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A SURVEY ON METHODOLOGICAL ASPECTS OF COMPUTER SIMULATION AS RESEARCH TECHNIQUE

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ABSTRACT

Computer simulation has evolved to a standard means for planning, analyzing, and optimizing complex systems. Yet, a twofold usage can be observed: as a tool for generating data and as a method for deriving knowledge. The objective of this paper is to outline epistemological consequences arising from this methodological uncertainty by analyzing the state of discussion as well as challenges of using simulation as a research technique for deriving knowledge. On basis of the WSC archive, we performed a survey to analyze the methodical application of procedure models established in computer simulation and to identify whether these models provide differentiated methodological support for conducting simulation studies. The contribution of this paper is a survey on procedural approaches as well as the proposition of methodological challenges of computer simulation as a research technique in information systems research.

1 INTRODUCTION

Nowadays, the application of computer simulation has been established as a technique for analyzing, understanding and developing systems in information systems research. But, according to the context of the phenomena being investigated and the research question stated, the impact, focus, and conduction of simulation studies may differ. Thus, a proper definition of the procedure of computer simulation is important for generating comparable results. Methodical aspects of computer simulation have been regarded for a long time and the community has developed frameworks, assisting the application of computer simulation. However, considering methodological aspects for improving the theoretical understanding of this technology as part of the research process itself has been neglected. (Hudert et al. 2010)

Challenges in practice and industry are a starting point for information systems research. But, in contrast to business administration and computer science, formal verification and empirical analyses are not appropriate for validating new findings. In consequence, computer simulation has evolved to a standard means here. Doing so, there is a gap between the application of computer simulation for proofing beneficial behavior of a new approach and the epistemic foundation of computer simulation as research technique. Without providing standardized models for the conduction and evaluation of simulation experiments, credible results cannot be generated. Thus, the objective of this paper is to analyze the state of discussion as well as challenges of applying computer simulation by means of information systems research.

The paper organizes as follows: In Section 2, the evolution of computer simulation is introduced briefly. Therefore, purposes for applying computer simulation are classified and, based on this, a definition of simulation as a tool and method is provided. Afterwards, established procedure models for conducting computer simulation studies are derived from surveying the archive of *Winter Simulation Conference (WSC)* and the models' ability to provide a differentiated methodological support for conducting simulation studies is analyzed. Finally, challenges of using computer simulation in information systems research are derived.

2 EVOLUTION OF COMPUTER SIMULATION

Almost 70 years ago, the foundation for computer simulation has been laid. Back then the invention of ENIAC (a "general purpose electronic computing machine" (Goldstine and Goldstine 1946) developed for calculating fire tables during World War II) enabled scientists to automatically execute mathematical computations for solving numerical problems (Ulam 1990). Since then, hardware for executing simulation experiments has been enhanced and the application areas expanded. Nowadays, computer simulation is applied in various disciplines and has become an essential technique in scientific research. By observing and adjusting simulation models, hypotheses concerning the behavior of artificial systems can be evaluated and the impacts of modifying real systems can be estimated ex ante (Banks 1998). However, findings made by analyzing artificial systems are often used for drawing conclusions in regard to the real world. Especially in the context of investment decisions, simulation is frequently used for purposes of planning alternative approaches. Common areas of application are, for example, factory planning including material-flow simulation (e.g. Kühn 2006) or traffic simulation when building new road networks or redesigning traffic junctions (e.g. Lattner et al. 2011). Therefore, the necessity of general conditions and guidelines for assuring a certain level of quality is obvious. Reliable results can only be generated if the preparation and execution of simulation experiments are conducted under well-defined or even standardized conditions. Only in this case, results may be used as a profound basis for decision-making or as an origin for further research.

Since the beginnings of simulation research, numerous articles have been published discussing the classification and application of the technology. In this regard, various approaches describing conditions for conducting simulation studies have been proposed as well. Furthermore, the definition of the term computer simulation itself is varying in literature. Humphreys compared partially opposing definitions and derived the following definition: "A computer simulation is any computer-implemented method for exploring the properties of mathematical models where analytic methods are unavailable." (Humphreys 1990) In contrast, Banks developed another commonly used definition of the term computer simulation: "A simulation is the imitation of the operation of a real-world process or system over time." (Banks 1996) The definitions mentioned above emphasize the ambiguity in the understanding of the technology. Computer simulation can either be regarded as a *method* (e.g. for the generation of knowledge (Ören 1987)) or a *tool* (e.g. for generating artificial scenarios by imitating real systems (Reynolds 2008)). Yet, when performing simulation experiments, most of the authors do not seem to be aware of this fundamental methodological uncertainty. Accordingly, a proper application of computer simulation is difficult.

3 POSITIONING OF SIMULATION

In order to understand the process of performing simulation studies, objectives of applying simulation have to be considered first. This question originated in philosophy of science, as it concerns foundations, approaches and implications of computer simulation. Winsberg, whose research mainly focuses epistemological considerations of computer simulation, describes three main fields of application. For one thing, it can be used for heuristic reasons. In this case, a distinction is made according to the purpose of the simulation. It can either be used for communicating knowledge (e.g., visualizing (natural) processes by simulation for improving the understanding) or for representing information (e.g., to communicate features of a system or structure to others by making them explorable using simulation). Summarizing, it can be considered as experience-based problem solving technique (Winsberg 2010).

Furthermore, depending on the availability of input data, simulation can as well be used for understanding and prediction purposes. In case of data not being available, simulation can create artificial copies of real world systems for further consideration. Doing so, the expected behavior of a system can be evaluated under certain conditions and data can be collected. In case of existing data describing the system's behavior, simulation can be used for understanding the mechanisms leading to this behavior and how certain events occur (Winsberg 2014). These different purposes lead to an even greater variety of aspects and goals of simulation. Regarding the heterogeneous areas of application stated above, it is obvious that computer simulation needs to be considered in a sophisticated and differentiated way. Depending on the way of use, individual procedure models need to be applied. Hence, a suitable differentiation of simulation purposes needs to be provided first. In literature the terms *tool* and *method* are frequently used in the context of the application of computer simulation. But it appears that these terms are either being used without questioning their actual meaning or even as synonyms. Yet, they seem to be appropriate for a fundamental differentiation of the fields of application.

3.1 Simulation as a Tool

The Oxford Dictionary defines a *tool* to be “a device or implement [...] used to carry out a particular function” (Oxford Dictionaries 2014). Transferred to computer simulation this implies an instrumentalized use. Fishwick describes a tool as “handy and useful” (Fishwick 1997) in the context of simulation research. This description corresponds to the statements of other authors, classifying computer simulation as a research tool. Schmidt, for example, mentions using simulation for evaluating whether components of a system accomplish their purposes during systems analysis. He justifies this statement by outlining the similarity of necessary steps being conducted to those of other modeling approaches. Hence, he describes particular functions fulfilled by computer simulation in the context of operations research and thus declares it to be a tool (Schmidt 1984).

Gogg and Mott outline purposes of simulation applying it as a tool, too. From their point of view, simulation is an “analytical tool that can significantly facilitate the problem-solving process” (Gogg and Mott 1993). When creating a representation of a real process or system, simulation can help to determine which input is most qualified for generating a desired output. Corresponding to the opinion of Maria it may be summed up that computer simulation is frequently considered to be a useful technology for the evaluation of the performance of a, possibly artificial, system by applying and comparing different configurations (Maria 1997).

3.2 Simulation as a Method

In contrast, the term *method* is defined as “a particular procedure for accomplishing or approaching something, especially a systematic or established one” (Oxford Dictionaries, 2014). Compared to the definition of *tool*, a procedural manner is essential for method-oriented computer simulation. Contrary to a practical understanding of computer simulation suggested in 3.1, a method emphasizes systematic and adaptive properties of a technology. Especially when seen from an epistemological perspective, a method describes the entire process starting from a hypothesis regarding a certain subject in order to generate causal explanations for certain phenomena (Carter and Little 2007).

A variety of disciplines, which are traditionally not familiar with using software systems, began adopting computer simulation as an essential part of their process of knowledge generation in research. Sociologists, for example, create artificial societies using computer simulation. Based on these virtual worlds, experiments, which cannot be performed in real-world environments, can be carried out. Thus, the possibility of detailed observation can be provided and new insights can be gained.

Gilbert refers to the new set of opportunities becoming available to research disciplines by the use of computer simulation as *simulation-based research* (Gilbert and Troitzsch 2005). Social scientists, e.g., are being enabled to set up hypotheses or research questions concerning hypothetical scenarios and complement the model by using assumptions or empirical observations. However, the demand of simulation approaches initiated or requested by other research disciplines, for instance social sciences, is not unilateral. It has been perceived by computer science as well. Davidsson, for example, took up the social scientists’ demand of a computer science view on social simulation and positioned it as a research method between the two disciplines (Davidsson 2002). The examples mentioned above represent the methodical use of computer simulation, as they describe a procedure for approaching a particular goal.

3.3 Two sides of the same coin?

In this section, we defined the terms tool and method as characteristics of applying simulation. By enabling scientists to quickly adopt existing models and to generate alternative, artificial worlds, new possibilities of exploration and exploitation emerge. However, knowledge generated using simulation studies needs to be justified methodologically. The twofold use of simulation poses a challenge in this context. By reducing the technology to its usefulness to carry out a particular function, systems can be analyzed, performance measured or problems solved. Likewise, methodical usage of simulation can be assigned to prediction or understanding purposes. The process of knowledge generation can either be predictive or it can support researchers to gain a deeper understanding of specific phenomena. Obviously, in computer science research, both directions are reasonable means. In either way, it is necessary to identify scientific requirements and current state of discussion for conducting simulation experiments.

4 STATE OF DISCUSSION

Starting from a theoretical, i.e., philosophy of science oriented, perspective, we analyze challenges for applying computer simulation with special focus on research. Following, an evaluation of the community's state of discussion concerning process organization in computer simulation in depth is presented. Therefore, we surveyed the entire archive of WSC, which contains more than 5.500 contributions and is available online. Due to the long existence of the conference, the archive seems appropriate to be used for reflecting the community's state of discussion and its evolution. Based on this, we preselected the most relevant articles by evaluating the titles and abstracts of all on-topic contributions including their references. These articles have then been analyzed in detail and classified for this paper. The methodology applied here is based on a longitudinal analysis using human expert knowledge for selection and interpretation. In contrast, a broad analysis of a research field requires a more automated approach, i.e., applying semantic content analysis to available publications in this field using, e.g., techniques from the field of big data analysis as shown in (Diallo et al. 2015). In this paper, we present results of the first step in such an combined analysis, focusing on a longitudinal analysis.

4.1 The Winter Simulation Conference as Contemporary Witness

Since 1968, WSC has taken place annually (except for 1972) and presents itself as "the premier forum on simulation practice and theory" (Wilson 1996) which, considering the conference's history, indicates an overview of relevant work conducted in context of simulation. Therefore, the entire archive has been analyzed with focus on work describing the execution of simulation experiments.

A first brief evaluation of the contributions to WSC revealed that the greater part of articles focuses on the development of simulation models for certain practical cases of application, rather than acquiring or introducing guidelines for performing simulation experiments successfully. Generating reliable and reproducible results appears not to be of central relevance. Considering the development of the conference over time and the range of subjects covered a trend can be recognized. In the late 60s and early 70s, when computer simulation was still in its early stages of development, contributions on how to improve the technique of simulation can be found occasionally. The issues considered by the authors were, e.g., related to the estimation of reliability in simulation experiments (Fishman 1968), the use of experimental design techniques in simulation (Frank 1968), or the necessity of a methodology for simulation (Mihram 1973). Thereafter, up to the mid and late 70s, methodological and process-oriented aspects of computer simulation have been neglected. The conference and its tracks mostly focused on the creation of simulation models for solving social, technical, medical or economical issues, for example in the context of health service (Kennedy 1973), financial markets (Frankfurter and Horwitz 1971) or even aerospace engineering (Flanagan et al. 1973). Towards the end of the 70s, a refocusing of WSC can be observed. Henceforth, papers and tracks regarding methodology of computer simulation were no longer uncommon and became an inherent part of the conference.

4.2 Epistemology of Computer Simulation

Considering computer simulation as a research method in contrast to "just applying" computer simulation in an industrial context, the credibility of computer simulation is in question. From a philosophy of science point of view, simulation is a technique for generating data, i.e., given a model and probabilistic attributes, new information about the system's behavior is derived automatically. The draw-back of simulation is that it is similar to testing a system from a computer science perspective: only single points in the state space are evaluated and no guarantee about the behavior in other states can be provided. Going back to the perspective of philosophy of science the question arises, what kind of research approaches simulation is related to: Behavioristical, Empirical or Theoretical?

At first sight, computer simulation seems to be derived from empirical research, however, in simulation we construct an artificial system, i.e., the simulation model, and therefore an additional validation problem occurs for the modeling step. These considerations lead to the idea that results based on computer simulation are less valid than results derived by empirical research. The possibility of varying parameters and repeated simulation runs provides an excellent starting point for a sophisticated research method. Consequently, the question arises how to make the potential of computer simulation accessible to research. For summarizing position papers related to this, experts from different WSC-related domains arranged a panel for "Epistemology of Modeling and Simulation", discussing the science-philosophical foundation of computer simulation (Tolk et al. 2013).

To establish computer simulation as research method, philosophy of science demands an independent replication of results, that results are not a consequence of chance, and that individual preferences of a researcher do not influence the results (Heath and Hill 2009). The replication of results by different researchers is an important aspect to derive knowledge which is not only subjective but of general interest, i.e., a paradigm can only be established, if a majority of researchers follows the new knowledge (Kühn 2006). In simulation, a special situation exists: As part of the research process, the real world phenomenon is abstracted to a mathematical artificial model. To achieve comparability the identification of similar research objects in the artificial models is important and thus, a common language is needs to be provided.

In the last years, significant research has been performed to analyze and develop formal conceptual models by applying semantic methods like ontologies (Turnitsa et al. 2010). On the basis of well-defined conceptual models, as an abstraction of simulation models themselves, the re-implementation of a model by different researchers or using different tools is improved significantly. Thus, cross-validation is supported (Robinson 2013). However, the influence of the researcher or research strategy has to be eliminated, too.

The underlying problem is well known in the field of natural sciences. Here, a researcher has to define relevant research parameters in advance: Objectives, input, expected output, rules for the evaluation of data, and a protocol for doing the research. Transfered to computer simulation, this implies that systematic procedure models are required for reliable application of simulation as a research technique. As current work exists on conceptual models, the focus of this paper is to identify the current state of research on procedure models.

4.3 Procedure Models

As a result of the previous advances in simulation research, the first procedure models considering the entire simulation process were presented as part of WSC in the early 80s. However, even though computer simulation is used by diverse scientific disciplines, a review of the relevant contributions reveals a number of apparently universal procedure models. The models presented in the following section, and especially in table 1, are a compilation of contributions presented during WSC and the authors' references.

Considering the commonest publications in the context of simulation processes, Law and Kelton are mentioned frequently. As long ago as in 1982, the two researchers identified and published essential steps in simulation studies. In ten steps they describe the **procedure of a simulation study**. Furthermore, each step is explained briefly and in a comprehensible way. Most of the elements of a simulation study mentioned by

Law and Kelton appear in later models as well, even though interpretation or order might vary. The authors are referencing (Shannon 1975) and (Gordon 1978) as influences of their work. However, Gordon will not be considered any further within this paper, as his work focuses on techniques for system simulation and hence ignores the modeling aspect (Law and Kelton 1982).

Even though Shannon did not propose a procedure model to WSC until 1998, he suggested stages of simulation studies that "may be distinguished" (Shannon 1975) already back in 1975. Shannon's and Law/Kelton's procedure models mainly differ in two aspects. On the one hand, Shannon makes a distinction between system data, describing the boundaries and behaviors of a system, and input data, for executing the model. On the other hand, the experimental design will be double-checked in Shannon's model. After a preliminary **experimental design** has been defined, the final design is specified after the verification and validation process, before the experiments will be conducted (Shannon 1998).

The remaining models, as they mainly refer to Shannon's and Law/Kelton's work, will not be textually introduced in particular. Instead, only remarkable extensions, comments or unique features relevant for this paper will be emphasized. Nevertheless, the entire setup of each model is shown in table 1.

For visualizing procedure models, most authors have chosen sequence diagrams. Doing so, they illustrate the modular structure of the models and underline the interdependency between the individual steps. These requirements, which are closely related to software projects, indicate that simulation studies have to be planned properly as well, in order to support a successful progress. While Law and Shannon recommend this step, Balci, Centeno, Friedman, Maria, Musselman, and Schmidt do not seize it.

Another central component of most procedure models analyzed during the survey is the aspect of **verification and validation** (V&V). Hence, at WSC, this is an ubiquitous research topic, too. Verification is the process of examining the program code, checking it for mistakes causing the algorithms not to behave in the intended way. Validation, in contrast, describes the correct representation of the real world phenomena through the model. In order to validate a program or model, the verification needs to be completed successfully. In case of computer simulation, V&V can be applied to the conceptual model and the simulation model as well as to the results. However, all authors, except for Montgomery and Sadowski, recommend V&V of the simulation model, whereas validating the conceptual model is not even suggested by half of them. Balci even complements V&V with testing techniques and proposes the application during the entire study. Finally, the validation of the results and, as the circumstances require, a revalidation of the model are only proposed by Montgomery and Schmidt (Kleijnen 1995, Sargent 1998).

While executing simulation experiments, the steps proposed by the procedure models differ the most. Some authors limit their requirements to the pure execution of the simulation experiments. Other authors, however, emphasize the importance of defining variables for the **surveillance of the model** during experimentation. Furthermore, seizing a sufficient number of simulation runs is another underrated challenge when performing simulation studies. (Lattner et al. 2011) These general conditions are taken into account by less than half of the procedure models.

Summarizing, it can be determined that most of the procedure models mentioned above consist of three major components: The planning of the simulation study including the collection of relevant data describing the system to be modeled, the definition and development of a simulation model and environment (tool or framework), and the conduction of the actual simulation experiments. Considering, that individual experts are required for the realization of these components, a main challenge in simulation studies is to integrate and synchronize the collaboration in a suitable way.

5 METHODOLOGICAL CHALLENGES

In the previous chapters we analyzed and discussed computer simulation from a methodical and technical perspective. However, there is a methodological perspective on computer simulation as part of information systems, too. This perspective is related to philosophy of science, where different questions of deriving findings as well as adducing evidence are in question. In information systems research, there are three dominant research approaches: formal-logic oriented, behavior oriented, and design oriented. In this context

Table 1: Comparison of different simulation procedure models: Steps numbered consecutively in chronological order. Additional letters imply the combined execution of the steps.

	(Balci 1990)	(Banks 1996)	(Carson 2004)	(Centeno 1996)	(Friedman 1996)	(Law & Kelton 1982)	(Maria 1997)	(Montgomery 2001)	(Musselman 1994)	(Pegden 1995)	(Pritsker 1999)	(Sadowski 1992)	(Schmidt 1984)	(Shannon 1975)
Define the problem	1	1	1_a	1	1_a	1_a	1	1_a	1_a	1_a	1_a	1	1	1_a
Formulate objectives	2_a	2	1_b	2/4	1_b	1_b		1_b	1_b	1_b	1_b	2	2	1_b
Plan the project/study		3	1_c			1_c		1_c		2	1_c	3		2
Collect real system data	2_b	5	3/4	3	2_a	2_a	2_a	2	2	3	3_b	4_a	3	3
Create conceptual model	3_a	4	2		3_a	2_b	3		3	4	2	4_b	4/6	4
Validate conceptual model					3_b	3						5	5	
Identify/collect input data	3_b				2_b		2_b		4	6			7	6
Select response variables					2_c			3						
Translate the model in simulation language	4	6	3/4	5	4_a	4_a	4_a		5	7	3_a	6	8	7
Verification of the model	*	7	5_a	6_a	4_b	4_b	4_b		6_a	8_a	4_a		9	8_a
Validation of the model	*	8	5_b	6_b	4_c	6	5		6_b	8_b	4_b		10	8_b
Experimental design	5	9	6_a		5_a	7	7	4		5/9	3_c			5/9
Conduct experiments	6_a	10	6_b	7_a	6	$5/8_a$	8	5	10_a	10	5	7	11_a	10_a
Sufficient number of runs		12			5_b	8_b			10_b					10_b
(Statistical) analysis of output data	6_b	11	7	7_b	7	9	9	6	7	11	6	8	11_b	11
Documentation of results	8	13	8	8		10	6		8	12	7	9		12
Validation of the results, revalidation of the model	7							7					12	

computer simulation can be positioned as a research method for design oriented research. Doing so, it can be applied as methodology for supporting problem identification, conceptualization, and evaluation. Following this perspective, the general approach to computer simulation is slightly changed. The underlying question is, if the procedure models identified in the previous section are suitable and sufficient for scientific simulation studies. Therefore, we will introduce methodological challenges on the basis of discussing the use of computer simulation in information systems research.

The standard approach in computer simulation when applied practically is to derive output measures from a given objective, e.g., specification of goals like reduction of mean throughput time. Challenges occur in the research-oriented use of computer science as not only the fulfillment or the improvement of an output measure are in question but also the modeling itself can be part of the research findings. While in practical applications the final model with its current configuration is sufficient, in research sensitivity and variability of a model in different configurations should be considered. This leads to a different focus in the simulation study and the first methodological challenge: **the procedure of performing experiments has to be aligned with the overall research methodology** used.

Furthermore, with respect to other disciplines, like medicine, there is an intense specification face for experiments before starting with the "lab work". This includes the selection of methods to be applied during the research process and a specification of result interpretation methods. A specific requirement occurs in simulation studies as the simulation model may change during experimentation, e.g., when optimizing systems, such that experiments performed so far need to be rerun using the adapted model. This issue is as well related to testing in software engineering. Thus, we propose the **definition and specification of an experimental frame** as a second methodological challenge.

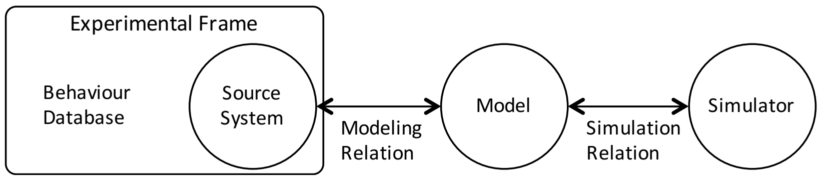

Figure 1: The basic entities of simulation studies and their relationships. (Zeigler et al. 2000).

A significant task when specifying the experimental frame is to consider the impact of determination of parameter variations, e.g., step size, number of replications, and granularity on the feasibility of the experiment and complexity of the simulation model. Simulation models consist of entities, each containing multiple parameters as well as external events or input data. When specifying variations of the experimental frame, e.g., step sizes, intervals for the parameters as well as input factors have to be selected. However, the high number of variation possibilities may easily lead to a combinatorial explosion of the number of parameter configurations. This can cause simulation times to exceed realistic scopes. Consequently, the feasibility of an experimental frame as well as the complexity of the computational complexity of the simulation model has to be considered. Furthermore, the feasibility also depends on the availability of multiple cores or multiple computational resources as well as the scalability of the simulation systems. The underlying challenge here is to **estimate the computational complexity of simulation models and to decide on the feasibility of an experimental setting**.

In the early days of computer simulation, the researcher has been the developer of simulation systems or researches and system developers have worked together very closely. Modern simulation systems follow the fundamental architecture discriminating simulation models from model executing, i.e., they universally execute any model specified with the underlying formal language. Zeigler (see fig. 1) describes such architectures consisting of three different components: source systems, models and simulators. The source system represents the real or virtual environment that shall be simulated, having a modeling relation to the model itself. The model, as it generates the output data of the simulation, is the core part of the entire simulation, however, it is highly dependent on the other components. The simulator then complements the model by adding a *simulation relation* to it. It serves as a computational device and executes the model. With an increased level of maturity in simulation technologies, various systems are available for practical application by domain experts. As a result, computer simulation has to deal with problems related to the use of statistics software, where users may apply algorithms, which are not suitable for a concrete problem. Here arises the fourth methodological challenge: **domain experts can inappropriately use simulation systems and derive potentially incorrect justifications** for findings from the results.

But even if researchers are aware of simulation technology, a valid model is required for deriving relevant findings from simulation study. A common assumption in the scientific community is that a valid simulation model cannot exist, as only the real world itself could serve as a valid model. For information systems research this implies that the abstraction or modeling has to cover the relevant aspects of the underlying problem. Thus, this solution could cover aspects or include technologies, which do not exist in the real world. This prevents the use of standard approaches for validation and verification. The resulting methodological challenge is to **gain a maximum level of validity with a compact model that allows for analysis and evaluation** of innovative approaches.

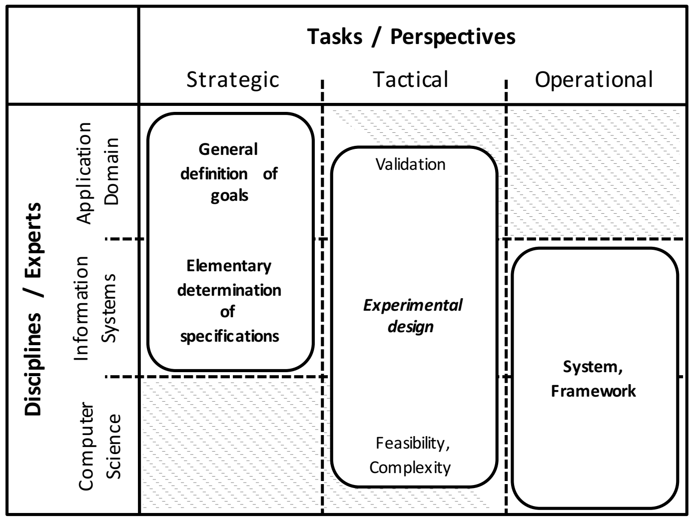

Figure 2: Disciplines involved in simulation study and their task fields.

The challenges introduced above are of high concern, when performing information systems research. Neglecting these challenges could serve as show-stopper because unjustified findings can be derived. However, information systems research is not only affected by these challenges, but can also play a leading role in developing solutions for addressing these challenges. In figure 2, a typical situation in information systems research is illustrated: information systems researchers are in change of managing the simulation experiment, modeling the domain, and specifying requirements for the technical level, computer scientists are responsible for the simulation system, and domain experts define the objectives.

However, the entire study can also be seen from a task-oriented point of view. In management sciences the terms *strategic*, *tactical* and *operational* are commonly used in context of planning or decision-making. Considering simulation studies, strategic decisions involve the application domain and information systems. In coordination between these two disciplines superior goals as well as elementary specifications leading to a conceptual model are being defined. Tactical tasks, as designing the experiments, will be managed by information systems research. However, approaches for validating the simulation model and its results need to be contributed by the application domain. Furthermore, issues concerning feasibility and complexity of experiments are located in the domain of computer science. Operational tasks, such as the requirements on simulation tools and frameworks will be mutually agreed between computer science and information systems research.

6 CONCLUSION

Simulation technology is of increasing concern for information systems research. The deriving of results as well as the procedure of simulation studies have to follow methodological rules. Thus, we aimed at analyzing the state of discussion in computer simulation, the identification of procedure models for systematic appliance of simulation studies, and deriving challenges for sophisticated simulation as part of research approaches. The survey of the WSC archive revealed that various procedure models exist, however, the simulation procedures do not discriminate between a tool-oriented and a method-oriented direction of computer simulation. Furthermore, the focus of the procedure model lies on structuring the process of simulation rather than ensuring a high level of scientific quality. This leads to an open question to be answered in future research: Are unspecific procedure models sufficient to support scientific conducting of simulation experiments of either direction?

As a first step, we discussed the application of computer simulation in information systems research and derived the following methodological research challenges:

1. Align research and simulation procedures,
2. Specify an experimental frame,
3. Estimate the complexity of simulation models and the feasibility of an experimental setting,
4. Prevent inappropriate use of simulation systems, and
5. Maximize validity without losing explanatory power of the simulation model.

The identified procedure models are partially meeting the challenges. Especially for the first challenge, procedure models introduced in computer science research are a promising starting point. However, these procedure models do not include methodological aspects, such that further development of procedure models in context of information systems research seems to be necessary. Furthermore, the majority of procedure models specifies the what to do, rather than the "how to" aspects. The specification of essential aspects of experimental frames - as required in the second challenge - are as well part of procedure models. Additionally to those aspects handled in the procedure models, the specification of rules for evaluation and interpretation of the results has to be considered. Feasibility of research as well as complexity of the model is not handled by the analyzed procedure models (see Challenge 3). The fourth challenge is not only dedicated to the decision whether or not to apply simulation in a specific domain or research question as discussed in some of the procedure models. Our assumption is, that many researchers are not willingly using simulation in an inappropriate way but that the lack of system support, like experiment management, supports a "slacky" execution of simulation systems. Thus, this challenge can also be met by introducing assistance functionalities to apply simulation systems in an appropriate way. As V&V is an inherent problem of computer simulation, the fifth challenge is already in focus of the procedure models. Following the discussion of V&V in the scientific community, further research is needed here, too.

Summarizing, procedure models introduced in computer simulation are a first step to scientific conduction of simulation studies. Specific challenges arise when applied in research to ensure a high quality in the scientific process. As many of these issues are related to process management, modeling and specifications tasks, and intelligent assistance, the information systems community is a promising discipline to meet these challenges and provide feasible solutions, here.

In previous research, we were contributing to developing assistance functionalities for simulation systems as well as working on the application of knowledge-based and machine learning algorithms to simulation (Bogon et al. 2012, Lattner et al. 2011) However, we recognized that the missing methodological foundation of computer simulation in information systems research could evolve to a showstopper. Thus, in future research, we are aiming at developing solutions for meeting the previously introduced challenges in order to increase quality of simulation-based research. The underlying objective of this paper is to initiate a discourse in information systems research, which aims at a common understanding of the epistemological consequences of simulation as well as scientific "standards" for ensuring high quality in conducting simulation-based research.

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REFERENCES

Balci, O. 1990. "Guidelines for successful simulation studies". WSC '90, 25–32: IEEE.

Banks, J. 1996. *Discrete-event system simulation*. 2nd ed ed. Prentice-Hall international series in industrial and systems engineering. Upper Saddle River, N.J: Prentice Hall.

Banks, J. 1998. *Handbook of simulation*. Wiley Online Library.

Bogon, T., I. J. Timm, U. Jessen, M. Schmitz, S. Wenzel, A. D. Lattner, D. Paraskevopoulos, and S. Spieckermann. 2012. "Towards assisted input and output data analysis in manufacturing simulation: The EDASim approach". In *Proceedings of the Winter Simulation Conference*, 257.

Carson, II, J. S. 2004. "Introduction to Modeling and Simulation". WSC '04, 9–16. Washington, D.C.: Winter Simulation Conference.

Carter, S. M., and M. Little. 2007. "Justifying knowledge, justifying method, taking action: Epistemologies, methodologies, and methods in qualitative research". *Qualitative Health Research* 17 (10): 1316–1328.

Centeno, M. A. 1996. "An Introduction to Simulation Modeling". WSC '96, 15–22. Washington, DC, USA: IEEE Computer Society.

Davidsson, P. 2002. "Agent based social simulation: A computer science view". *Journal of artificial societies and social simulation* 5 (1).

Diallo, S. Y., R. J. Gore, J. J. Padilla, and C. J. Lynch. 2015. "An overview of modeling and simulation using content analysis". *Scientometrics* 103 (3): 977–1002.

Fishman, G. S. 1968. "Estimating Reliability in Simulation Experiments". 6–10. New York, New York, USA: Winter Simulation Conference.

Fishwick, P. A. 1997. "Computer simulation: growth through extension". *Transactions of the Society for Computer Simulation* 14 (1): 13–24.

Flanagan, P. D., J. B. Currier, and K. E. Willis. 1973. "Simulation in the Design of Automated Air Traffic Control Functions". WSC '73, 449–462. New York, NY, USA: ACM.

Frank, A. L. 1968. "The Use of Experimental Design Techniques in Simulation". 11–12. New York, New York, USA: Winter Simulation Conference.

Frankfurter, G. M., and B. Horwitz. 1971. "Earnings Per Share, Debt Financing Costs and Debt Composition - a Simulation Model". WSC '71, 341–357. New York, NY, USA: ACM.

Friedman, L. W. 1996. *The simulation metamodel*. Norwell, Mass: Kluwer Academic Publishers.

Gilbert, G. N., and K. G. Troitzsch. 2005. *Simulation for the social scientist*. Maidenhead, England; New York, NY: Open University Press.

Gogg, T. J., and J. R. Mott. 1993. "Introduction to simulation". In *Proceedings of the 25th Conference on Winter Simulation*, 9–17: ACM.

Goldstine, H. H., and A. Goldstine. 1946. "The electronic numerical integrator and computer (ENIAC)". *Mathematical Tables and Other Aids to Computation*:97–110.

Gordon, G. 1978. *System Simulation*. 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall PTR.

Heath, Brian and Hill, Raymond and Frank Ciarallo 2009, October. "A Survey of Agent-Based Modeling Practices (January 1998 to July 2008)".

Hudert, S., C. Niemann, and T. Eymann. 2010, January. "On Computer Simulation as a Component in Information Systems Research". In *Global Perspectives on Design Science Research*, edited by R. Winter, J. L. Zhao, and S. Aier, 167–179. Springer Berlin Heidelberg.

Humphreys, P. 1990. "Computer simulations". 497–506: JSTOR.

Kennedy, O. G. 1973. "The Use of Computer Simulation in Health Care Facility Design". WSC '73, 172–198. New York, NY, USA: ACM.

Kleijnen, J. P. 1995. "Verification and validation of simulation models". *European Journal of Operational Research* 82 (1): 145–162.

Kühn, W. 2006. "Digital Factory: Simulation Enhancing the Product and Production Engineering Process". WSC '06, 1899–1906. Monterey, California: Winter Simulation Conference.

Lattner, A. D., T. Bogon, and I. J. Timm. 2011. "An Approach to Significance Estimation for Simulation Studies.". 177–186.

Lattner, A. D., J. Dallmeyer, and I. J. Timm. 2011. "Learning dynamic adaptation strategies in agent-based traffic simulation experiments". In *Multiagent System Technologies*, 77–88. Springer.

Lattner, A. D., H. Pitsch, I. J. Timm, S. Spieckermann, and S. Wenzel. 2011. "AssistSim - Towards Automation of Simulation Studies in Logistics". *SNE*:119.

Law, A. M., and W. D. Kelton. 1982. *Simulation modeling and analysis*. McGraw-Hill series in industrial engineering and management science. New York: McGraw-Hill.
Maria, A. 1997. "Introduction to Modeling and Simulation". In *Proceedings of the 29th Conference on Winter Simulation*, WSC '97, 7–13. Washington, DC, USA: IEEE Computer Society.
Mihram, G. A. 1973. "Simulation: Methodology for the System Sciences". WSC '73, 712–714. New York, NY, USA: ACM.
Montgomery, D. C. 2001. *Design and analysis of experiments*. 5th ed ed. New York: John Wiley.
Musselman, K. J. 1994. "Guidelines for Simulation Project Success". WSC '94, 88–95. San Diego, CA, USA: Society for Computer Simulation International.
Ören, T. I. 1987. "Quality assurance paradigms for artificial intelligence in modelling and simulation". *Simulation* 48 (4): 149–151.
Oxford Dictionaries 2014. "Online Dictionary - Definitions".
Pegden, C. D. 1995. *Introduction to simulation using SIMAN*. 2nd ed ed. New York: McGraw-Hill.
Pritsker, A. A. B. 1999. *Simulation with Visual SLAM and AweSim*. 2nd ed ed. New York : West Lafayette, Ind: Wiley : Systems Pub. Corp.
Reynolds, P. F. 2008. "The role of modeling and simulation". *Principles of modeling and simulation: A multidisciplinary approach*:25–43.
Robinson, S. 2013. "Conceptual modeling for simulation". In *Simulation Conference (WSC), 2013 Winter*, 377–388: IEEE.
Sadowski, R. P. 1992. "Selling Simulation and Simulation Results". WSC '92, 122–125. New York, NY, USA: ACM.
Sargent, R. G. 1998. "Verification and validation of simulation models". 121–130: IEEE Computer Society.
Schmidt, J. W. 1984. "Introduction to Simulation". WSC '84, 64–73. Piscataway, NJ, USA: IEEE Press.
Shannon, R. E. 1975. *Systems simulation: the art and science*. Englewood Cliffs, N.J: Prentice-Hall.
Shannon, R. E. 1998. "Introduction to the Art and Science of Simulation". WSC '98, 7–14. Los Alamitos, CA, USA: IEEE Computer Society Press.
Tolk, A., B. L. Heath, M. Ihrig, J. J. Padilla, E. H. Page, E. D. Suarez, C. Szabo, P. Weirich, and L. Yilmaz. 2013. "Epistemology of modeling and simulation". In *Winter Simulation Conference 2013*, 1152–1166.
Turnitsa, C., J. J. Padilla, and A. Tolk. 2010. "Ontology for modeling and simulation". In *Simulation Conference (WSC), Proceedings of the 2010 Winter*, 643–651: IEEE.
Ulam, S. M. 1990. *Analogies Between Analogies: The Mathematical Reports of S.M. Ulam and His Los Alamos Collaborators*. University of California Press.
Wilson, James R. 1996, August. "The Winter Simulation Conference: The Premier Forum on Simulation Practice and Theory".
Winsberg, E. 2014. "Computer Simulations in Science". *The Stanford Encyclopedia of Philosophy* (2014).
Winsberg, E. B. 2010. *Science in the age of computer simulation*. Chicago: University of Chicago Press.
Zeigler, B. P., H. Praehofer, and T. G. Kim. 2000, January. *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*. Academic Press.

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