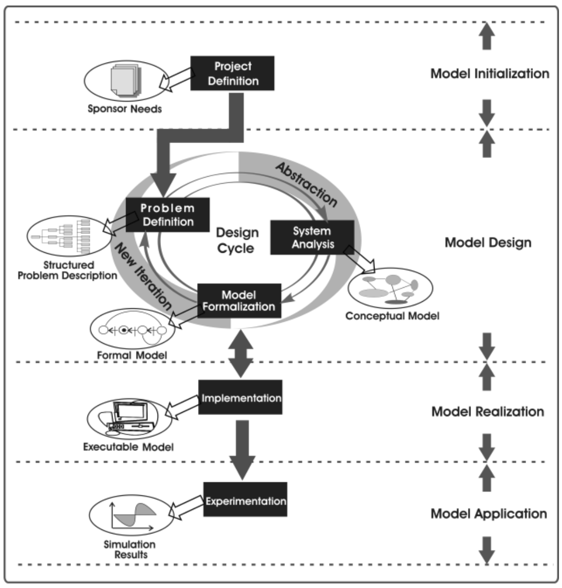

Figure 3. Progress stages of an M&S project.

sation, and *Simulation Results* (SR) are achieved in *Model Application*.

As a standard process for software and hardware development, the V-Modell XT does not contain all necessary elements specifying the development of simulation models and applications. Therefore, the following missing aspects must be taken into account when applying the V-Modell to conduct an M&S project:

- **Model Design** The specification and formalisation of a well-defined simulation model is not a part of software development. During the model design process, the mathematical / logical / graphical / verbal representation of the real system of interest is developed for the objectives of a particular study. Since a typical simulation study requires multifaceted knowledge in different disciplines [15], a variety of representation means such as mathematical equation systems, queuing networks, Petri nets, process algebra [16] and Discrete Event System Specification (DEVS) [17] etc. can be used for developing the work products SPD, CM and FM. The associated activities and roles are also to be integrated in the V-Modell XT. It should be noted that some models, such as the different model types defined in Model Driven Architecture (MDA) [18] proposed by the Object Management Group, could be also established during software development process, however, they (for example models described in UML [19]) serve as aids for specifying the functionalities, the structures, and the behaviors of a software system, and are used in converting a well-formed simulation model into a software and hardware form. This aspect is addressed at the progress stage Model Realisation and completely covered by the V-Modell.
- **Data Modelling** Throughout the entire M&S development life cycle, an enormous amount of information must be gathered, analyzed and modeled in terms of qualitative and quantitative data. This task is referred as to data modelling [20]. Three types of data [21] are to be handled: some data are used to specify the model components, and finally, become integrated into the model built; while other data are used either to compare with the simulation results for test purpose or to perform simulation experiments. According to the different applications of input data, data modelling has to closely cooperate with each project progress stage, and therefore, is considered as an integrated part of model development [22]. This aspect has also to be contained in the V-Modell XT-M&S.
- **Model Application** Model Application refers to the process of experimenting with the simulation model for a specific purpose, including design of model experiments, execution of simulation runs and interpretation of simulation results. This aspect is out of the consideration range of every software and hardware development process.

2.2 M&S Verification and Validation

As discussed above, the essential M&S-specific aspects model design, data modelling, and model application are not contained in the V-Modell, while others like model initialisation and model realisation are completely covered. This means that the M&S-specific components should be additionally introduced in the V-Modell. For the purpose of model V&V, two issues must be followed:

1. the M&S-specific elements must be in form and content completely compatible with the V-Modell XT;
2. appropriate V&V activities must be defined to evaluate each (intermediate) product of the common V-Modell XT as well as the M&S-specific aspects consistently.

To specify the aspects of model design, data modelling and model application in the context of the V-Modell, the M&S-specific work products as well as the associated activities and roles have to be additionally defined in the form of process modules. Furthermore, it is also to be determined in which order the new products should be completed and which V&V activities should be applied to ensure their quality. This means that appropriate project execution strategies and additional decision gates are also to be introduced. More details about the extension of the V-Modell will be discussed in the next section.

Regarding assessment of product quality, the V-Modell XT defines concrete requirements for performing V&V activities. Each product defined in the V-Modell must be evaluated. An evaluation can be conducted either by the developer himself, the so-called self-evaluation, or by independent verification and validation (IV&V) [12, 23]. In the V-Modell, it is clearly specified whether an IV&V is required for a product.

V-Modell Component	M&S-specific Extension
Process Modules	Model Design Model Application
Decision Gates	Model Designed Data Edited Simulation Prepared Simulation Conducted Results Interpreted
Templates	Documentation templates

Table 1. M&S-specific extensions.

The process module Quality Assurance of the V-Modell is used to specify how and by which means the project quality is intended to be ensured, including the essential V&V activities for planning, execution and documentation of product evaluation. To achieve unified V&V of all products, quality assurance measurement must be defined for the M&S-specific products consistently with the original products.

Therefore, appropriate V&V activities should be specified for evaluating each new product involved in Model Design and Model Application by using the same quality assurance mechanism of the V-Modell. Since the quality of data modelling is also a crucial factor for the credibility assessment of M&S applications, correctness and accuracy of data acquisition, data analysis, data transformation and data use must be estimated in accordance with model V&V for each model development phase [14, 22]. Thus, evaluation of each individual product and credibility assessment of an overall completed M&S application can be achieved within the scope of the V-Modell XT.

2.3 Documentation of Model Development and V&V

Documentation is an essential issue for a successful simulation study. However, under pressure, time and cost constraints, model documentation in practical applications is often sacrificed first [24], or conducted only in an arbitrary and informal way [25, 26]. Suchlike problems of documentation not only reduce the application efficiency of simulation models and make their reuse as well as further development difficult, but also lead to increasing risks of using improper V&V results. Therefore, a structured and well-defined documentation is required for developing M&S applications as well as for conducting their V&V.

According to [25], the M&S documentation should describe detailed information about historical, technical, developmental, maintenance and implementation aspects of a model, including all assumptions, implications and impacts of using the simulation results. Concerning model verification and validation, not only planning, design and execution of each individual V&V activity, data used, conclusions, but also separate evaluation results of the intermediate products SPD, CM, FM, EM, and an overall summary should be documented [27]. This documentation approach should be also integrated into the V-Modell XT-M&S, and corresponds to each phase of model development and V&V.

3 Adaptation of Modelling and Simulation Processes

As described above, an M&S project requires specific work products, activities, roles and work flows compared to the standard V-Modell XT. This section presents the integration of the M&S-specific components in compliance with the basic structure of the V-Modell. Based on the extension, a refined tailoring concept is introduced, which enables the step-by-step adaptation of an M&S project to suit actual requirements of model development, V&V and documentation.

3.1 M&S-specific Extensions to the V-Modell XT

Largely in the form of additional process modules and new decision gates, the M&S-specific components are integrated into the V-Modell as shown in Table 1. Furthermore, useful templates are introduced for the purpose of documentation of model development and V&V [28]. A more detailed description of the M&S-specific extensions can be found in [13,14].

The new process module *Model Design* comprises the necessary activities and work roles to prepare the intermediate products of *Structured Problem Description* (SPD), *Conceptual Model* (CM) and *Formal Model* (FM). Since data modelling cooperates closely with model development, the aspects of the associated data acquisition, data analysis, and data transformation are also specified. Additionally, with respect to model V&V, this process module includes the specification of V&V requirements for each contained model element, guidelines for definition of test cases and V&V execution, and documentation of V&V activities and results.

The other new process module *Model Application* contains the activities, roles and products required for planning, designing, executing, and documenting model experiments, as well as for interpreting simulation results. The necessary products and activities for the purpose of V&V are also defined in this process module.

In order to indicate the milestones in the project sequence, where the M&S-specific work products have to be evaluated, new decision gates are introduced in project execution strategies for every project type. For an M&S project of the developer (supplier) side, two additional decision gates *Model Designed* and *Data Edited* are defined for ensuring that the M&S-specific work products SPD, CM, FM, and the associated input model are completed correctly and accurately. On the other side, for an acquirer (client) project, the new decision gates *Simulation Prepared*, *Simulation Conducted* and *Results Interpreted* enable to conclude that the model experiments are performed as planned, and the observed simulation results are also interpreted appropriately.

To enable a well-defined documentation of model development and V&V, concrete structure and contents requirements for each model element created during the M&S life cycle are provided and specified in the form of document templates.

3.2 Tailoring of an M&S Project in Stages

In due consideration of the new process modules and decision gates, the M&S-specific project types including the individual project type variants for an acquirer and a supplier and the corresponding project execution strategies are introduced. Thus, an M&S project can be principally tailored by using the V-Modell XT's own tailoring concept, which enables the selection of the mandatory process modules and a suitable project execution strategy in the order of determining the project type, then the possible project type variant, and finally, identifying the values of the associated project characteristics. As mentioned previously, there are no additional tailoring steps defined for further adaptation at the product and even at the subject level in the V-Modell XT.

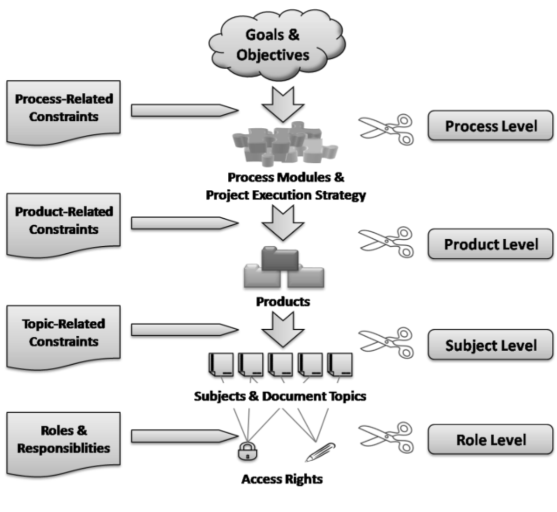

Figure 4. Multistage adaptation of an M&S project.

For the purpose of reaching a more precise tailoring decision on a suitable set of necessary work efforts concerning model development, V&V and documentation in relation to project-specific time, cost and application constraints, a refined adaptation process is defined and applied to conducting an M&S project. As illustrated in Figure 4, the tailoring efforts of this approach are organized in a hierarchical structure, and the project-specific selection can be made respectively on different levels, viz., the process level, the product level, the subject (or topic) level, and the role level.

Basically, each M&S-tailoring process starts at the process level. In the event of adaptation at this level, the same tailoring process as in the V-Modell is performed, in which a mandatory set of process modules and a suitable project execution strategy with well-defined decision gates are selected in accordance with identified project requirements and constraints.

Based on more detailed project constraints related to the product level, the already determined process modules can be further tailored. As a result of this process, only relevant work products and their associated V&V activities for the current project are specified. When further details about how to select essential subjects of a product or to determine concrete documentation topics are available, the subject-related adaptation can be arranged.

Compared to the process tailoring, the last two tailoring steps are optional and only applicable, when the corresponding product- and subject-related constraints are identifiable in the course of an M&S project. Otherwise, all selected process modules must be fully taken into account. Finally, depending on the tailoring results at the process, product, and subject levels, the right to access a particular model element is defined for all involved roles according to their assigned responsibilities.

Similar to the original tailoring concept of the V-Modell XT, both static and dynamic adaptations are arranged in this tailoring context. Static tailoring refers to selecting required process modules or even products and subjects based on a prescribed and already identified set of requirements and constraints at the beginning of an M&S project.

Typically, identifying project requirements and constraints all at once is, however, virtually impossible, for example, the exact impact of using an existing model component or using a particular simulation tool on project execution can be only investigated, when some experiences have been already gained in the context of the current project. In addition, the application profile of a project might be changed during the development process. Therefore, certain modifications of the determined process modules, products, subjects, and the project execution strategy still need to be made in the course of developing an M&S application. This kind of adaptation is designated as dynamic tailoring.

4 An Application Example

This section illustrates how this multistage adaptation process can be used for tailoring a model development project on the supplier side by means of a simple practical example. This example is based on a real simulation project [29], in which a training simulator is to be developed by using some legacy model components available from an early M&S project. As an extended system component, the completed simulator has to be integrated into an existing computer aided training system environment, and has to cooperate with other components.

In order to keep compatibility with the other existing system components, a specified simulation development tool needs to be applied to the model design and implementation phases of this M&S project. The hardware part of the simulator comprises the training workstations and other physical devices for networking, operation, display etc. Based on information available at the beginning of the project, tailoring efforts can be arranged within the scope of project planning. As described above, the tailoring process begins at the process level. Namely, the project manager has to determine a mandatory set of process modules and a suitable project execution strategy for the current project.

Like the standard tailoring concept of the V-Modell XT, the M&S-specific adaptation at the process level is structured as follows:

1. determining the project type,
2. selecting the correct project type variant, and
3. identifying the values of the associated project characteristics.

With respect to the project constraints identified so far, the newly introduced project type “M&S Development Project (Supplier)” is to be selected. Process modules to be used for this project type include *Drafting and Conclusion of Contract (Supplier), System Development, Delivery and Acceptance (Supplier)* and the new process module *Model Design* in addition to the V-Modell Core, namely *Project Management, Quality Assurance, Configuration Management* and *Problem and Change Management.*

Two possible project type variants, namely “Project with Development, Enhancement, or Migration” and “Project with System Maintenance”, are available to this project type. Obviously, the former is to be selected in this case. Since the existing model components are applied to the development of this simulator, the predefined project execution strategy “Component-Based Development” is well suited for this project context.

Afterwards, other project characteristics are to be considered. In this example, the project subject characteristic is of major interest. As the training simulator involves software and hardware parts, two more process modules *Software Development* and *Hardware Development* are finally identified.

The next step is the tailoring within the selected process modules at the product level. Because no detailed project constraints related to the product level are identifiable at this point in time, all the work products defined in these process modules, especially the M&S-specific products *Structured Problem Description* (SPD), *Conceptual Model* (CM), *Formal Model* (FM) and *Executable Model* (EM) are considered as required (or obligatory) in the project plan so far. The same applies to the associated documentation and V&V activities.

Since the previous tailoring decisions are made according to the project-specific constraints identified at the beginning of the project, these adaptation efforts can be viewed as static tailoring. In addition to static tailoring, further modifications of the already determined work products, the work flows in the project execution strategy, the related documentation and V&V activities can be made in the course of the model development project. In this case, some adaptations with respect to the development of the work products FM and EM have to be conducted because of the application of the simulation environment “Virtools” [30].

Since the physically correct behaviors and interactions of all the objects considered in the simulation study have to be realized by means of the “Havocs Physics Engine” which is integrated in the simulation environment of Virtools, and its associated mechanisms are, however just like a black box, not available to the development team members, it becomes apparent at the time of this M&S phase that the platform independent Formal Model can not be created and the complete documentation of FM is also impossible according to the project constraints. In the model document of FM, the reasons for this tailoring decision need to be documented.

Similarly, the detailed impact of using this simulation tool on the development of the M&S product EM can be only identified in the course of the model development. In this project context, the source code of the training simulator is in large part automatically generated by the applied simulation tool. Only the software of the control system and user interface needs to be designed and implemented completely by the development team.

Based on the information obtained at this time, further tailoring decisions relating to the documentation at the subject (or topic) level can be made. Finally, as the result of this adaptation step, the documentation to be conducted for the work product EM includes only:

- description of the overall software and hardware systems involved in the training simulator;
- description of the proprietary development software, namely the control system and user interface.

5 Conclusion

Applying a well-structured and flexibly adaptable M&S process is an essential requirement for effectively developing simulation models and conducting their V&V. This work introduces a lightweight approach to adaptation of the German standard IT development process, the V-Modell XT, for conducting M&S projects. As the V-Modell does not specify some essential M&S-specific aspects, the related components in terms of model development, V&V and documentation are additionally defined and integrated in accordance with the basic structure of the V-Modell, without modifying any existing elements.

In addition, based on the M&S-specific extensions, a refined tailoring approach is presented, which facilitates the project-specific adaptation of model development, V&V and documentation at several levels. Furthermore, two different ways of tailoring − static tailoring and dynamic tailoring − are discussed. While static tailoring reaches a selection decision at the beginning of a project, additional modifications of selected products, activities and documents are subject to dynamic tailoring. The application of this multistage M&S-tailoring process is then demonstrated by a practical example.

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Verification and Validation for Simulation in Production and Logistics

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Verification and Validation (V&V) of simulation models and results are very important parts of discrete event simulation studies for production and logistics applications, as wrong or inadequate simulation results can have massive impact on strategic and investment-related decisions. The authors propose a procedure model for V&V that is applicable for simulation studies in this sector, based on a simulation procedure model that clearly defines the phases of the study and the results of each phase. This paper summarises the background of these procedure models, gives an overview on both models and then illustrates the elements of the V&V procedure model on selected examples, giving exemplary questions to be answered during the V&V and explaining the context of these questions in the framework of the procedure model.

Introduction

Discrete event simulation (DES) is an established analysis method for production and logistic systems. It is frequently used when decisions with high risks have to be taken, and the consequences of such decisions are not directly visible, or no suitable analytical solutions are available. This, however, implies that correctness and suitability of the simulation results are of utmost importance. Therefore, verification and validation (V&V) are highly relevant within simulation studies in this application domain.

According to the differentiation of the terms verification and validation in the literature, the authors associate verification with the question “Are we creating the X right?“ and validation with the question „Are we creating the right X?“ (cp. [1]). Verification does not prove the correctness of X, e.g. the data or the model, but the *correctness of the transformation* from one phase into another one. Validation in contrast aims to analyse the suitability of X related to the given task and the sufficiently accurate modelling of the system under consideration. For both – correctness and suitability – it is characteristic that they cannot be completely proven. Thus, the goal of V&V is not the complete and formal proof of the model validity, but the estimation of its credibility.

Only by a systematic approach and by structuring into single, directly usable sub-tasks with specific V&V techniques, V&V can be managed. Therefore, a procedure model is required that defines V&V-related activities for each single modelling step and its results.

1 Related work

There is a great amount of research efforts dedicated to procedure models, V&V, and simulation. The intention of this chapter is to give a short overview on some of literature in the field. However, at the beginning it is important to clarify the differences between simulation procedure models and V&V procedure models. A similar survey on procedure models can be found in [2], and a more detailed overview on such models is provided in [3].

1.1 Classes of related procedure models

In general, the related work on procedure models may be divided in two different classes: The first class contains *procedure models for simulation studies,* which to a different degree include elements for V&V. The second class of procedure models consists of *procedure models for V&V*. They are meant to support a professional handling of V&V activities within a simulation study, i.e. they describe V&V activities in detail and the relationship of these activities to the procedure model for the simulation study.

However, research on V&V is not limited to the application domain of simulation in production and logistics, which is the focus of this paper. For example, simulation in the military domain is an application area were procedure models for V&V are of high importance. Also, other scientific disciplines, e.g. management science and, especially, computer science, have developed procedure models covering V&V activities to a certain degree. There are approaches, e.g. the V-model XT mandatory for IT development processes for German federal engineering projects, with a large relevance for the development of simulation models.

1.2 Procedure models for simulation

Several procedure models for simulation have been published and can be found in textbooks (cp. [4, 5, 6]) as well as in guidelines (cp. [7, 8]). These models are quite heterogeneous in scope and level of complexity. However, they typically do have in common the following five elements which can be found in nearly all of the models:

- Initialisation phase, defining the task and its feasibility
- Plan for tackling the task
- Detailed model design, including the actual computer code
- Testing
- Operation and maintenance

The cited models cover V&V activities within the proposed procedure to a very different extent. What they again do have in common, though, is that they typically name V&V as an essential part of the procedure without giving clear indications on how to perform V&V activities.

1.3 Procedure models for V&V in the simulation domain

The main purpose of procedure models for V&V is to support the performance of a professional V&V process. This requires a consistent procedure that is related to a procedure model for simulation.

In the literature, papers on V&V procedure models as well as on V&V techniques can be found. V&V techniques are not in the focus of this paper. A very broad overview on techniques is given in [9]. The use of the techniques in different phases of the simulation study is outlined in [10] and [3].

The General Accounting Office of the US Government provided an approach that names criteria for V&V such as documentation, theoretical validity (concerning the validity of the conceptual model), data validity, operational validity (concerning the validity of the executable model), model verification, ease of maintenance, and usability [8].

The US Department of Defense (DoD) with its Defense Modelling and Simulation Office (DMSO) considers the V&V process to be part of a general problem solving approach, comprising a procedure model for simulation as well as a process for accreditation [11]. Additionally, [12] recommends good practices as a guideline for each process element. In the defense domain in Europe similar research towards a generic V&V process can be found. In the year 2004, first efforts have been started to harmonise these approaches, internationally [13].

The procedure model presented in the remainder of this paper has been significantly influenced by the work of Brade [14], who defined a stepwise procedure for the V&V of models and simulation results. It is based on a simulation procedure which leads to explicit intermediate results for each phase as input for the next phase. Following Brade's approach, the result of a phase needs to be checked intrinsically, with respect to the directly preceding phase, and also with respect to *all* preceding phases. The number of checks grows with each phase of the modelling process.

Some more recent papers acknowledge the role of data for simulation applications by emphasising the specific importance of data validity. Skoogh and Johansson [15] present a methodology for input data management including some aspects on data validation. Wang and Lehmann [16] propose an extension of Brade's V&V triangle by explicitly covering data validation.

Comparing the approaches discussed in this subsection, it becomes obvious that focus and level of detail are very different. The DMSO for example is rather proposing a general procedure for the V&V process. Other models suggest more specific procedures, however, differing in scope and content. The models do have in common, though, that they were not specifically designed for applications in production and logistics.

1.4 Models related to V&V from other domains

Simulation in production and logistics covers aspects of operations research, mathematics, statistics, computer science, and engineering. Most of these disciplines consider to some extent verification and validation of their applications, techniques, or models. Thus, for an interdisciplinary research field like simulation in production and logistics it is necessary to analyse the results of these domains, too.

Examples of V&V in *Operations Research* can be found in Landry und Oral [17], which show large similarities with the procedure models given above. In *Computer Science*, Bel Haj Saad et al. [18] propose an extension of procedure models used in software engineering, thus enabling their application for simulation purposes. A broad discussion of V&V in other disciplines can be found in [3].

1.5 Conclusions from related work

The comparison of the summarised procedure models shows some similarities, but also significant differences. There is a similar set of basic steps in each procedure model for simulation and V&V typically is included as a necessary activity, e.g. as one of the steps. However, the consideration of V&V ranges from just naming its relevance to detailed procedure models. The idea behind this paper is that verification and validation are essential parts of a simulation project from its very start until completion. This conviction leads to the three basic requirements for a valid procedure model for V&V:

- A simulation procedure model, defining the phases of a simulation study as reference points needs to be formulated.
- The results of the specific phases of the simulation procedure model ("Phase Results") need to be defined.
- An explicit V&V procedure model that supports the execution of V&V needs to be stated.

Accordingly, Chapter 2 firstly defines a simulation procedure model with the Phase Results. Then, a V&V procedure model is defined in Chapter 3 and its elements are illustrated in Chapter 4.

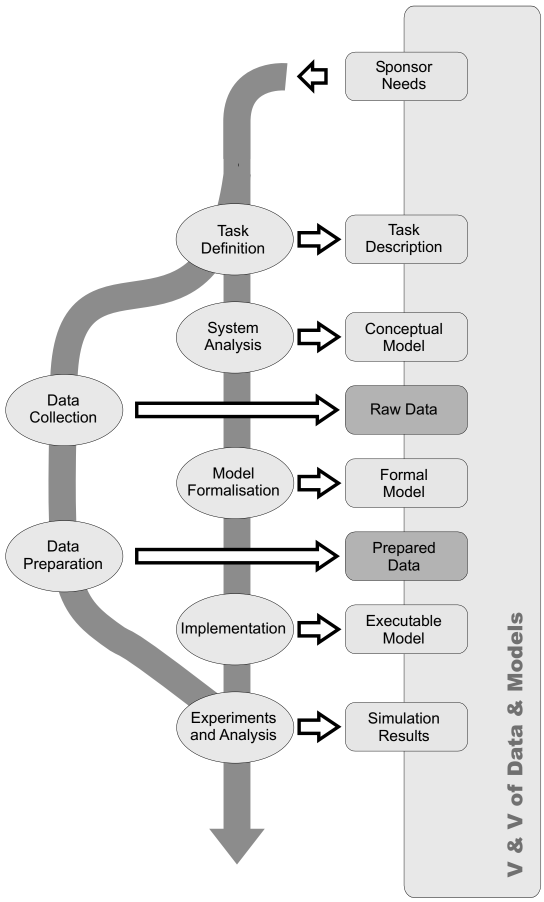

Figure 1. Procedure model for simulation incl. V&V [3].

2 Procedure model of simulation with V&V

In order to be able to propose a procedure for V&V, it is necessary to understand the role of V&V within the procedure that is applied for simulation. The authors propose a suitable procedure model for simulation including V&V (Figure 1), based on a guideline of the German engineers' association VDI [8].

Starting from the Sponsor Needs, this procedure model considers only tasks that normally occur after the acceptance of the task and cost plan for a simulation study, not distinguishing between external and internal service providers. Therefore, the proposed procedure starts with the Task Definition, which is considered to be the first analysis step within a simulation study. The procedure model is characterised by the stringent definition of intermediate results, and separate paths for models and data. The model path is structured into Task Definition, System Analysis, Model Formalisation, Implementation, and finally Experiments and Analysis (ellipses in Fig. 1). A Phase Result is assigned to each phase (rectangles in Fig. 1). Phase Results can be models, documents, or a combination of both. In the following, for simplification the term document is used for the Phase Results in general. The document *Sponsor Needs* is no Phase Result, but the base for starting the simulation study.

According to the importance of the Phase Results, the authors recommend a generic document structure for each of the Phase Results [3, summarised in 2].

The phases Data Collection and Data Preparation (with the results Raw Data and Prepared Data) are deliberately defined in a second path, as they can be handled in parallel with respect to content, time, and involved persons. Therefore, the position of Raw Data in Figure 1 does not indicate that they can only become available after the Conceptual Model. Raw Data does not need to be completely collected before the elaboration of the Formal Model. The same applies to the Prepared Data, analogously. The procedure model just defines that Data Preparation requires Data Collection to be done, and that for the use of the Executable Model the Prepared Data have to be available.

As V&V has to be conducted during all phases of the modelling process, V&V – both of the data and the models – is arranged along the whole simulation study (see the rectangle on the right of Fig. 1). Even the document Sponsor Needs, whose development is not subject of the simulation study, should be validated before starting the Task Definition, with respect to consistency and completeness in terms of the major topics to be covered.

Thus, V&V is not at all a task that is conducted at the end of a study. In particular, it should never be considered as a procedure that is iterated after the implementation until the model seems to operate correctly. In contrast, V&V has to accompany the simulation study from the start until the very end, and specific V&V activities are indispensable within each single phase of the modelling process.

3 Procedure model for V&V

Based on the procedure model for simulation in production and logistics including V&V (Figure 1), the procedure for V&V itself can be defined. The considerations in the previous chapter already imply that this procedure model for V&V must support all phases of the simulation procedure model. In addition, the procedure model should list and structure the single steps that are necessary for V&V, and provide guidelines for the execution of these steps.

In general, at each point of time during a simulation study all documents and models can be analysed with respect to all other documents and models that have previously been created. However, in most cases this approach will be neither acceptable in terms of time consumption, nor economically feasible. On the other hand, the execution of activities for V&V just "by accident" can never be acceptable. For a systematic procedure it is essential that a dedicated decision procedure is applied to identify those activities that are necessary and economically reasonable for the specific project. For this purpose, a V&V *Procedure Model* is required. This procedure model can be used to establish and monitor process quality at the simulation service provider itself as well as for the communication between the service provider and the customer. In the latter case, it can be used as a common guideline. The scope and the level of detail of this procedure model need to be adapted to specific modelling constraints, in order to achieve an efficient and pragmatic application.

3.1 Systematic of the V&V Procedure Model

The V&V Procedure Model proposed by the authors is shown in Figure 2. It takes into account the principles given by the simulation procedure (Fig. 1). Therefore, it is separated into two major sections representing the model path and the data path. The lower part of the procedure model relates to data collection and preparation; the upper part relates to modelling and simulation. Thus, the eight rows of the V&V Procedure Model represent the results of the phases defined by the simulation procedure model.

In order to conveniently refer to the Phase Results, they are enumerated from 1 (Sponsor Needs) to 6 (Simulation Results).

The results with respect to data cannot be clearly related to the modelling phases, as explained above. In order to avoid any misinterpretation, they are not characterised by numbers. Instead, the letters "R" (Raw Data) and "P" (Prepared Data) are assigned to these documents.

Each row of the V&V Procedure Model consists of *V&V Elements*, which are depicted as rectangles. The V&V Elements comprise a set of possible *V&V Activities*. In order to establish a unique relation to the V&V procedure, each V&V Element is denoted by two indices:

- The first index defines the Phase Result which is validated by the activities of this V&V Element
- The second index defines the Phase Result which is used as the reference for the V&V with respect to this V&V Element

3.2 Classification of V&V Elements

The circle in some of the V&V Elements given in Figure 2 stands for an intrinsic test, i.e. the document is analysed with respect to itself, and only to itself. Such *Intrinsic V&V Elements* always have an index with two identical digits (or letters), as both the first and the second index indicate the same Phase Result.

A simple arrow indicates the test of a Phase Result with respect to the results of a previous phase. For example, the simple arrow in element (3,2) stands for the reference from the Conceptual Model to the Task Description, asking if the requirements defined by the latter document are correctly mirrored by this Conceptual Model. The arrow indicates the direction of this relation.

The third type of V&V Elements provides a relationship between the Phase Results of modelling phases and the results of data collection and preparation. Therefore, these elements are indexed by one letter and one digit, and represent tests in combination of both documents. As the modelling and the data collection and preparation phases of the simulation process model are to a certain degree independent, the test of a data document *against* a modelling document or vice versa do not appear to be an appropriate description. None of the documents can be fully derived from the others, even if this can be the case for some parts of the documents. Therefore, there is no direction of the relationship, and the element is indicated by a double-sided arrow.

The last type of V&V Elements, which is marked by a triangle, stands again for the test of one Phase Result (of the modelling phases) to another one. But, for the tests of this fourth type the availability of the Prepared Data is a precondition, and the test is conducted using these Prepared Data. Negative results can have their roots in any of the three Phase Results used for the test. This type of V&V Element is applicable only in the two last phases (Implementation as well as Experiments and Analysis).

3.3 V&V Documentation

The results of the V&V Activities conducted for each V&V Element have to be carefully documented as this is the only way to review the validation activities at a later point in time. This leads to a set of reports for each phase of the simulation study, which can be used for detailed credibility assessment of the simulation study. In addition, these reports might be exploited in case of a change in the targets of the simulation study, in order to decide if the model is valid for the modified Task Description. Similar to further accompanying documents (proposals, project plans, meeting minutes, decisions on assumptions, status reports) these reports can be related to the Phase Results according to Figure 2.

4 V&V Elements

In this section, the V&V Procedure Model will be illustrated using seven V&V Elements as examples. The examples have been selected in order to cover all the classes of elements defined in section 3.2. For all these elements, key issues are briefly explained and typical questions given, starting with two intrinsic elements.

The questions for the V&V Element (1,1) check whether the documentation is complete, consistent, accurate and currently valid, e. g., whether the document Sponsor Needs comprises all sections of the proposed document structure and whether the given requirements are free of contradictions (Figure 3). Other questions check whether the described solution approach and methods as well as the project objectives sufficiently fulfil the intended purpose of the study. Additionally, some of the questions are meant to prove that the project plan is free of contradictions and the specification of the project scope is reasonably justified. Important questions relate to the feasibility of the specified Sponsor Needs with regard to

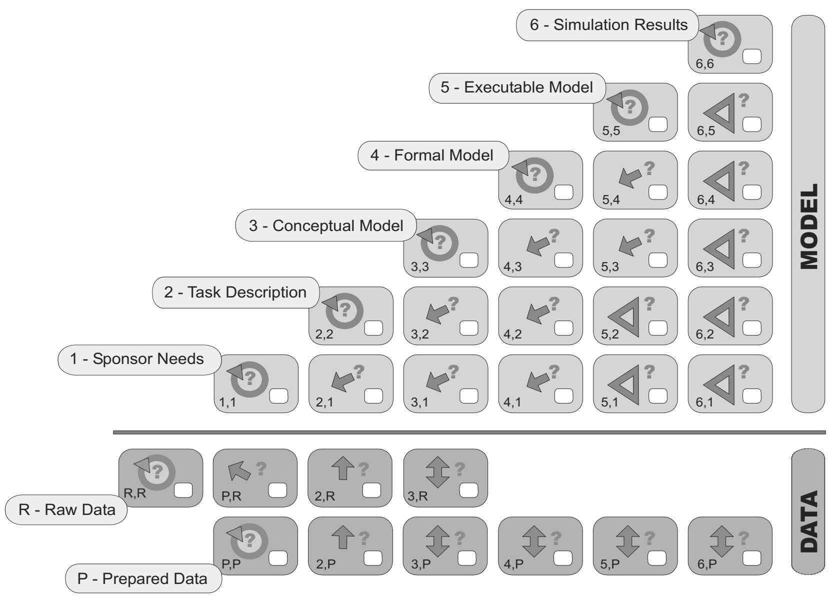

Figure 2. Procedure model for V&V of simulation in production and logistics applications (cp. Rabe et al. 2008).

- Do the Sponsor Needs comprise all bullet points mentioned in the document structure?
- Are good reasons given in case of omitted bullet points?
- Are the indicated system variants sufficient for the intended purpose of the study?
- Are the given simulation study requirements free of contradictions?
- Are the given system variants to be examined free of contradictions?
- Will the expected results serve the intended purpose of the study?
- Does the planned use of the model match the problem definition?
- Is the specified scope of the project reasonably justified?
- Is the solution approach comprehensible and free of contradictions?
- Can the described situation at the sponsor, the preconditions and the study goals be confirmed?
- Do problem definition and study goals indicate which solution method should be selected and whether simulation is an adequate method?
- Are the tasks to be contributed by other departments or external partners defined in a clear and reasonable way?
- Is the conduction of the project possible under the given organisational, financial and technical constraints?
- Are the buy-off criteria for the successful execution of the project described clearly?

Figure 3. Questions for V&V Element (1,1).

- Is the documentation complete?
- Are the data available in accordance with the Raw Data document?
- Is a process in place to ensure that the data acquisition is repeatable?
- Are standards and specifications of the IT department taken into account (e.g. interface specifications)?
- Has the data acquisition been performed completely and accurately according to the given specifications?
- Have the data been checked for measuring errors?
- Are the specifications for consistency fulfilled on entity type and entity level?
- Are the attributes within the given ranges?

Figure 4. Questions for V&V Element (R,R).

the given organisational, financial and technical constraints as well as the complexity of the task and the scope of the system.

Some of the questions for the V&V Element (R,R) are meant to check organisational issues such as the existence of a process for repeated data acquisition or the handling of regulations possibly imposed by an IT department (Fig. 4). As with all V&V Elements, the completeness of the documentation needs to be verified. Specifically for intrinsic data validations, questions about data availability, data completeness, data accuracy as well as consistency need to be answered.

- Are all system components with their characteristics and relations represented in the Conceptual Model in an appropriate way?
- If system components or relations are omitted, is this sufficiently justified?
- Does the Conceptual Model take the system interfaces into account as given by the Task Description?
- Are all assumptions given by the Task Description transformed into the Conceptual Model?
- Does the Conceptual Model contain explicit or implicit assumptions, which are in conflict with the Task Description?
- Does the Conceptual Model take into account all organisational system data (e.g. shift models) or system load descriptions (e.g. seasonal fluctuations) that are relevant according to the Task Description?
- Are the control rules specified in the Task Description taken into account in the Conceptual Model, and are their relationships defined?
- Is there a suitable variant in the Conceptual Model for each system variant required according to the Task Description?
- Can the output values required by the Task Description be determined on the basis of the Conceptual Model?
- Does the Conceptual Model represent the goals defined in the Task Description appropriately in scope and level of detail?
- Is it comprehensible that the indicators (e.g. for model acceptance or result evaluation) can be computed by the simulation model?
- Does the model structure specified in the Conceptual Model support the allocation of tasks as specified by the Task Description (e.g. distributed modelling)?
- Does the Conceptual Model take into account the modelling constraints as given by the Task Description (libraries, modelling conventions)?
- Does the Conceptual Model permit the variation of parameters and - if necessary - of structures according to the project goals and the requirements of the experimental design?
- Are the period of use, the users, their qualification and the kind of the use taken into account as requirements in the Conceptual Model?
- Are there elements specified in the Task Description that should be re-used? Are these recognisable and described as re-usable within the Conceptual Model?
- Is it conceivable that the run time of the simulation model will be in the desired range as given by the Task Description
- Are the solution methods that should be applied defined in the Conceptual Model and does their use seem to be plausible?

Figure 5. Questions for V&V Element (3,2).

For the V&V Element (3,2) the V&V of the documentation of the Task Description as well as the description of the planned or real production or logistics system is part of the V&V investigation (Figure 5). The element is meant to check the Conceptual Model with respect to the task specified in the Task Description, the planned use of the model, the defined solution approach and the model requirements. Therefore, questions concern whether all specified processes and structures, system elements and structuring requirements as well as organisational and system load specifications are adequately considered. Also, the level of detail and the specified output values have to be checked taking into consideration the problem definition and the system as given.

Complementing the V&V Element (3,2), the V&V Element (3,1) validates the adequate consideration of the intended goals and constraints described in the Sponsor Needs within the Conceptual Model (Figure 6). Therefore, V&V questions check whether the external partners named in the Sponsor Needs are involved in designing the Conceptual Model and whether the functionality of the system is taken into account as given in the Sponsor Needs. If there are any substantial differences these have to be justified as well. However, the most important validation aspect is the applicability of the Conceptual Model, which has to be checked by different questions. It has to be made sure that the Conceptual Model is specified adequately for the intended model application, i.e., that the Conceptual Model represents the Sponsor Needs appropriately in scope and level of detail and that the specified output values and measuring points are appropriate to achieve the kind of results requested in the Sponsor Needs.

- Are the external partners named in the Sponsor Needs involved in designing and aligning the Conceptual Model?
- Is the Conceptual Model agreed upon with the sponsor concerning goal and purpose of the simulation study?
- Is the functionality of the system taken into account as given in the Sponsor Needs, including the system's processes and structures?
- Are the system interfaces taken into account as given in the Sponsor Needs?
- Are the specified output values, analysis approaches and measurement points appropriate to achieve the kind of results requested in the Sponsor Needs?
- Do the problem definition and the purpose of the study suggest a re-use of model parts? If so, is this accordingly covered by the Conceptual Model?
- Does the design of the Conceptual Model lead to implicit assumptions, which are in contradiction to the Sponsor Needs?
- Does the Conceptual Model represent the Sponsor Needs appropriately in scope and level of detail?
- Is it comprehensible how the different kinds of results expected according to the Sponsor Needs are going to be generated by the model?
- Are variable parameters specified as such? Are their impacts comprehensible? Do they help to achieve the simulation goals?
- Are all described system variants specified in the Conceptual Model? Can the simulation goals be achieved with the intended model variants?
- Are the Conceptual Model and the simulation model implementation specified therein adequate for the intended model usage?
- Is it conceivable that the run time of the simulation model will be in the desired range?
- Is it conceivable that the buy-off criteria will be fulfilled?

Figure 6. Questions for V&V Element (3,1).

The Conceptual Model as well as the documentation on Prepared Data comprises information about data structures and attributes. Hence, the V&V Element (3,A) asks for consistency of the two specifications (Figure 7). Additionally, it is intended to ensure that the data required according to the descriptions in the Conceptual Model are available and at an appropriate level of detail. Also, (qualitative) estimates of the expected model performance should be done. The question on data preparation during runtime also strives to preserve computational performance. To conclude with, data at system's interfaces and data not explicitly required by the Conceptual Model should be investigated more closely.

- Do structure and attributes of the data specified in the Conceptual Model and the Prepared Data match?
- Are the data available that are required to set the parameters for the model elements?
- Is the granularity of the data sufficient with respect to the level of detail of the Conceptual Model?
- If a preparation of data is required that is not specified in the Conceptual Model: What are the reasons?
- Are the data that are necessary at the system interfaces available in accordance with the Conceptual Model (scope, level of detail)?
- If the Conceptual Model specifies data preparation at runtime, why can this preparation not be done in advance (independently from the model)?
- Given the level of detail of the Conceptual Model and the expected amount of Prepared Data: Can a satisfying performance of the model be expected?

Figure 7. Questions for V&V Element (3,A).

The V&V Element (5,2) validates the Executable Model against the Task Description using to a certain extend Prepared Data (Figure 8). The Task Description contains specifications on issues such as system components with their features and relations, control rules, visualisation and required output. Part of the V&V Element (5,2) is to check whether these specifications are met by the Executable Model. While these checks are rather a matter of completeness, some more complex assessments need to be made with respect to the overall model behaviour: core questions are whether the level of detail of the Executable Model matches the Task Description's requirements and whether the Executable Model may be considered as an appropriate representation of the subject given in the Task Description. Additional considerations in this context are the features of the implemented interfaces, the overall structure of the Executable Model, and the completeness of the computed output values, all in comparison with the information in the Task Description. Furthermore, some more formal or technical aspects have to be verified: possible modelling guidelines must have been observed, the simulation software package needs to be compliant with the requirements as well as other hard- or software. Other V&V steps in this element analyse possible additional assumptions made during the modelling process against the Task Description. Finally, the model runtime needs to be studied using the Executable Model together with some Prepared Data and it has to be made sure that all indicators needed for a possible buy-off process are calculated.

- Can all system components with their features and relations be found in the Executable Model?
- Can the control rules and mechanisms given in the Task Description be clearly identified within the Executable Model and are they understandable?
- Does the Executable Model comprise additional assumptions with respect to those given in the Formal Model, and are these assumptions acceptable with respect to the Task Description?
- Are the elements that are visualised in the Executable Model in line with the Task Description?
- Is the required presentation of the output provided (e.g. 3D-Animation)?
- Are all modelling guidelines maintained (libraries, naming conventions)?
- Does the used simulation software fulfill the requirements given in the Task Description?
- Is the specified hard- and software used in compliance with all given restrictions?
- Does the level of detail of the Executable Model match the Task Description?
- Is the impact of parameters and structures as given in the Task Description?
- Do all interfaces provide the specified functionalities?
- Does the executable model reflect all model structuring requirements?
- Is it possible to compute all specified output values with the Executable Model?
- Are all indicators calculated that are necessary for the buy-off criteria specified in the Task Description?
- Does the Executable Model represent the Task Description appropriately in scope and level of detail?
- Is the model run time in line with the Task Description?

Figure 8. Questions for V&V Element (5,2).

The V&V Element (6,2) validates Simulation Results against the Task Description and here again Prepared Data are necessary (Figure 9). A very general and generic test is the comparison of all requirements for experiment and presentation with the available results. More in detail, the compliance of the input parameters and the experimental design with the Task Descriptions needs to be checked. Closely related is the verification whether the Prepared Data named in the experimental design are in line with the Task Description. Specific aspects such as the simulation period need to be verified. Also part of this V&V Element is to validate that all output values are consistent with the Task Description and that all specified system variants can be analysed. At the very heart of this V&V Element is the consideration of the Simulation Results with respect to the overall purpose of the simulation study and the satisfaction of possibly given buy-off criteria. Last but not least, the Simulation Results are only of value for the stakeholder of the simulation study if they are presented and documented in an appropriate, comprehensible and clear manner.

5 Conclusions and Outlook

The quality-oriented application of simulation in production and logistics tasks requires that the sig-

- Have all requirements for the experimentation and for the presentation of the results been taken into account?
- Are the Prepared Data that are required according to the experimental design in line with the Task Description?
- Are the input parameters in the experimental design and in the simulation model in compliance with the Task Description?
- Does the simulation period match the Task Description?
- Are the output values in line with the requirements according to the Task Description?
- Are the simulation results suitable according to the purpose of the simulation study given in the Task Description?
- Is it possible to analyse all specified system variants?
- Do the results satisfy the buy-off criteria defined in the Task Description?
- Are the simulation results presented appropriately for the target group and documented in an understandable and clear manner?

Figure 9. Questions for V&V Element (6,2).

nificance of V&V is acknowledged, and the related activities are budgeted as an important part of the simulation study. In joint efforts, the members of the project team have to assure that models are sufficiently accurate, that the estimation of their credibility can be re-assessed at any time, and that the V&V activities are defined, systematically. Therefore, this paper proposes a well-structured procedure model, which increases the probability to recognise (early) if the task description, models, or result analysis could lead to invalid conclusions, and structures the steps to be done for V&V, thus providing the possibility to prove all activities at any later point of time.

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Efficient Validation of Process-based Simulation Models

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Validation is often time-consuming for simulation models of complex systems especially if failures indicating discrepancies between the system and the corresponding model occur rarely. Some failure types can be detected on the basis of the model's structure employing corresponding efficient techniques. In this paper we present some techniques used in the Collaborative Research Centre 559 ("Modelling of Large Logistics Networks") for the validation of process-based simulation models. These techniques are based on efficient algorithms from the Petri net area, but details are completely hidden from the end user by means of a corresponding toolset. Here we present some internals showing how specific aspects of simulation models can be validated efficiently.

Introduction

Building simulation models of complex systems is a non-trivial task. On the one hand the modeler has to abstract from several details, on the other hand he needs to capture those characteristics of the system which are relevant for the analysis objective. The task even gets more difficult if not fully automated systems being influenced by human decisions and interactions have to be modelled. The main problem is that a simulator is usually a computer program which runs fully automated so that human influence must be captured by rules readable by machines. In the course of the Collaborative Research Centre 559 "Modelling of Large Logistics Networks" (CRC 559; [1, 2]) we made the experience that during the construction of a simulation model several interim versions of the model do not correctly reflect the system behaviour. We found that various discrepancies between the system and the model can be discovered by investigating functional properties [1, 3, 4]. An example is the occurrence of (partial) deadlocks in the simulation model which do not appear in the real system. Especially in models of logistics systems such functional deficits/failures are based on an incorrect modelling for example of human behaviour. A case in point is the well-known concurrent use of a limited number of resources, which are allocated one by one and are only released after having been used (e.g. think of a truck driver who needs a forklift and a free ramp for unloading). The resultant deadlocks are well-known effects in fully automated systems and corresponding simulation models, but normally do not happen in humanly controlled systems.

Certainly, there are several methods for the validation of simulation models (e.g. [5, 6]), but they are often based on the inspection of simulator executions which is time-consuming for large models and in particular if the functional deficits occur rarely. One could think that such rare events can be neglected, since an experienced modeller will detect them in case they really happen, but there are situations where such deficits will go unnoticed. E.g., if faulty simulation models are used in optimisation procedures [7] "optimal" areas might remain undiscovered or, e.g., if (parts of) the simulation models are used as a basis for automated code generation of system control programs the functional deficits are carried over to the real system. In a nutshell, it seems advisable to eliminate such functional deficits from the model.

As mentioned, the usual testing of simulation models is time-consuming concerning the detection of rarely occurring failures, but some failure types can be detected by inspecting the model's structure which can be done efficiently. In this paper we present corresponding techniques which help to validate simulation models with respect to failure types concerning boundedness, liveness and ergodicity of the simulation model. As a base model world we use the process-based model world ProC/B, which has been used within the CRC 559 for the modelling of logistics systems [8]. ProC/B is a modelling language associated with a toolset (cf. Figure 1) which performs validation and simulation of models at the push of a button and hides analysis-specific details from the end user [8, 9]. Here we will look behind the scenes. The detection of functional deficits in ProC/B models is done by mapping those models to Petri nets (PN) keeping essential characteristics [3, 4]. Petri nets [10] are distinguished by very efficient algorithms for checking functional properties and we show how these algorithms can be employed for the validation of ProC/B simulation models.

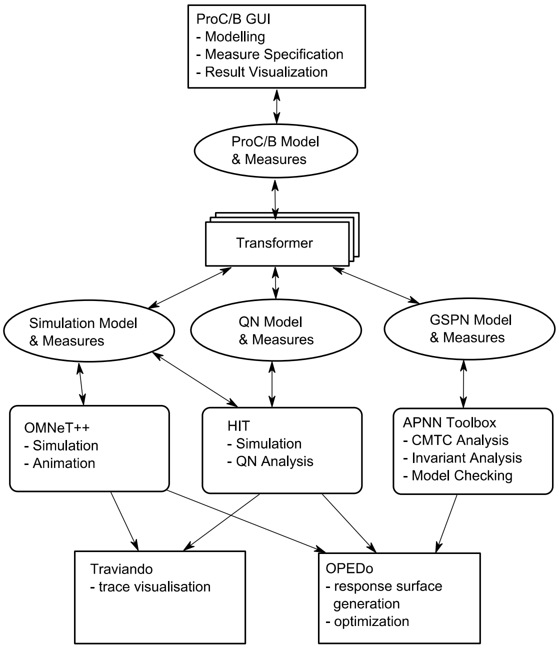

Figure 1. ProC/B Toolset.

This paper is organised as follows: In the next section we briefly introduce the ProC/B model world followed by the main section (Section 2) of this paper where we present an efficient procedure for the validation of ProC/B models. After discussing the general approach we describe the validation in detail with respect to three functional properties: boundedness, liveness and ergodicity. The paper ends with the conclusions in Section 3.

1 ProC/B

Process chains are established for the modelling of logistics networks and also have been the core paradigm within the CRC 559 [11, 12]. ProC/B is a formalization of a subset of this paradigm and was developed with the intention to support an automated analysis of corresponding models accentuating performance aspects. The philosophy of ProC/B is to describe system behaviour by process chains and system structure by functional units. Figure 2 and Figure **3** present a typical example of a ProC/B model [3]. The model is hierarchical and represents a freight village. The top level of the model is shown in Figure **2** where the behaviour of two process types (trucks and trains) is described by corresponding process chains. A process chain consists of several activities modelled by so-called process chain elements (PCEs). A PCE might specify amongst others a pure delay of the process or the call of a service. Services

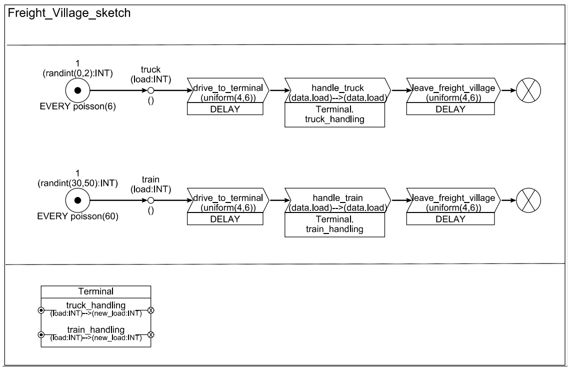

Figure 2. Freight village example.

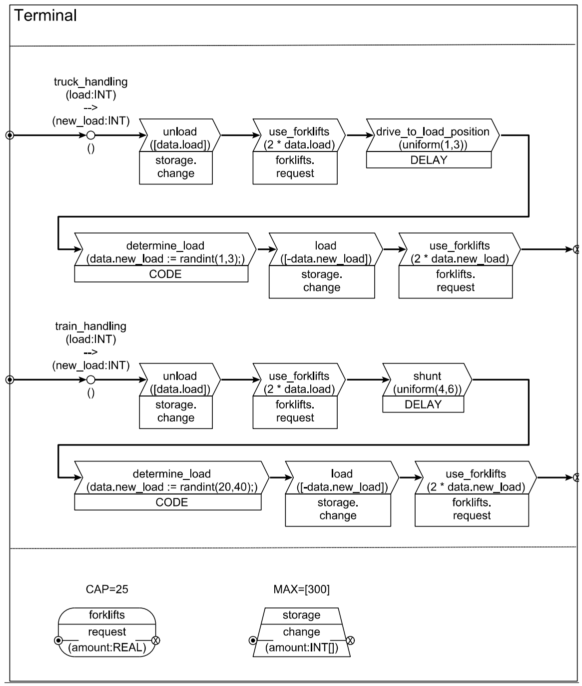

Figure 3. Internals of Function Unit *Terminal***.**

are offered by functional units (FUs) and are described again by process chains whose activities might use services offered by other internal FUs. Figure 3 displays the internals of the FU Terminal whose services are used by trucks and trains (cf. Figure 2). The hierarchical description ends at predefined, so-called standard functional units (cf. Figure 3). ProC/B models might contain two types of standard FUs: servers and counters. Servers (see forklifts in Figure 3) model timing aspects and their behaviour is similar to that of queues in a queuing network. Counters (see storage in Figure 3) model space and a request to a counter is immediately granted if the result respects upper and lower bounds, otherwise the calling process gets blocked until the

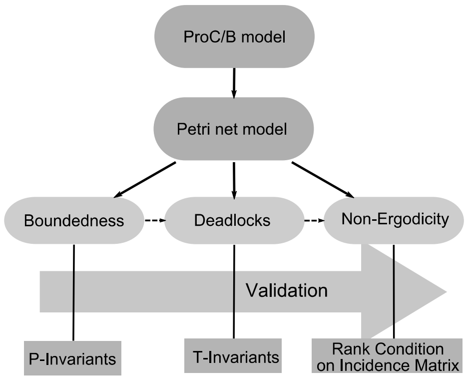

Figure 5. PN techniques for the validation of ProC/B models.

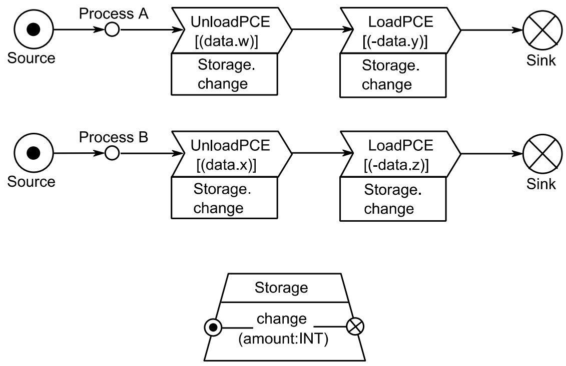

Figure 4. Two processes supplying a storage.

change becomes possible. For more details on ProC/B and this specific example we refer the reader to [3] and [8]. As one can imagine ProC/B offers the possibility to describe systems such precisely that an automated analysis is possible.

The modelling and analysis of ProC/B models is accompanied by a toolset which offers a graphical user interface for description and several analysis modules (see Figure 1). Analysis is done by transforming the model specification to the input languages of other tools thus using their analysis capabilities. One such transformation concerns a mapping of ProC/B models to Petri nets. Since an exact mapping would be too complex, only those parts of Proc/B models are captured by the mapping which are primarily relevant for the analysis objectives. E.g., most variables occurring in the ProC/B model are ignored for the transformation, but synchronisation constructs are considered. Therefore, the output of the analysis algorithms might result in so-called non-faults, i.e. faults which hold for the Petri net, but are not occurring in the ProC/B model. Nevertheless such faults or their absence hint at non-validity or validity of the ProC/B model.

2 Validation of ProC/B Models

ProC/B was developed with user-friendliness in mind. It can be used by non-experts to form even complex models of logistics networks and their working processes. Surely with increasing complexity of the model also the possibility of errors in the model increases and appropriate support is needed. The ProC/B Toolkit features several techniques for the validation of models. The methods we present in the following do not intend to check, e.g., whether an accurate representation of input data has been chosen, but try to support a plausibility check for the model internals.

2.1 General Approach

Validation of ProC/B models is here based on a transformation from process chains to Petri nets. Figure 5 shows how validation is performed: An existing ProC/B model is converted to a Petri net model. The new representation is used for validation with respect to Petri net properties. In particular support is offered for checking boundedness, identifying deadlocks and searching for non-ergodic behaviour. The applied techniques are completely hidden from the user, so no knowledge on Petri nets or any functional property is required. The first step in the validation process is to transform the ProC/B model to a Petri net representation. For each language element there is a blueprint of PN parts to be placed instead of the original element. For example, Figure 4 is the original ProC/B model of a typical stock-keeping scenario. The corresponding Petri net is shown in Figure 6.

Details on the transformation can be found in [3, 4, 8]. Petri nets, originally introduced by Carl Adam Petri [13], are a formalism for the description of concurrency and synchronisation aspects in systems [10]. They describe behaviour of systems by the states that can occur, but usually neglect timing aspects, although variants of Petri nets exist which also consider time (see e.g. [14]). A common variant of Petri nets are so-called Place-Transition nets. A Place-Transition net is a five-tuple $P = (P, T, C^+, C^-, m_0)$ which can be interpreted as a graph containing two different types of nodes: places P and transitions T. Connections are defined by two incidence matrices: backward incidence matrix $C^- = \left(c_{ij}^-\right) \in \mathbb{N}_0^{|P|\times|T|}$ and forward incidence matrix $C^+ = \left(c_{ij}^+\right) \in \mathbb{N}_0^{|P|\times|T|}$. If $c_{ij}^- > 0$ an arc with weight c_{ij}^- leads from place i to transition j. Similarly, element c_{ij}^+ gives the weight of an arc from transition j to place i.

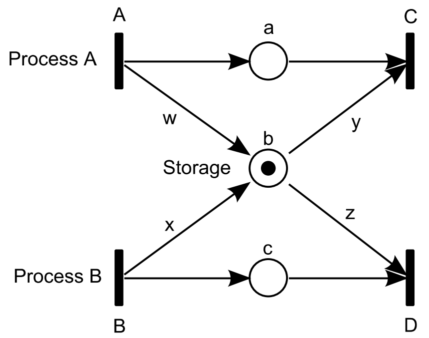

Figure 6. Petri net representing two process chains and one storage.

Places are initially marked with the contents of the positive vector $m_0 \in \mathbb{N}^{|P|}$. A graphical representation of Petri nets uses circles for places and bars for transitions. The positive elements of the incidence matrices are shown as directed arrows given a weight. The marking $m(p)$ of a place $p \in P$ can be seen as tokens placed on the place as solid dots.

Enabled transitions change the marking of places that are connected by arcs via "firing". Transition j is enabled in marking m if there are enough tokens available on input places: $m \geq C^- \cdot e_j$ with e_j as the j-th unit vector. Firing transition t will destroy $C^- \cdot e_j$ tokens from all input places and generate $C^+ \cdot e_j$ tokens on the output places.

Figure 6 shows the Petri net derived from the storage system in Figure 4. It contains four transitions A-D and three places a, b and c. Transition A has two outgoing arcs, while place b has two incoming and two outgoing arcs. There are arcs with weights $w - z$, specifying that adjacent transitions produce or consume multiple tokens per firing. In a concrete ProC/B model w-z will be concrete values, but we will keep the notation with variables in the following to consider different modelling failures. In case the model specifies stocked or removed storage units by random variables, average or user specified values will be used in the Petri net representation.

Markings are central in Petri net theory as they express the state of the net. One goal of Petri net analysis is to check whether unwanted markings can be reached. The set of all reachable markings is given by the initial marking m_0 and the firing rule specifies which markings can be reached from a given marking by firing transitions. The total effect firing transitions have on the marking is described by the incidence matrix

$$C = C^+ - C^-$$

For example, the incidence matrix C of the storage system can be written as:

$$C = \begin{bmatrix} 1 & 0 & -1 & 0 \\ w & x & -y & -z \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

The effect of firing transition t_j at marking m is given by the j-th column of matrix C and can simply be calculated as follows. Let e_j denote the j-th unit vector. Then the product $C \cdot e_j$ gives the j-th column, so that the successor m' of a marking m can be calculated by

$$m' = m + C \cdot e_j$$

Since for every reachable marking there exists a firing sequence of transitions, the corresponding unit vectors can be subsumed in a linear combination $\bar{q}$ (Parikh vector [15]).

Thus the state equation of a Petri net with initial marking m_0, firing vector $\bar{q}$ and incidence matrix C can be written as

$$m = m_0 + C \cdot \bar{q}$$

Some very efficient Petri net analysis techniques are based on the investigation of this incidence matrix C. For example, the state equation gives us a necessary condition whether a marking m_f related to an unwanted model state can be reached. E. g., setting $\bar{q} = x, m = m_f$ gives

$$C \cdot x = m_f - m_0$$

and if no positive integer solution for x exists then m_f can not be reached from the initial marking m_0.

Another option for Petri net analysis are reachability graphs. Reachability graphs have markings as nodes and two nodes m and m' are connected with a directed arc labeled t if marking m' is reachable by firing transition $t \in T$ enabled in m. A reachability graph can be constructed by generating the reachability set $RS(PN, m_0)$ starting at initial marking m_0 as the root node and adding reachable markings as leaves for each enabled transition. This step is repeated at the leaves and the resulting tree is later simplified to a graph $RG(PN, m_0)$ by merging equivalent nodes. Usually properties of a Petri net are defined on the basis of the reachability graph/set, so that its generation is a common option for analysis in case the set is finite which means that the Petri net is bounded (cf. Section 2.2). The main problem is that even simple Petri nets can have large reachability graphs/sets and their handling would require a lot of memory and CPU time.

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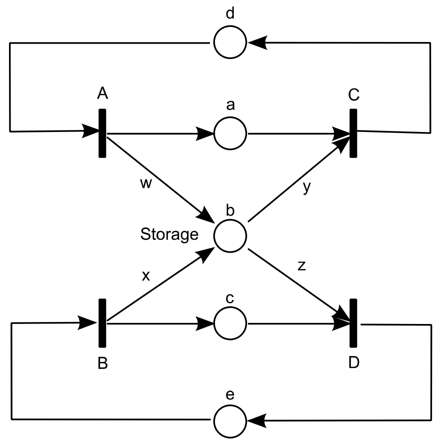

Figure 7. Modified Petri net PN_C.

Petri net theory also offers other analysis methods that can be chosen according to the actual requirements and area of application. The following two properties are checked with a very prominent technique based on the inspection of the structure of the Petri net, namely invariant analysis.

2.2 Boundedness

Boundedness is a property of Petri nets useful to test models of production and storage systems.

In the logistics model world, a bounded system will output the same number of goods as the number of goods entering it (or for manufacturing systems: be at least in a fixed relation). Several types of errors can occur when this property is not satisfied: imagine the model is faulty in the way that goods are not removed when they are accomplished. Concerning Figure 6 this might happen if $w + x > y + z$ which might cause the number of tokens on place b to increase to infinity. Showing that the number of goods is not bounded would indicate that the modeler has forgotten to organise the outgoing transports in an appropriate way.

A Petri net PN is called bounded if the number of tokens on each place is upper bounded by k at every reachable marking, i.e.

$$\exists k \in \mathbb{N}: \forall m \in RS(PN, m_0): \forall p \in P: m(p) \leq k$$

With a limited number of tokens at each place the set of reachable markings is also bounded:

$$\exists k \in \mathbb{N}: |RS(PN, m_0)| < k$$

Since almost all logistics systems (and thus ProC/B models) are open systems, those systems are not bounded in principal. Nevertheless checking for boundedness in an appropriately modified model helps to find modelling errors. As part of our validation approach the Petri net is modified to a closed net by short-circuiting the transitions representing the source and the sink of a process chain. The result of this modification on the net in Figure 6 is shown in Figure 7. Since we now have a closed Petri net checking for boundedness makes sense.

A sufficient condition showing the boundedness of the Petri net can be deduced from the state equation. Multiplying the equation with $v \in \mathbb{N}^{|P|}$ we get

$$v^T \cdot m = v^T \cdot m_0 + v^T \cdot C \cdot \bar{q}$$

and choosing a vector v with $v^T \cdot C = 0$ establishes a condition on all reachable markings:

$$v^T \cdot m = v^T \cdot m_0.$$

Such a vector $v \neq 0$ is called a place invariant.

Place invariants covering places p_i with $v_i \neq 0$ fix the ratio of tokens on places no matter which marking is reached. A Petri net is said to be covered with a positive place invariant v if

$$\exists v \in \mathbb{N}^{|P|}: v^T \cdot C = 0 \quad \text{and} \quad v > 0.$$

The existence of such positive invariants gives us a sufficient condition for boundedness: a Petri net is bounded when it is covered by a positive place invariant implying that the weighted number of tokens is constant at all markings.

We are going to check PN_C (cf. Figure 7) for boundedness. The new incidence matrix C_C of the modified net of Figure 7 is:

$$C_C = \begin{bmatrix} 1 & 0 & -1 & 0 \\ w & x & -y & -z \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}$$

For general values of w-z, place invariants of PN_C are $v_1 = (1,0,0,1,0)$, $v_2 = (0,0,1,0,1)$ because $v_1 \cdot C_C = v_2 \cdot C_C = 0$. Invariants v_1 and v_2 do not cover place b as there is no linear combination of invariants (which is itself an invariant) covering the second element. The uncovered place b is associated with the ProC/B storage in Figure 4 and the ProC/B toolset will mark model elements that are not covered with invariants as potentially unbounded. The user has the option to resolve this warning, e.g. by setting a limit for the maximum storage capacity.

This step might be unnecessary when each process loads the same number of goods it unloads, i.e. if $w = y$ and $x = z$. Under these conditions there are two more invariants, $v_3 = (y, -1, x, 0, 0)$ and $v_4 = (-y, 1, 0, 0, x)$. They can be combined to $2y\, v_1 + v_3 + 2v_4 = (y, 1, x, 2y, 2x)$ covering all places in PN_C. In this case the ProC/B toolset would not output a corresponding warning, indicating that the situation seems to be basically modeled correctly.

2.3 Deadlocks

Deadlocks might be caused by processes being dependent on each other and concurrently waiting for each other. This is a good example of errors easily solvable by humans and being problematic in computer simulations [16]. Consider the loading/unloading process model of Figure 4 and the derived closed Place-Transition net PN_C of Figure 7. PN_C deadlocks if $w + x < y + z$ since eventually a marking m_d will be reached with

$$m_d < C^- \cdot e_j, \forall j$$

Thus also transitions C and D representing loading processes have to stop. In the real system these load processes might represent trucks or trains which have to pursue a tight timetable and surely there will be some responsible person, e.g. the driver, solving this "deadlock situation". Even though the original ProC/B model represents an open system and thus will not deadlock, the occurrence of a deadlock in the closed Petri net indicates a model aspect which should be checked by the modeller.

Deadlocks are related to the liveness property. A transition t is live at marking m if

$$\exists m_r \in RS(PN, m): m_r \geq C^- \cdot e_t,$$

i.e. that one can always reach a marking, starting from m, so that transition t is enabled. A Petri net is live if all transitions $t \in T$ are live at all reachable markings of the Petri net. Obviously, in a live Petri net no deadlocks can occur.

Invariant analysis gives a necessary condition for liveness. After checking the closed loop net PN_C for boundedness we know that its reachability set is finite. The corresponding finite reachability graph thus consists of one or several strongly connected components and in each such component all transitions must occur as labels if the Petri net is considered to be live. Since we can reach any node/marking in a strongly connected component from any other marking of this strongly connected component, each marking m can be repeatedly reached. In terms of the state equation this means

$$\exists \bar{q} \in \mathbb{N}^{|P|}: m = m + C \cdot \bar{q}$$

which only holds if $C \cdot \bar{q} = 0$. Such a vector $\bar{q}$ is called a transition invariant. If a bounded Petri net is live then one can show that it is covered with at least one transition invariant $\bar{q} > 0$ [14, 15]. This implies that if one does not find a positive solution $\bar{q} > 0$ for $C \cdot \bar{q} = 0$ the Petri net is not live.

A valid transition invariant for the net PN_C in Figure 7 is $v_1 = (1,0,1,0)$ assuming $w = y$. It covers transitions A and C belonging to process A. Both transitions are live when the loaded quantity equals the unloaded. Of course, a similar invariant $v_2 = (0,1,0,1)$ under condition $x = z$ exists for transitions B and D. With $w = y$ and $x = z$ $v_1 + v_2$ is also an invariant covering all transitions and a closer inspection shows that PN_C is live. Apart from the symmetric case $w = y$ and $x = z$, invariant $v_3 = (x - z, y - w, x - z, y - w)$ exists assuming goods are exchanged between both process chains and $w \neq y$ and $x \neq z$. $v_3 > 0$ e.g. holds if $x > z$ and $y > w$. So in summary, the closed Petri net of Figure 7 is only covered by positive transition invariants if the quantities for unloading and loading match. The ProC/B toolset will mark corresponding uncovered ProC/B model elements thus indicating those model parts which should be inspected more carefully by the user.

Coverage by positive transition invariants is a necessary condition for liveness in bounded Petri nets. There are also Petri net techniques available giving characterising conditions for liveness or the existence of deadlocks. We only want to mention two here: the investigation of special classes of Petri nets (see [14, 17]) and the partial exploration of the reachability set/graph (cf. [18]).

Net classes are specified by imposing restrictions on the interconnection of places and transitions. For several net classes checking for deadlocks or liveness can be done very efficiently on the basis of the net's structure. As an example we consider the net of Figure 8, which belongs to the class of state machines.

The net class of state machines contains Place-Transition nets with transitions having only one incoming and one outgoing arc. Let $\cdot t$ be the set of input places and $t \cdot$ the set of output places of transition $t \in T$. A Place-Transition net is called a state machine if and only if

$$\forall t \in T: |\cdot t| = |t \cdot| = 1$$

Figure 8 shows an example of a state machine PN_{SM}. The criteria for liveness in state machines is that the net considered as a graph is strongly connected and

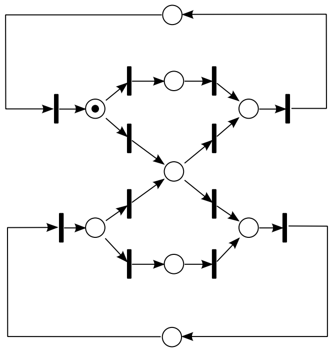

Figure 8. State Machine PN_{SM}.

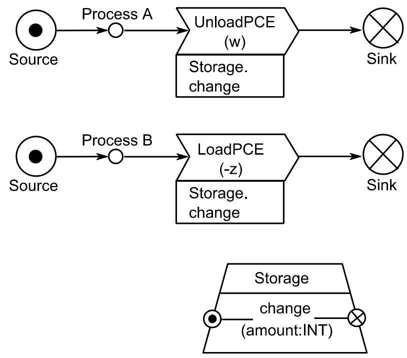

Figure 9. Simple non-ergodic process chain model**.**

$m_0 \neq 0$. One characteristic of state machines is that firing does not change the number of tokens in the whole net, i.e.

$$\exists k \in \mathbb{N} : \forall m \in RS(PN_{SM}, m_0) : |m| = k$$

and thus obviously a live state machine is also bounded. A token on a place will always enable at least one transition, so the net is live at m_0 with just a single token that can move around freely. Therefore the initial marking with one token as shown in Figure 8 gives a live Petri net PN_{SM}. Similar conditions based on the structure of the net are known for other net classes as well (cf. [14]).

The stubborn set method [18] is a method which only needs to partially explore the reachability graph of the Petri net in order to verify for specific properties, e.g. the absence or existence of deadlocks. The main idea is that only a small part of the state space is explored, and the exploration is made such that all deadlock states of the whole reachability graph are also part of the smaller subset. Looking for deadlocks is then only necessary in the smaller subset.

2.4 Non-Ergodicity

Non-ergodicity can be observed in models of logistics networks in situations with an interdependence between two or more processes. This interdependence is typically caused by a synchronisation between the processes or by stock-keeping scenarios.

Figure 9 shows a very simple process chain model consisting of two process chains and a storage. The upper process chain unloads goods to the storage, while the lower process chain loads goods from the storage. In this scenario process A can be interpreted as a server for process B and vice versa, since process A delivers goods that are loaded by process B and process B frees storage space needed by process A to unload. Assume the case $z = w$ and that arrivals of process A occur at rate λ and arrivals for process B at rate μ. Then μ is the service rate for process A and λ the service rate for process B. From queueing theory it is known that for process A (with arrival rate λ and service rate μ) $\lambda < \mu$ has to hold for a steady-state distribution to exist. At the same time the condition $\mu < \lambda$ has to hold for process B, which already demonstrates that this type of situation is problematic.

A similar situation occurs here if the average number of delivered and loaded units differ, i.e. if $z \neq w$.

Non-ergodicity implies that the steady-state distribution does not exist and thus non-terminating simulations are useless for those models. In general non-ergodicity is not a surprising effect when dealing with overload situation to determine the model's peak performance. In these cases an appropriate choice of model parameters yields an ergodic model, but for logistics networks typical situations exist (cf. Figure 9) where non-ergodicity is an intrinsic characteristic of the model and cannot be avoided by selecting different parameters for e.g. the interarrival times. In most of these cases non-ergodicity implies an incorrect modelling of the system resulting from the negligence of characteristics of the system.

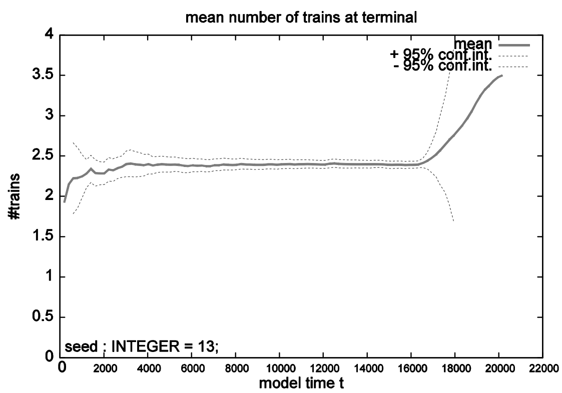

Figure 10. Simulation result of a non-ergodic model**.**

Figure 10 shows a simulation result of a non-ergodic model of a freight village taken from [3]. The figure indicates that non-ergodicity is difficult to detect by simulation, since the result seems stable for a long period of time and the simulation might even have been stopped before the non-ergodic behaviour became visible from the results. Hence, it would require very long simulation runs and a large amount of CPU time to detect non-ergodic behaviour by simulation, if it is detected at all.

For Petri nets an efficient technique for the detection of potentially non-ergodic models is available [19] which is based on rank computations for the incidence matrix of the Petri net. This technique can also be applied to process chain models as described in [3].

Let m denote the number of transitions of the Petri net and $N(s) \in \mathbb{R}^m$ be a vector counting the number of transitions firing in the time interval $[0, s]$. For an ergodic Petri net the mean firing flow vector

$$N \coloneqq \lim_{s\to\infty} E[N(s)]/s$$

exists and the expected input flow of tokens at a place equals the expected output flow, which can be expressed using the incidence matrix C resulting in $C \times N = 0$. The kernel of matrix C is defined as

$$kernel(C) \coloneqq \{x \in \mathbb{R}^m | \, C \times x = 0\}$$

and thus N is in the kernel of C.

In general the computation of N is difficult, but for some transitions the corresponding values of N can be determined easily. This holds for source transitions and sets of transitions that partially exhibit an Equal-Conflict (PEC set), i.e. for transitions with the property that at any marking either all or none of those transitions are enabled.

Figure 11 shows the Petri net representation of the process chain model from Figure 9. For the two source transitions the components of vector N can be determined easily and a computation of the basis of the kernel of the incidence matrix shows that the firing rates of those transitions are dependent. The basis of $kernel(C)$ is given by (z, z, z, w, w, w) for the Petri net from Figure 11, where the first three entries correspond to the transitions of process A and the last three entries to the transitions of process B, implying a dependence between the source transitions (here $a \in \mathbb{R}$ has to exist with $\lambda = az$ and $\mu = aw$). Thus, the Petri net of Figure 11 is sensitive towards small changes of the firing rates of the two source transitions.

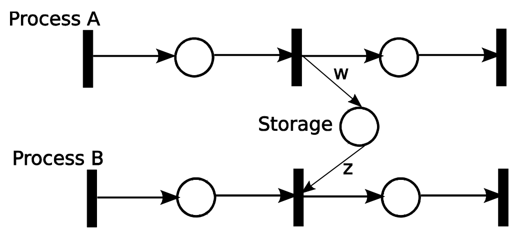

Figure 11. Petri net representation of the process chain model from Figure 9**.**

This kind of sensitivity is called *e-sensitivity* in [19] and indicates potential non-ergodic nets. Furthermore a formal criterion for detecting such nets is given. Let $k_1, \dots, k_r$ be a basis of the kernel and $\tilde{T}$ a PEC set. Then a Petri net is e-sensitive if

$$rank\left(\left(Proj(k_1, \tilde{T}) \dots Proj(k_r, \tilde{T})\right)\right) < |\tilde{T}|$$

holds, where $Proj$ denotes the projection of vector k_i onto $\tilde{T}$.

For potentially non-ergodic nets the approach identifies a set of transitions implying e-sensitivity. Since each of the transitions corresponds to an element of the process chain model, they can be used to identify the critical part in the process chain model.

Applying this approach to the model of the freight village introduced in Section 1 identifies the model as being potentially non-ergodic too. As already mentioned this hints at an incorrect modelling of the system, e.g. we ignored existing time tables and delivery schedules for the trucks and trains in this model.

Ergodic models can be found when restrictions on concrete values are modified. Figure 12 shows an ergodic system if e.g. $\lambda(w - y) < \mu(z - x)$ with $w > y$, $z > x$. The loading process chain element of process B uses the alter-or-skip service [20]: it will pick up all available, but not more then z goods from the storage. This allows process B to continue even if the storage is empty. For details on the theoretical background the interested reader is referred to [19]. [3] explains how the approach can be automatically applied to ProC/B models.

3 Conclusions

In this article we gave insight into some possibilities for the validation of process-based models as being offered by the ProC/B toolset. Validation is based on the automated transformation of ProC/B models into similar behaving Petri nets and usage of corresponding Petri net analysis techniques. Due to the complexity of realistic ProC/B models (and simulation

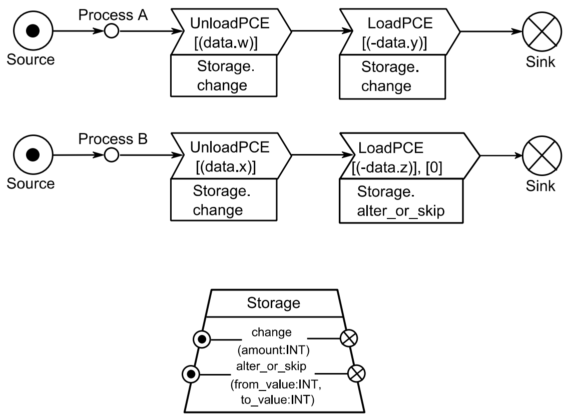

Figure 12. Simple ergodic process chain model**.**

models in general) the transformation does not account for all details of the ProC/B model. This might result also in non-faults, i.e. faults occurring in the Petri net, but being nonexistent in the ProC/B model, so that the output of the Petri net analysis has to be considered as an indication of possible errors in the ProC/B model. The essential advantage of the presented Petri net techniques is their efficiency. The analysis investigates the structure of the Petri net and renders the generation of the state space unnecessary, so that a modeler is able to validate specific model aspects during the construction phase within a short time. As Figure 4 suggests, one might first apply invariant techniques, since this step might result in a change of the model also having impact on the model's ergodicity. Once those tests are passed, ergodicity might be checked, since subsequent corrections usually do not change the invariants.

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Mapping of Time-Consumption During Input Data Management Activities

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The success of a discrete event simulation project relies heavily on input data quality. In order to achieve high quality data a significant amount of time needs to be spent, either due to absence of data or problems with defining and extracting existing data from databases. This paper presents a distribution of the time-consumption for the activities in the input data phase during discrete event simulation projects. The results show where efforts need to be focused to reduce time-consumption and improve quality of input data management.

Introduction

The competition between companies in all markets has increased considerably during the recent decades and it is getting more and more important to optimise the efficiency in production [1]. To improve productivity, some organisations use analysis tools like Discrete Event Simulation (DES) in major change projects as well as for continuous improvements. However, the input data needed to analyse the production is often not available, or at least, it takes plenty of time to collect and prepare the data for further analysis.

DES is a powerful tool for productivity analysis and it is argued that input data management is the most crucial and time-consuming step in DES projects [2] [3]. The time spent on input data management is typically as much as 10-40% of the total time of a DES project [4]. This set-back sometimes tempts organisations to choose less complex analyses with lighter requirements on input data quality. As a result, these analyses yield results of poor, or at least, inferior quality.

Few previous studies have closely mapped the input data phase in order to find the reasons for the heavy time-consumption [5]. Even fewer studies focus on identifying the input data activities which are most favourable to improve. The aim of this work is to identify the most time-consuming activities in the input data phase of DES projects. The results will show where to put important efforts in future research, in order to reduce time-consumption and increase quality of input data management. Not only in simulation projects, but also for projects using other production analysis methods.

1 Input Data Management in Discrete Event Simulation

One always present step in DES projects is the input data phase, usually called “Data Collection“; see for example the widely applied methodologies described in Banks *et al.* [3], Law and Kelton [6], and Rabe *et al.* [7] (Figure 1).

These methodologies merely show the input data management step as a black box. However, in practice input data management includes several activities such as collection of raw data from various sources, transformation of data to information and documentation. Here, *data* is referred to as “a set of discrete, objective facts about events” [8] (e.g. 1000 repair times for a machine). *Information* on the other hand, is slightly simplified defined as “data with meaning” [9]. In this case, information can be exemplified by a statistical representation of Mean Time To Repair (MTTR), which contains both relevance and purpose for the receiver (the simulation model).

In this paper, the input data phase is described in more detail than on the black box level. We have divided the internal time-consumption within the input data phase into separate activities and measured the time-consumption for each activity.

The focus on input data is surprisingly low in previous scientific contributions within the field of DES. Perera and Liyanage [5] is one of few contributions that really address the difficulties related to the input data management in DES projects. They rank the major pitfalls in input data collection as follows:

1. Poor data availability
2. High level of model details

3. Difficulty in identifying available data sources
4. Complexity of the system under investigation
5. Lack of clear objectives
6. Limited facilities in simulation software to organise and manipulate input data
7. Wrong problem definitions

There is also lack of publications on systematic guidelines to overcome these issues and to reduce time-consumption in input data management (one is Bernhard and Wenzel [10]). Instead, earlier research performed on reduction of time-consumption in input data management has primarily focused on the level of human involvement in the process. A study made by Robertson and Perera [2] describes four alternative solutions for managing data for DES models:

1. Tailor-made solution

- Data primarily derived from the project team
- Data manually supplied to the model by the model builder
- Data resides in the simulation tool

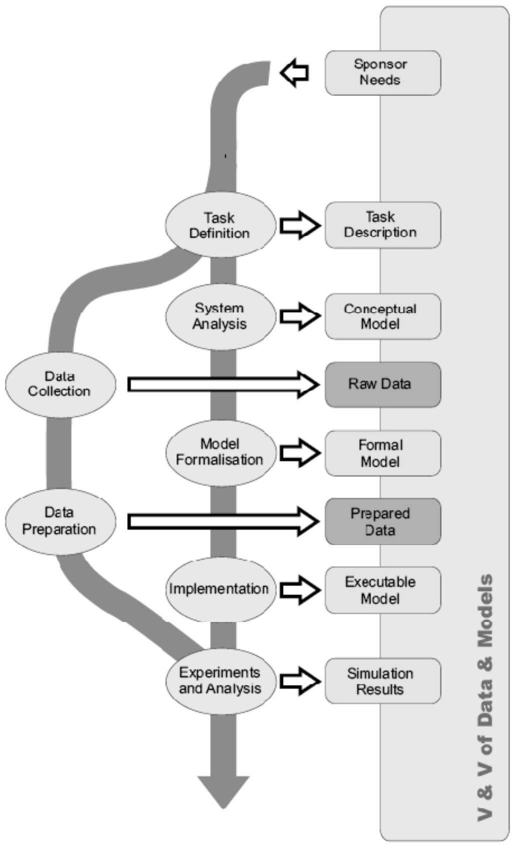

Figure 1. Steps in a simulation study [7].

2. Spreadsheet solution

- Data primarily derived from the project team
- Data manually supplied to the computer application (e.g. MS Excel spreadsheet)
- Data automatically read by the model via a computer application
- Data Resides in the computer application

3. Off-line database solution

- Data primarily derived from a Corporate Business System (CBS)
- Data automatically supplied to an off-line database from the CBS
- Data automatically read by the model
- Data resides in an intermediary simulation database

4. On-line database solution

- Data primarily derived from the CBS
- Data automatically supplied to the model from the CBS
- Data resides in the CBS

The same publication states that solution 1 and 2 were most frequently used in industry, which is most likely still a valid statement. However, some research work and industrial applications have strived towards less human involvement in the input data management process. For example, some years ago the tendency shifted towards integration of systems, in which DES is one component that share data and information with many other applications within the same package. DELMIA from Dassault Systèmes [11] and SIEMENS Teamcenter [12] are two examples of such Product Lifecycle Management (PLM) software packages. Moreover, simulations driven by an off-line simulation database using input data from Enterprise Resource Planning (ERP) systems have also been performed [13]. This is one example of the contributions towards solution 3 and 4, described above.

However, the situation remains; Robertson and Perera [2] state that: ”It is strongly argued that data collection is the most crucial and time consuming stage in the model building process”. Therefore, this paper evaluates if this statement is still valid and shows where future efforts should be concentrated. This is done by summarising the time-consumption within DES projects in general, in the input data phase in specific and even more important in the activities of the input data phase.

2 Material and Methods

The study embraces the analysis of 15 DES projects performed between 2000 and 2007. The projects have been performed in a wide range of companies with regard to line of business, size of organisation and previous experience in DES. The plants in which the projects were performed are all located in the Nordic countries, mainly in Sweden. Both pure industrial cases and simulation projects performed in cooperation between industry and academia are included among the 15 projects.

Semi-structured interviews [14] were conducted with members from each project in order to define the work procedure and activities in the input data phase of the projects. The agenda of the interviews was focused on the kind of problems, related to input data, which arose during the project. Furthermore, an additional aim with the interviews was to identify key factors for rapid and precise input data management, from a practitioner's viewpoint.

The respondents were also asked to fill in a questionnaire where the time-consumption for the whole project as well as for each specific activity in the input data phase was specified. Moreover, information about availability and sources of input data in the projects were gathered in order to detect reasons of extensive time-consumption as well as factors for successful input data management. All times responded in the study are given in the unit "man-days". One man-day equals to one eight-hour working-day for one person. For example, if two persons have spent two days to carry out a task together, the amount of time reported to this study is four man-days. The respondents were asked to write the time given with a resolution by minimum one man-day but if they were able to recall in greater detail they were allowed to answer in fractions of man-days.

The authors compiled all collected information in a data-sheet and analysed it in order to map the time-consumption for all activities and to find patterns in prerequisites and work procedures, which can reduce time-consumption in data management. The findings from the questionnaires were then combined with the information from the interviews. The results are presented in Section 4.

3 Input Data Management Activities

In the presented analysis of time-consumption, the input data process in DES projects is divided into nine separate activities. Each activity consists of several tasks. The number of tasks and the way to execute each task can differ slightly between simulation projects because of differences in prerequisites and objectives. However, the work procedures are structurally very similar among simulation input data phases, and the activities defined below cover the process of all studied projects.

Below, each input data management activity is briefly described to enable measurements of the time-consumption. However, a more thorough description, including supportive guidelines, is provided in Skoogh and Johansson [15].

3.1 Identification of Input Data Parameters

The identification of required input data parameters has earlier been addressed as one of the key activities for successful input data management. The process is often performed in cooperation with people having expert knowledge of the modelled manufacturing process. The parameters to include are often dependent on project objectives, on model complexity and on level of model detail. Therefore, there is an ongoing interaction between construction of the conceptual model and identification of input data parameters [3].

3.2 Accuracy Requirement Specification

It is of great advantage if the project team can forecast each input parameter's impact on model behaviour. If accuracy requirements can be specified for each factor, the effort spent on information collection can be optimised. Accordingly, more resources and time can be assigned to important parameters instead of less central ones. As a result of this activity, the required number of unique data-points for each parameter is decided.

3.3 Mapping of Available Data

Once the relevant parameters are selected, the project team needs to search for and map the input data already available, without need for manual gathering in the real world production system. Such available data can generally be found in simple manual systems (e.g. spreadsheets with previously performed time studies) or in more complex computer based systems such as ERP-systems, Manufacturing Execution Systems (MES) or other databases holding process information (e.g. time-stamps logged by Programmable Logic Controllers (PLCs)).

However, it is hazardous to instantly rely on the applicability of information from this kind of systems, without further investigations. Despite that database specifications and people with extensive practical experience say that data is available, simulation engineers frequently find the data in a crude form or measured in a manner that makes it useless for simulation. Consequently, the activity of mapping available data includes identifying sources, understanding the sources and making sure that it will be possible to extract required data from the systems.

3.4 Choice of Gathering Methods

When the available data has been mapped, a gap between required data and available data will be detected in most simulation projects. Hence, some additions will be necessary. In this activity the project team decides which methods to use in order to gather missing data from the modelled system. The choice will mainly depend on possibilities to measure and on the expected accuracy of each parameter according to earlier specifications (section 3.2). Examples of gathering methods are time studies, frequency studies and interviews.

3.5 Document Creation

In order to store all data that will be collected from available sources or from real world measurements, a document needs to be created. A well-designed document helps to structure the data collection procedure. It also gives greater possibilities to reuse data in future studies and to make small adjustments if errors occur, or if the modelled system changes during the project time.

3.6 Data Collection

The data collection activity can be divided into two parts. One is the extraction and compilation of available data from the identified sources. The other is to gather the missing data according to the previously specified methods (Section 3.4).

Extract and Compile Available Data Despite the availability of data, some efforts are almost always needed to extract relevant information from the data sources. As mentioned before, more complex databases often contain data in forms that require some transformation before it can be used for further analysis in a simulation project. One example is breakdown data that is often logged in a crude form where start and stop times of all stops are stored. In this case, efforts are needed both to sort out the stops of interest for the analysis, and to calculate the absolute length of breakdowns.

Gather Missing Data Many times this activity is fairly straight-forward since the procedure is well outlined in previously presented activity (Section 3.4). However, depending on the chosen methods, type of modelled process and requirements of accuracy, it can be a time-consuming activity.

3.7 Data Analysis and Preparation

The outcome of the data collection activity is often a large set of data points, e.g. 100 measured cycle-times or 2000 repair times extracted from a maintenance database. In the data analysis and preparation activity, the way to represent the data in the simulation model is selected. Regardless of whether an empirical or statistical representation is chosen, some preparations are performed in this activity. For example, the statistical representation requires fitting the data set to a statistical distribution.

3.8 Data Validation

Before the data is used in the simulation model, a separate data validation activity helps to ensure accuracy in further analysis. An early control of the data representations' correctness usually saves iterations in later model validation, where more sources of error are involved. The data representation can be validated using production follow-ups or expert knowledge, e.g. Turing tests [16].

3.9 Final Documentation

It is important to document the results of the input data phase, since they are of vital importance for the model outputs and furthermore for the decisions taken with reference to the analysis. The final documentation is also necessary in order to make future simulation projects less time-consuming by enabling reuse of input data.

4 Survey and Interview Results

The results and analysis section is divided into two parts. The first part presents the analysis of time-consumption for input data activities and the second part shows the data availability in the studied DES projects.

4.1 Analysis of Time-Consumption

The respondents were asked to assess the time spent in each of the activities during the input data phase of the 15 DES projects included in the study. The percentages of time in each activity with regard to the duration of the entire input data phases are presented

Project	Input data parameter identification	Accuracy requirement specification	Mapping of available data	Choice of gathering methods	Document creation	Data collection	Data analysis and preparation	Data validation	Final documentation
# 1	12%	2%	2%	2%	0%	60%	12%	4%	5%
# 2	3%	0%	7%	7%	1%	51%	7%	22%	0%
# 3	5%	2%	12%	1%	2%	63%	1%	6%	6%
# 4	5%	2%	4%	5%	5%	61%	7%	5%	5%
# 5	3%	3%	12%	1%	6%	57%	12%	0%	6%
# 6	3%	0%	15%	3%	5%	58%	8%	5%	5%
# 7	1%	4%	2%	2%	1%	40%	25%	12%	12%
# 8	9%	0%	9%	4%	9%	52%	9%	4%	4%
# 9	5%	0%	9%	5%	5%	45%	23%	5%	5%
# 10	4%	4%	9%	4%	7%	50%	7%	9%	7%
# 11	33%	11%	11%	7%	0%	24%	2%	11%	2%
# 12	14%	7%	14%	11%	7%	21%	14%	4%	7%
# 13	5%	0%	10%	10%	5%	50%	10%	5%	5%
# 14	5%	3%	13%	5%	8%	56%	3%	5%	3%
# 15	10%	0%	21%	0%	0%	62%	8%	0%	0%
Average	**8%**	**2%**	**10%**	**4%**	**4%**	**50%**	**10%**	**7%**	**5%**

Table 1. Time-consumption for each input data activity with regard to the entire input data phase.

in Table 1. Around half of the input data management time is used for actual data collection, both from available sources and from manual gathering. *Mapping of available data* together with *data analysis and preparation* are the other two activities on the top-three ranking of time-consuming activities.

It is not surprising that the collection activity claims a significant amount of time. Some more detailed findings about the most time-consuming parameters, and how data availability influences time-consumption, will be further examined later in this section. However, the fact that mapping of available data is a top-three ranked activity is more conspicuous. But information from many of the respondents is very similar and claims that the major reasons are the complexity of the data sources and that the available data is not collected and stored in a way that is ready for use in simulation models. Hence, a lot of time is needed to understand the data sources and to ensure that the data is relevant in the specific case. Ensuring that it will be possible to extract and transform required data into a suitable representation for the simulation model, also adds to the extensive time-consumption.

Table 2 shows the ranking among input data parameter classes with regard to required collection time. Process times, breakdown data, set-up times, tool changes and material handling data are all straightforward parameter classes, but production planning and organisational data contain some sub-types. Information needed for production planning incorporates data such as production schedules, arrival patterns of incoming parts, and sales data. Organisational information contains data about staffing plans, shift schedules and breaks. Note that the sum of the time-consumptions for all parameter classes is not equal to 100% since all classes are not applicable in every studied project.

Interview responses indicate that the reason for the heavy time-consumption for process data depends on problems with defining the process delimitations, e.g. when a cycle starts and stops.

For breakdown data, the corresponding problem is to sort out the stops of interest for the simulation study, among all other kind of logged process-disturbances in the IT-systems. Both process data and breakdown data often include large amounts of data since they are considered to be particularly important for model performance and dynamics.

4.2 Data Sources and Availability of Information in DES Projects

The availability of data necessary for production analysis is not satisfying in most of the studied DES projects. Only one of the 15 cases had all data available when the project started, and combined with a study performed by Johansson et al. [17] it is obvious that insufficient work has been performed in order to

Parameter class	**Time-consumption (percentage of the entire input data phase)**
Process times	42%
Breakdown data	32%
Production planning data	19%
Material handling data	14%
Set-up times	12%
Tool-change times	8%
Organizational data	7%

Table 2. Required time efforts for collection of input parameter classes.

Parameter class	All data available	No data available	Combination of available and manually gathered data
Process times	33%	27%	40%
Breakdown data	64%	9%	27%
Production planning data	18%	55%	27%
Material handling data	0%	62,5%	37,5%
Set-up times	22%	44%	34%
Tool-change times	20%	80%	0%
Organizational data	40%	40%	20%

Table 3. Percentage of studied projects having all, none or parts of the needed input data available.

support analyses with proper input data. Two projects out of the 15 had no data at all to start with, and had to gather all data manually. Table 3 shows the data availability for each input parameter class, presented as the percentage of projects having all, none or parts of the required data available.

As seen in Table 3, breakdown data is the category that is most frequently collected and stored, followed by organisational data and process times. Contrarily, material handling data was not fully available in any of the projects. It is important to note that it is not relevant to directly compare time-consumption for different parameter classes, since the amount of raw data and importance for model performance varies significantly among the classes. Therefore, one should not draw the conclusion that data availability is insignificant for the time-consumption because breakdown data collection takes more time than to gather data for material handling equipment (Table 2), despite the fact that breakdown data has higher availability.

The study results rather show that a large share of available data has a positive correlation with rapidity of input data collection. One single example is that the only project having all needed data available is also the project with lowest percentage (12%) of time spent in the input data phase. Investigating the actual time for collection of input data in projects with full data availability compared to projects that fully or partly include manual gathering supports the same conclusion. To illustrate, the mean time required for collection of process times was less than one week when data was fully available and slightly more than three weeks when manual gathering was needed.

5 Discussion

The survey and the interview results clearly show the difficulty for companies to effectively manage their data for use in production analysis tools like DES. It is obvious that no evident progress has been made to reduce the time-consumption for input data management in recent years. For instance, this study shows that the time-consumption for input data management in DES-projects is still 31% on average, which is a high percentage compared to older studies. The opinion is also supported by the fact that only 7% of the studied projects had all required input data available when the project started. This is almost the same availability ratio as Johansson *et al.* [17] found six years ago (6%).

Two of the top-three time-consuming input data activities both shed light on the same difficulty in input data management at present. Both problems with actual data collection (50%) and mapping of available data (10%) indicate a potential for reduced time-consumption by implementation of intelligently-designed computer-based data sources.

According to the findings presented in the results and analysis section, companies can gain a lot of time in production systems analysis by keeping track of data describing their processes. This in turn enables DES to be used more frequently; hence increased performance in production is achieved. There are several ways of continuously having up-to-date information available, some examples are automated PLC-logging or previously performed time studies stored in databases. However, it is very important to note that the design of the majority of existing databases is not developed with the needs of analysis tools like DES in mind. No less than 10 out of 13 projects in the study, having some available data at hand, reported problems with extracting relevant information from the databases due to problems with understanding the data structures, mapping relevant data for their specific application and sorting out the information needed among an often huge set of data. These findings are also supported by earlier research performed by Perera and Liyanage [5].

Moreover, companies often overestimate their ability to provide data for analysis tools like DES, which might be a result of the extensive information flow in present production systems. However, when the projects start they frequently lack important data or find that data is measured and stored in a way that is unsuitable for simulation models. Consequently, a lot of time needs to be spent on identification of relevant information and on recalculations or complementary measurements. This common statement of respondents has resulted in problems with keeping the time plans for input data management in the studied projects. Only 20% of the projects reported that their input data phases where completed in time.

Requirements stated above are not just based on a DES perspective but also on the viewpoint of other production analysis methods. Companies could gain much productivity by keeping track of their production data more carefully. One way is to design future data systems having the viewpoints of production analysts in mind. But not to forget, today's purposes with the systems are also important to support, e.g. maintenance and process control.

There are some factors in the study that might affect the precision of each individual case study result. Since the exact number of hours responded in the study was not documented in all cases, the reported time-consumption is dependent on each respondent's perception and memory. However, the possible impact of this factor is reduced by the choice of recently performed projects, for example 13 of the 15 projects are performed within two years from when the questionnaires were completed. Moreover, it is important to remember that the purpose of the study is to identify time-consuming activities and serve as a guideline for future research, rather than presenting the exact number of hours needed to carry out the activities. To increase the precision of the study some more samples would have been favourable to add.

Another factor that has been hard to determine in every specific project is the input data precision and quality. Consequently, it's hazardous to exclude the quality dimension's influence on time-consumption from the survey results. However, all projects managed to validate their models according to the real world system, which indicates that the data quality was satisfying in all cases. Many of the projects (73%) also validated the input data separately to production follow-ups or to process expert knowledge.

6 Conclusions

To summarise the findings from this study, some results deserve to be highlighted:

- The work to increase the support of input data to production analysis has not yet resulted in successful implementations in industry. The time needed for input data management in DES projects is still around 31% of the total project duration. Moreover, the percentage of companies having all data available for DES projects is as low as 7%.
- The three most time-consuming input data activities are *data collection*, *mapping of available data*, and *data analysis and preparation*, respectively.
- One major reason for the heavy time-consumption is the need for manual gathering due to insufficient data availability.
- Another reason is the complex design of many computer based data systems, which slows down the identification of available data as well as the extraction of information from the systems.

There is also a newly published paper related to this contribution [15], which proposes a methodology for increased efficiency in input data management. It aims to improve the present working procedures (mapped above) by describing good practice guidelines for each activity.

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Simulation Model Quality Issues in Product Engineering: A Review

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Dynamic models are of central importance in engineering design for many fields of application but, within some areas, surprisingly little attention is given to the confidence that can be placed on predictions from such models and the implications of model quality, or the lack of it, for design. In recent years the growth of interest in the possible benefits that generic models and model component re-use provide has stimulated new interest in questions of model quality and in the closely associated issues of model testing, verification and validation. This paper considers the link between model quality and the quantitative testing of continuous system simulation models in product engineering and reviews techniques available for the verification and validation of such models. Recent developments and current trends in this field are emphasised, with particular reference to generic models and the re-use of model components. The paper also considers some of the problems inherent in applying rigorous testing and validation procedures. Implications for the education and training of engineering students in the areas of modelling and simulation are considered.

Introduction

In the context of product engineering applications the purpose of a model is to explain complex behaviour, to assist in decision-making processes, or to provide a basis for design. In creating a representation that is appropriate for the intended application there is usually a trade-off between the level of detail included in the model and the speed of solution.

Continuous system dynamic models for the type of product engineering applications under consideration in this paper are most often based on the underlying physics of the system in question but may, to a greater or lesser extent, also involve sub-models that are functional input-output descriptions (i.e. “black-box” models). These may, in turn, be derived from other more detailed physically-based models or may be identified from tests carried out on the corresponding elements of the real system. The models under consideration thus range from completely transparent descriptions based on physical principles, through the intermediate “grey-box” descriptions, to the entirely empirical black-box form of model.

For engineering design applications a good model can have many possible benefits, including early assessment of performance, both within the normal operating envelope and beyond it. Understanding of parameter inter-dependencies and knowledge of key sensitivities within the model can also be of critical importance for design optimisation.

Since a model is, by definition, only an abstraction of the system it represents, perfect accuracy cannot be expected and the key question becomes one of determining the model quality level necessary for the application and assessing the adequacy of a chosen model for some intended use. This implies reducing errors to defined levels for specified regions of the operating envelope of the system. The role of testing, verification and validation procedures can then be regarded as defining boundaries within which a model must operate to specified levels of accuracy. These topics associated with practical issues of model testing are thus of central importance in considering issues of quality in mathematical models and related computer simulations.

As has been pointed out by Sargent (e.g. [1]), Balci (e.g. [2, 3, 4]), Ören [5], Brade [6, 7] and many others, model validation cannot be separated from the model building process. Model building is iterative and, if appropriate methods are used and validation is applied at each stage, confidence in the model should increase from iteration to iteration.

In the early stages of a product engineering design project relatively simple conceptual models are used to examine “what if” situations and allow design trade-off studies to be performed. At this stage little, if any, formal model validation is possible and, inevitably, the error bounds on model predictions are relatively large. Any assessment of model quality and fitness-for-purpose at this point is likely to be based on general design experience and on comparisons with earlier models of other systems having characteristics that are in some way similar. However, as the project moves forward, more complex models may be integrated more fully into the design process and more and more data should become available for model testing. This is likely to involve data at the component level initially, then data resulting from tests on larger blocks and, at a much later stage, data from the testing of complete prototype systems.

Thus, as test data become available, a flow of information starts to be established from the real system to the model, in contrast to the situation at the start of the engineering design process where the flow is entirely from the model to the system being designed. This bi-directional transfer of information is a characteristic of all the later stages of the design and development process. It ensures that the model is being updated continuously as knowledge about the real system is accumulated.

One important development in recent years has been the adoption of a more generic approach to modelling in several engineering fields, including power electronic systems (e.g. [8, 9]) and gas turbine systems (e.g. [10]). In this context the word "generic" is defined as meaning "general" or "not specific" and implies the use of a standard structure and standard building blocks within a model. This approach is likely to become more and more widespread and may be applied in many different application areas in future. The most significant benefit of the generic approach is a more rapid and less costly development process for new models compared with the conventional situation which involves the development, on a one-off basis, of new models for each new design task. Other benefits arise because of the fact that the development and use of a generic model demands a more systematic and rigorous approach to issues of model validation together with better documentation.

Making a model generic in any application area can present difficulties. The essential requirements must be identified first of all and a suitable framework established which provides the necessary flexibility to allow a variety of more detailed needs to be satisfied. Within the generic approach a given system may need to be represented at several different levels of detail at different stages of a design project. This means that sub-models, representing specific parts of the complete physical system, may need to be available at several different levels of complexity, ranging from purely functional forms at the initial stage to highly detailed and fully validated model components for use in the final stages of the project life-cycle. The models at different levels of resolution will, inevitably, all have strengths and shortcomings and need to be mutually calibrated in some way [11]. Ideally, the structures for the different levels of model will be directly related and the models at different resolutions will form an integrated group. The relationship between the different levels of each sub-model within the generic structure must be fully understood by users.

Issues that can arise in the development of a generic model for a new application area have been considered in detail in two recent papers dealing with the modelling of electro-optic sensor systems [12, 13]. The generic model is, in this case, intended to be used in the design of specific types of electro-optic systems such as infra-red search and track systems, missile warning systems and thermal imager system.

The approach adopted for these electro-optic applications involved developing models of specific systems as an integral part of the development of the generic model. Specific configurations of the generic model could then be evaluated and tested, as could modules within the generic description. As confidence in the generic model increased new modules within the generic model structure could be added. However, as the generic model became larger it became more and more important to avoid major changes in the overall structure of the model. Any modifications to a generic model of this kind have to be comprehensively tested using regressive testing methods, similar to those used in software engineering, for particular configurations of the model investigated in earlier tests.

In applying a generic approach to model development, a need may arise to create a model of a new system, not considered already using an available generic structure. This introduces new challenges which encourage re-use of established sub-models but further test the generic philosophy. If the approach fails at any point with a new application then either a flaw has been found in the engineering design or a limitation has been found in the generic model. In the latter case the generic model has to be modified and its capabilities extended.

Modelling errors and uncertainties arise in many different ways, including unjustified modelling assumptions, errors in *a priori* information such as parameter values, inaccuracies in the numerical solution of the model equations and errors in experimental data.

Complex simulation models are sometimes developed and used without rigorous testing and model documentation is often non-existent or inadequate. Poorly tested and undocumented models also may get passed from project to project and thus may end up being used in ways that the original model developer never intended. This contrasts strongly with accepted good practice in the software engineering field where rigorous testing, documentation and version control are all integral elements of the required process for software development. Such methods do not completely eliminate inappropriate or incorrect use of software but they do provide a level of regulation that is often missing in the case of simulation models.

The importance of model quality for product engineering applications was highlighted, about fifteen years ago, in a UK Office of Science and Technology report [14] by the Technology Foresight Panel in the Defence and Aerospace sector. This report includes a statement that "Improved modelling of physical and manufacturing processes will improve our ability to predict the behaviour, costs and risks of future systems and dramatically reduce the development timescale". The report continues with a statement "While it is essential that modelling and simulation is supported by validation trials, improvements will reduce the need for costly and time-consuming developmental testing" [14]. Since that time phrases such as "simulation-based acquisition" and "smart procurement" have entered widespread use within companies involved in defence contracts and have been the focus of discussions within other sectors of industry. In the USA, in particular, the work of the Defense Modeling and Simulation Office (DMSO) within the US Department of Defense (DoD), had significant influence on issues of model testing and of verification, validation and accreditation (VV&A) of models. Although the role of DMSO has been taken over by the Modeling and Simulation Coordination Office (M&SCO) the issues of model quality and VV&A methodology continue to be given priority. M&SCO is involved with annual DoD Modeling and Simulation Conferences and DMSO organised a series of specialist workshops involving staff from government establishments, companies and universities for broad ranging discussions on issues of model quality and techniques for verification and validation (e.g. [15, 16]).

In the USA a SMART initiative (Simulation and Modeling for Acquisition Requirements and Training) has also been established which calls for reuse of models to promote validity, reliability and efficiency of development in areas such as missile systems [17]. The US Office of Naval Research (ONR) has also been very active in promoting new work in this area, especially in the context of power electronic systems and electrical drives. ONR has been responsible for active support of the concept that "the model is the specification" [9]. In other words, it is being suggested that as part of the process of preparing formal specifications for complex new systems a simulation model has to be prepared and that this model becomes the point of reference in determining whether or not the performance of the proposed system is acceptable (e.g. [18, 19]). This means that modelling and simulation activities become a vital element of the acquisition process from the Request for Proposal (RFP) stage onwards. For the customer, the provision of simulation models by competing contractors allows for the comparison of different approaches in a quantitative way at the tendering stage. However, simulations used for such competitive evaluation must have a high degree of transparency and must involve similar sets of assumptions.

US Government laboratories, such as the Los Alamos National Laboratory, the Sandia National Laboratories and the Lawrence Livermore National Laboratory have large research programmes in the general area of model validation methods. Reports on some aspects of the work being undertaken in these programmes may be found in papers presented at the DMSO Foundations `04 V&V Workshop [16].

Within this paper general issues relating to model quality are first reviewed and this leads to a closely-related section of the paper in which methods of verification and validation are outlined. Within a subsection dealing specifically with validation a number of graphical methods are described, together with discussion of quantitative measures and several other approaches to model and system comparison and model analysis. The control systems applications area receives some specific attention. The paper includes a section in which important questions of model documentation are reviewed. This leads to a section involving discussion about the way in which most engineering students are introduced to system modelling concepts within their academic studies and to the inevitable problems if inadequate consideration is given to issues of model verification, validation and documentation at an early stage. The final discussion section attempts to bring together the most important aspects of the review.

1 Model Quality Issues in Product Engineering

There are good examples, often in safety-critical application areas, such as the nuclear industry and the aerospace, defence and marine sectors, where rigorous model testing and formal approval schemes are routinely applied. However, the model development process used within many engineering organisations often involves surprisingly little systematic investigation to establish the quality of the models in terms of their useful range and limits of accuracy. Also, there are many cases where models are justified in a spurious way, possibly on the grounds that the model is one that "has always been used" or is "based on well-established physical principles so must be right" or is "based on an industry standard".

The use of models that are in some ways inadequate for an intended application can often lead to expensive redesign at late stages in the development cycle. The more complex the system being developed, the more likely it is that problems of this kind will arise.

Modelling and simulation activities are important from the concept development stage through requirements analysis to trade-off studies and detailed design. The real system and the associated simulation models generally mature together and the level of model fidelity should increase as a design and development project progresses. Whatever the approach being used for design, experience gained with the real system should be incorporated into the models at every stage.

Many modern developments in engineering involve a "system of systems" design and often require a number of design teams working together. Such collaborative development work means that there is no longer a single "designer" and soundly based, well-understood and well-documented models are essential if all involved in the design effort are to be effective.

Helicopter flight control system design is one example of a field in which model limitations are recognised as a factor that affects the achievable overall performance of the system. Here it is accepted that, until now, the success of modern methods of design has been limited significantly by the accuracy of available models for the vehicle (e.g. [19, 20]). Similar conclusions can be drawn in other application areas in which the eventual performance limits of a new system relate directly to the accuracy of the mathematical model upon which the design is based.

One of the issues that can arise in discussing model quality and validation in the context of control engineering applications is that models used for design are often developed using a combination of physics-based modelling and the experimentally based approaches of system identification and parameter estimation. For example, the structure of the model may be established using physical principles, but values of some of the key parameters of the model may have to be estimated from analysis of results of experiments and tests on the real system. This means that, prior to any experimental work aimed at assessment of model accuracy, a form of testing might have to be carried out as part of the model development process. It is therefore vitally important to ensure that data used in the system identification and parameter estimation stage of model development are not reused at any stage to investigate model quality. However, it is also important that in designing tests for the external validation of such models careful consideration should be given to the range and distribution of the data upon which the identification was based.

It is thus necessary to distinguish carefully between the processes of system identification and parameter estimation that are applied for model development purposes from the processes involved in establishing the quality of the resulting model. The term "model calibration" has therefore been introduced to describe the processes of parameter estimation and other forms of interactive tuning that may be applied to a model during its development. Model calibration is not the same as model validation and these processes take place at different points in the model development cycle.

2 Internal Verification and External Validation of Models

Reasons for errors and uncertainties in models include incorrect assumptions, errors in *a priori* information (e.g. model parameter values), errors in numerical solutions of model equations and errors in experimental procedures and measurements. Much effort has been devoted to trying to separate different aspects of the model development, testing and checking process and to categorise simulation model errors according to their origins [21]. Nevertheless, uncertainty is inevitable since we do not have a complete understanding of the natural world and our measurements and calculations are limited in their accuracy.

An unvalidated model produces results involving unknown and potentially unbounded errors. Even if the user has confidence that the model produces accurate answers most of the time, the situations in which it does not produce accurate output cannot readily be recognised or predicted.

It is important to be precise about the use of words describing the model testing process. It is particularly important to distinguish between the processes of "internal verification" and "external validation". The words "internal verification" describe a process that involves establishing that a computer simulation is consistent with the underlying mathematical model while "external validation" is the process of demonstrating that a mathematical model representing a given real world system is adequate for the intended application [21]. Internal verification is, therefore, the part of the process concerned with establishing whether or not the model is solved correctly, whereas external validation deals with issues of correctness in terms of the structure and parameters of the underlying model description in mathematical and logical terms. This convention is completely consistent with a well-established set of recommendations made in 1979 by the SCS Technical Committee on Model Credibility [22]. Unfortunately, the words "verification" and "validation" are often used in an imprecise fashion. There are also specialist areas (especially in some defence applications such as missile system modelling) where, in the past at least, traditional usage by engineers in some countries reversed the meaning of these two words, compared with the SCS Committee recommendations. It is believed that the inclusion of the adjectives "internal" and "external" helps to reduce the confusion that may otherwise exist when model quality and testing issues are being discussed.

The processes of internal verification of a simulation model are similar to the more general processes of software testing [23] and many of the principles and methods of software testing can be applied. On the other hand, external validation is a more demanding and open-ended task that involves comparisons between the behaviour of the model and the corresponding behaviour of the real system for chosen sets of experimental conditions. This can involve quantitative comparisons of the model's performance with the real system or a subjective judgement by someone who has a profound understanding of the real system.

Sargent [24] narrowed the definition to emphasise the issue of the accuracy needed for useful model-based predictions in the context of a specific application. This idea can be extended so that external validation is defined as the *confirmation* that the model output has a level of accuracy consistent with the intended use. If this type of approach is used, it is important to ensure that the required accuracy of the model is established prior to the start of the external validation process and not as part of that procedure. Thus, it is often useful to express the results of external validation processes in terms of the appropriateness of the model for a specific application rather than in more absolute terms of a "good" or "bad" description. Indeed, one can never prove that a model is valid; a model can only be proved to be invalid.

For external validation, an important distinction has also to be made between "functional" validation and "physical" validation. The first of these is concerned with the development of a model that mimics the input-output behaviour of the real system whereas physical validation involves establishing the acceptability or otherwise of the underlying assumptions and approximations [25]. As has been pointed out by Hemez [26], perfect matching of all available measured response data is an unrealistic goal and it is more important to ensure that models match available test data with a sufficient level of accuracy for the intended application. This helps to ensure that a given model reproduces test data with an acceptable level of accuracy, while also having a satisfactory robustness to uncertainty. Such uncertainty can be associated with many factors, including modelling assumptions, environmental and model parameter variability or ignorance in terms of initial conditions in the real system. As in control system design, there tends to be a conflict between performance optimality and robustness optimality in modelling [26].

Balci and his colleagues have, in recent years, been stressing the importance of expanding verification and validation from accuracy-centred assessment to assessment which is more quality-centred (e.g. [27]). Quantitative measures of model credibility are hard to define but discussions about the quantification of model credibility may also be found in many sections of the book edited by Cloud and Rainey [28], in the papers by Brade and Köster [29] and Brade, Maguire and Lotz [30] and in the classic textbook on the theory of modelling and simulation by Zeigler, Praehofer and Kim [31].

There have been many suggestions that model testing and accreditation should be more closely linked to ideas of software quality assurance in software engineering (e.g. [29]). This implies improvements in current tools and technologies and also supports the idea that many working in the field of modelling and simulation have much to learn from software engineering principles [23].

2.1 Methods for External Validation

External validation of simulation models is complicated by the fact that most models intended for practical engineering applications involve dozens or even hundreds of quantities that are established and input by the user (e.g. as model parameters), making the problem space very large. Similarly, most models can produce, as outputs, dozens or even hundreds of variables, each of which is likely to contain different levels of error which may also vary with time in the case of a dynamic description. Thus, it is important to establish, *a priori*, which of the output variables of a simulation model are of most interest to the user of the model for the given application. Different users will be interested in different performance measures in different modelling studies and this emphasises the importance of properly matching the model to the intended application at the outset and of establishing *a priori* how much error in the results can be tolerated.

External validation should be considered as an ongoing exercise within the overall modelling process, rather than as a one-off procedure carried out at the end of the model development cycle. It is also important to distinguish between holistic approaches that attempt to validate a complete model externally and model-component approaches in which external validation is carried out at a sub-model level at first. Both are based on the same general principles of external validation but the model component approach may also involve comparisons with test data from component manufacturers.

Confidence in a prediction is a function of the confidence demonstrated in sub-system models as well as in the complete model. This is particularly important where sub-system models can be tested experimentally. Exhaustive testing of sub-system models allows confidence to be established first at the sub-model level and extended gradually to less well-defined situations involving testing of the complete system model over a range of experimental conditions.

In the development of entirely new systems experimental data from the complete system cannot be available at the design stage. In some cases historical data from earlier systems of a similar kind can be helpful in the evaluation of the model of the new system under development. Successful application of this approach depends on good documentation of models of the earlier systems and of the tests carried out to evaluate those system models.

Methods of external validation (i.e. the procedures used to compare observed and simulated values) can be divided into subjective and objective categories. The first approach is based mainly on graphics while the second one involves quantifying the process through specific measures and statistical procedures.

Graphical methods for external validation are typically characterised by plots of simulated values (often continuous and represented by a line) and observed or measured values (usually discrete and represented by points) against an independent variable (often time). One important point of detail, sometimes missed by inexperienced observers, is that the deviation between the simulated and measured values is the vertical difference between corresponding points and should not be assessed simply as the shortest distance between the simulated and measured time history curves.

Another commonly used form of graph involves a simple plot of simulated values against the corresponding measured or observed values. Ideally the plot should be a straight line at an angle of 45 degrees to the axes. Deviations from the ideal are shown by the vertical distance between the points and the 45-degree line and can apply generally to the record as a whole or can be specific to certain sections of the data. Points above the 45-degree line are clearly over-estimated in the simulation while any points below the line are under-estimated. Although viewed by many as subjective, graphical methods are very useful and practical in model validation to complement quantitative measures. Different graphical methods tend to be used in conjunction as different methods of displaying information about a model may provide different types of insight [32].

Quantitative measures for system and model comparison are also very important. The most used deviance measures are the mean-square or mean absolute errors. For the case of n sets of measured and simulated values, the mean absolute error is expressed as the difference between observed values y_i and simulated values $\hat{y}_i$, by:

$$J_1 = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{1}$$

or using the closely related mean absolute percent error, given by:

$$J_2 = \frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{|y_i|} \tag{2}$$

This is a relative error and is inapplicable if any of the observed values happens to equal zero. An obvious disadvantage of these two measures is their sensitivity to single extreme values.

Such an approach can be extended to include some form of weighting function. This means that errors arising in specific sections of the time history can be given special emphasis. One such cost function is:

$$J_3 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^T w_i (y_i - \hat{y}_i) \quad (3)$$

where w is a weighting factor and the superscript T indicates the transpose.

A measure that has received particular attention for external validation applications in a number of different application areas is Theil's Inequality Coefficient (TIC), which is defined as:

$$J_4 = \frac{\sqrt{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2)}}{\sqrt{\sum_{i=1}^{n} y_i^2} + \sqrt{\sum_{i=1}^{n} \hat{y}_i^2}} \quad (4)$$

This measure has an advantage in providing values that lie between zero and unity, with values of TIC close to one indicating sets of model and system data that are very different. Values of TIC close to zero indicate small differences between the model and the system time histories.

Other scaled measures are commonly used for comparing model and measured system time histories. Measures based on statistical techniques have received attention in the context of model structure assessment. In particular, step-wise regression and spectral techniques have been used for a variety of practical modelling investigations [21].

One approach, which can be used with benefit in cases where relatively complex models are being considered, involves taking a number of key measured system or sub-system quantities and plotting these as radial lines on an appropriately scaled polar diagram. The length of each line is proportional to the corresponding measure. By constructing a polygon of model measures and a polygon of experimentally determined results from the real system on the same polar diagram an immediate indication of overall model quality is obtained. It should be clear from a comparison of this kind which aspects of the system are represented most accurately and which areas of the model require further investigation. Such diagrams also provide a good way of displaying results from sensitivity analysis of a model. The distortion of the model polygon following a specific imposed change is a useful indication of the overall effect on the model. Polar diagrams of this kind have been used successfully in the context of model testing for electro-optic sensor models [13] and have been considered in the context of fault detection applications as well as in other model testing situations [33]. Although developed independently for the purposes of model test visualisation, these diagrams have many features of Kiviat diagrams which are used in software engineering for visualisation of different metrics associated with software performance and computer hardware evaluation.

All of the quantitative measures mentioned above can also be applied to situations in which one model is being compared with another. This is really a form of verification rather than of external validation. It can arise in situations where a complex, computationally demanding and externally validated simulation model exists but there is a need to derive and test a simpler form of representation which runs on the computer significantly faster. Clearly, the measures and visualisation techniques discussed above can be helpful in the testing and assessment of candidate models in this type of situation, which arises frequently in the development of simulation models that are capable of running in fast timescales, including some real-time applications. An example of this kind may be found in some recently published work of Zenor et al. [34] describing the development of a multi-rate simulation of an underwater vehicle and associated electrical drive system.

2.2 Other Approaches to Model and System Comparison

In some situations, expert opinion plays a vital role in evaluating the suitability or otherwise of a simulation model. For example, a test pilot can quickly establish problem areas in a flight simulator or an experienced plant operator can identify features of a process simulation that do not fit well with his or her knowledge of real process behaviour. In some situations animation can be very helpful in allowing such experts to pinpoint problem areas. Critical examination and correct interpretation of simulation model behaviour from multiple time-history plots is generally far more difficult than viewing the model output in terms of an animation.

Complications arise with methods based on response comparisons when several output variables have to be considered simultaneously or when measurement noise is significant. Methods based on system identification provide a useful alternative to more direct comparisons and can be particularly helpful in giving physical insight about model limitations. The concept of identifiability can also be useful in the design of model validation experiments. Other tools, such as sensitivity analysis, have also been shown to be valuable [21].

Sensitivity analysis can be very important in another way. One very practical approach to external validation (once adequate agreement has been achieved following model calibration activities using system identification tools or other techniques for tuning), involves examining and comparing the effect of changes in the system and the model. For example, in a mechanical system this might simply involve adding mass to some element of the system and changing the corresponding parameter of the system model to test whether the system and model behave in the same way following this modification. If the behaviour is not the same (to some appropriate and predetermined level of agreement) the model will have to be reviewed in terms of its structure and parameters.

Although a generic model can never be fully validated, specific versions of the model can be tested using the general principles of external validation and the measures outlined in Section 2.1 above. More detailed discussion of issues that arise in the testing and external validation of reusable and generic models may be found the work of Malak and Paredis [35]. In the context of automated material handling system design, the paper by Mackulak, Lawrence and Colvin [36] provides useful quantitative information about the benefits of simulation model reuse in terms of model building and analysis for semiconductor material handling applications and provides useful comments on issues of validation in this type of application. Further discussion of the problems inherent in validating generic models may also be found in [12] and [13] for the specific case of electro-optic system models.

3 Engineering Control Systems Applications

Issues of model accuracy have for long been recognised as important in the design of high-performance automatic control systems (e.g. [37, 38]). For high-performance feedback systems it is important to have highly accurate linearised models of the controlled system (the "plant") in the frequency range close to the cross-over region. This is the part of the range where the phase lag for the forward path system transfer function approaches 180 degrees. Model uncertainties within the cross-over region can produce problems in attempting to meet given performance specifications in the closed-loop system.

Much research has been carried out in recent years on frequency-domain modelling for robust control design (e.g. [39]) and on plant model validation by means of system identification methods [40]. However, relatively little consideration has been given to problems of design in highly integrated systems where the traditional division into a "plant" and a "control system" becomes unclear. In particular, we need to consider how we can ensure quality in models that are used for controller design when the plant itself has not yet been completed and is being designed specifically to provide enhanced control capabilities. These are fundamental questions that have already been encountered in the design of advanced aircraft where "control-configured" design has become commonplace. They are likely to have to be addressed in many other control application areas in the future. It is generally accepted that an integrated approach to design should involve the use of generic, externally validated and re-usable sub-models. This is an important issue that is receiving attention in many areas of engineering.

External validation presents particular problems when considered in the context of highly integrated systems. Validation must be iterative and must be carried out in different ways at a number of different stages within the complete design process. With conceptual models at the initial stages of the design process, external validation can only be carried out in a general way. As details of the systems start to evolve validation may necessitate comparisons of reduced models suitable for control system design with computationally more intensive models [41]. At a later stage, detailed testing of sub-systems and hardware-in-the-loop simulation comparisons should become possible. Comparisons may also be made with models that formed the basis of earlier designs of a similar type.

Models are also important for systems that provide automatic fault detection and fault isolation. The critical issue in such systems is to be able to detect faults whenever they occur but avoid false alarms. Fault detection systems that are based on models usually involve monitoring of residuals formed from the differences between corresponding system and model variables. Ideally such residuals are zero in the absence of any fault condition and take non-zero values when a fault occurs. However, non-zero residuals can also arise from measurement noise, unmeasured process disturbances and modelling errors. Appropriate threshold levels for declaration of a fault condition must therefore be chosen. The issue of how to avoid false alarms due to model inadequacies is an important one in such fault detection systems and is closely linked to questions of external validation.

4 Model Documentation

External validation processes do not end when a model is accepted for a particular application. Model documentation, as with documentation of computer software, must allow for changes and further development of the system. Understanding about the limitations of a given model can increase considerably during the application phase of a design project and documentation should be properly updated and maintained for the whole life cycle of the project. This documentation may also be helpful for later developments involving the design of similar systems. Brade [7], as well as emphasising the need for more meaningful documentation and criticising the present lack of quality assurance as an integral part of the model development process, discusses at some length the potential and current limits of documents such as the Verification, Validation and Accreditation Recommended Practices Guide of the US Defense Modeling and Simulation Office [42].

Items in the record for a given model should include the purpose of the model and the intended application, a full model description and the corresponding computer simulation code where applicable, a list of all the assumptions and approximations in the model, details of tests carried out on the real system, details of checks carried out to ensure that the computer-based representation or simulation matches the mathematical description (the process of internal verification) and details of external validation processes applied along with the reasons for accepting or rejecting the model. The documentation should also include statements about the range of applicability of each accepted model.

The process does not end with the decision to accept a model for a particular application. As with the documentation of computer software, the system of model documentation must be capable of accommodating changes and must be updated and maintained for the whole life cycle of the system represented by the model. Regressive testing of models is as important as regressive testing in software projects.

5 Implications for Engineering Education

Methods of model development and testing being applied in industry at present can only be improved if those involved in education recognise the need for change. Engineers are usually introduced to mathematical modelling and encounter computer-based modelling and simulation methods early in their university education. However, the teaching of system modelling methods too often stops with the formulation of equations from physical laws and principles or by system identification and parameter estimation methods. Students are not forced often enough to consider what constitutes a good model and issues of model quality are too often glossed over. Indeed, model evaluation, if considered at all, is often presented as an afterthought rather than as an essential part of the iterative process of model development. Students need to appreciate that correction for model inadequacies can be expensive and time consuming if it is left to the implementation and final testing stage.

In the words of Hardy Cross, a former Professor of Civil Engineering at Yale, "… an important duty of teachers is to force students repeatedly back into the field of reality and, even more, to teach them to force themselves back into reality" [43]. Students must develop an understanding of the limitations of models and for this they need to make critical comparisons of models with real systems. They also need to be required to document models and model testing processes in the same way that they are required to document software that they prepare and test as part of their course-work.

6 Discussion

Validation may be defined as the process of assessing the credibility of a simulation model within its intended domain of use:

1. by establishing whether the simulation model is a correct representation of the underlying mathematical or other formal description (internal verification), and
2. by estimating the degree to which this model is an accurate representation of the real-world system for the intended use (external validation). Whatever the engineering application, the more demanding the system specification the more important it is that adequate consideration be given to these questions that involve issues of model quality.

All models have limitations and the purpose of validation must be to properly define and understand those limitations. However, any practical validation investigation can cover only a finite, and often relatively small, number of test cases. Thus, one should never attempt to prove that a model is correct under all sets of conditions. Instead, a degree of confidence should be established in the model so that its results can be recognised as being reasonable for the objective for which it has been developed. General statements about the validity or quality of a model are therefore inappropriate without reference to its application and the range of conditions considered. One of the inherent problems is the fact that quantitative measures of model credibility are hard to define and as models become more complex there are increasing problems of visualisation.

Continuing research on improved procedures for model development, enhanced computing environments and systematic processes for assessing, correcting and documenting models that are used in engineering design is important. It is also essential that work is directed towards further developing and maintaining libraries of validated simulation models and commonly used sub-models. This is particularly important in terms of being able to fully exploit the benefits of model re-use and the development of generic models.

A strategy is needed to ensure that modelling techniques are properly applied and more effort is needed in all of these areas if we are to reduce development times and costs. The current situation in system modelling contrasts strongly with accepted good practice in the software engineering field where rigorous testing, documentation and version control are an integral part of the recommended processes of software development.

Ideally, what we need is some way of producing confidence intervals for model predictions. Although this goal may be elusive in the case of general nonlinear physics-based parametric simulation models, it is interesting to note that in the Gaussian Process (e.g. [44]) type of nonlinear non-parametric model such additional information is readily available. Also, for linear models, the use of coherence estimates within frequency-domain descriptions of system outputs allows determination of the range of frequencies over which the linear model is applicable (e.g. [20]). More research aimed at applying such techniques to practical engineering problems and developing better ways for assessing the accuracy of predictions from nonlinear physics-based models is essential.

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SPL	Simulation in Production and Logistics Sigrid Wenzel, *s.wenzel@uni-kassel.de*
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Czech Technical University celebrates 300 years of its history in 2007. Under the name Estate Engineering Teaching Institute in Prague was founded by the rescript of the Emperor Josef I of 18 January 1707 on the basis of a petition of Christian Josef Willenberg (1676-1731). This school was reorganized in 1806 as the Prague Polytechnic, and, after the disintegration of the former AustroHungarian Empire in 1918, transformed in to the Czech Technical University in Prague.

About EUROSIM

EUROSIM, the federation of European simulation societies, was set up in 1989. Its purpose is to promote, especially through local simulation societies, the idea of modelling and simulation in different fields, industry, research and development. At present, EUROSIM has 14 full members and 4 observer members.

Congress Scope and Topics

The Congress scope includes all aspects of continuous, discrete (event) and hybrid modelling, simulation, identification and optimisation approaches. Contributions from both technical and non-technical areas are welcome. Two basic tracks will be organized: M&S Methods and Technologies and M&S Applications.

Czech Republic - EUROSIM 2010 Host Country

The Czech Republic is a country in the centre of Europe. It is interesting for its 1,000-year-long history, rich culture and diverse nature. The country is open to new influences and opportunities thanks to a high level of industrial infrastructure, safety measures and plural media. The location of the Czech Republic in the very heart of Europe contributes to the fact that one can get there easily and fast. Usually all it takes to enter the country is a valid passport. The Czech Republic belongs to the Schengen zone. The need for a visas to enter the Czech Republic is very exceptional.

Prague - EUROSIM 2010 Host City

Prague is a magical city of bridges, cathedrals, gold-tipped towers and church spires, whose image has been mirrored in the surface of the Vltava River for more than a millennium.Walking through the city, you will quickly discover that the entire history of European architecture has left splendid representatives of various periods and styles. There are Romanesque, Gothic, Renaissance, Baroque and Classicist buildings, as well as more modern styles, such as Art Nouveau and Cubist. A poet once characterized Prague as a symphony of stones.

About CSSS

CSSS (The Czech and Slovak Simulation Society) has about 150 members in 2 groups connected to the Czech and Slovak national scientific and technical societies (Czech Society for Applied Cybernetics and Informatics, Slovak Society for Applied Cybernetics and Informatics). Since 1992 CSSS is a full member of EUROSIM.

Invitation

Czech and Slovak Simulation Society is greatly honored with the congress organisation and will do the best to organise an event with a high quality scientific programme with some other acompanied actions but also with some unforgettable social events.

Mikuláš Alexík, EUROSIM president,
Miroslav Šnorek, president of CSSS, EUROSIM 2010 Chair