TO WHICH EXTENT ARE SIMULATION RESEARCH PAPERS RELATED TO THE REAL WORLD? -A SURVEY ON THE USE OF VALIDATION METHODS

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ABSTRACT

Validation is the methodology at the end of the simulation and modelling cycle that relates the insights gained by computer calculations to the real world scenario, that is subject of study. Validation establishes credibility concerning the simulation results and implications with respect to the real system. Validation is a very important aspect in real world simulation studies, since important financial and security related decisions concerning the planning, design and optimization of the real systems might be relied.

In our study, we conducted a survey on research papers in renowned simulation conferences and evaluated whether validation had been used at all, and if yes, which validation methods had been used to which extent. This reveals the relevance and trust of simulation results of the research papers concerning the real world problem addressed in that research.

We found that a majority of research papers neglect the application of validation methodology. Obviously, the validity of the results of simulation studies or the impact on practical problems in the real world seems to be questionable in a vast number of cases.

INTRODUCTION

The purpose of modelling and simulation studies is to use a computational model to capture the important aspects and features of the system under study. These models either plan a system, for which the goal is to show that the planned design will be working as desired, or optimize an existing system, for which the goal is to show how properties, features, or parameters of the system have to be changed in order to work in a more efficient way.

In both cases, the modelling and simulation life cycle consists of identification of the crucial features of the system. These features are then included in the computational model based on the belief that the behavior of the real system will be represented by these features.

However science is not based on belief, hence there exist methods to strengthen the assumption, that during the modelling process the most important and sufficient features have been taken into account and have been implemented in the simulation model.

The process is called validation, related methods are used to establish *trust* into the model and the results of the calculations. Trust in the sense that the calculated results obtained by experiments using the *model* are relevant for the modelled real system in the sense, that the real system will show the behaviour as predicted by the model. That means when a change in the configuration of the system model is studied and when this change leads to a possibly better functioning or more efficient operation, then the trust in these results (e.g. change of configuration X into configuration Y leads to 5% increased performance) should be high enough to base important, expensive or safety-critical decisions on it.

Basically the validation procedure can be divided into reproduction of the past/current or known behaviour of the real system and the ability to predict change of the behaviour of the real systems, when changes of parameters or features are applied.

In this sense the validation procedure is similar to the training process in machine learning. The models obtained by machine learning are in this sense also a condensed, non explicit models of some real system. Procedures for fitting the machine learning model to the real world are similiar. In the training phase, the machine learning model on the one hand is tuned to reproduce the known input-output relations. On the other hand, also the ability to predict unknown inputs correctly is tuned during the training phase. The ability to predict is tested using examples of input-output samples that have not been used during training of the model. Two kinds of errors are known during this phase: First, over-fitting can occur. That means that all training examples can be reproduced perfectly, however the prediction success of the model is low. Second, under-fitting, which means that not even the examples for training have been learned with sufficient precision. The goal when building of a machine learning model is to balance the reproduction and prediction success in order to get a model that represents the system's behaviour accurately enough however also in a such general way that the ability to predict new data is there.

Back to the validation of simulation models, the most

common approach is to model the real system step by step, possibly refining components and tuning parameters, until the known past or current behaviour of the real system can be reproduced. This is the very first and basic and in dispensable step when building a model.
Often models are build leaving out any comparison to reality by arguing that all parts and steps in the modelling process have been made in a logic and sensible way. However even in simple systems it can be shown that just using some assumptions can lead totally wrong or different behaviours. Looking at the $G/G/1$ with arrival and service rate being both equal to one, depending on the actual probability distribution the queue length can be infinite for both rates being exponentially distributed or maximal one for both rates being deterministic.
That means that details can decide on the overall behaviour of systems, especially when stochastic influence is present (usually is) or rare events. Since not for all parameters of the real systems there exist enough measurements or measurements at all, every model always is an *abstraction* of the system and not the exact detailed system.
It follows from that, that the validation of the model has to be done in order to establish a minimum of trust in the simulation results and to determine the parameter ranges and boundary conditions, under which the simulation results can be supposed to represent the real system's behavior.
The life cycle of simulation and modelling is an iterative process, repeatedly checking the assumptions and theories; and of course validating the behaviour and output data by statistically comparing the outputs of real system and model Sargent (2014).
As stated above, the reproduction validation is one essential method, other methods in the literature are:

- face validation
- historical data validation
- event validation
- confidence intervals
- key performance indicators
- animation
- internal validation and extreme condition test
- structured walkthrough
- black box white box
- comparison of output behaviour (most often between models)
- other/undefined

We deal with discrete event simulation systems which can additionally be agent based, that are usually stochastic systems. The stochasticity reflects uncertainties of measurements and estimations that have to be done. And also, hybrid simulation models which can be a linkage of the discrete event simulation with system dynamic or agent based models.

Literature Review

The methodology for the systematic literature review was adopted from Kitchenham and Charters (2007). This includes the planning, the execution and finally the presentation of the review.

Research Questions

First, the research questions have to be defined: what question should be answered be the literature review? what is my hypothesis?
The research questions of our study are:
RQ1: Is there any information about validation in the simulation study included at all?
RQ2: Which methods have been used for validation in the simulation study?
RQ3: Has real data/data from a real system been used for validation? Have the results of the simulation study be deployed in the real system and validated?
RQ4: Which weight has validation during the model development?
According to Kitchenham et al the search strategy has to be defined. The following renowned databases have been used:

- IEEE Xplore
- ACM digital library
- Google Scholar
- Springer
- ScienceDirect
- EI Compendex
- SciTePress digital library

In the first iteration, a*rated simulation conferences have been have been chosen and have been searched using the following search terms:

- a* rated simuilation conferences
- simulation
- simulation model
- valid
- validation

Finally, the following sources have been chosen:

- Winter Simulation Conference (WSC)
- International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH)
- International Building Performance Simulation Association (IBPSA)
- ACM Transactions on Modeling and Computer Simulation (TOMACS)

Data extraction

The results were put in the tables having the following format:

- title, year, author, DOI
- validation mentioned
- validation details
- validation methods
- reference to reality
- weight of validation
- evaluation

Subject of the search was the time span between 2017 and 2021, the conference and the titles. Then the abstracts and conclusions have been evaluated and also, if these papers include the term valid. These papers were then examined to determine whether they contained information about validation. In the end, the found articles were narrowed down from 389 to 104 articles.

RESULT

This section presents the results of the systematic literature review. It opens with an overview of all the reviewed papers, followed by the results to answer the research questions, and concludes with an evaluation of the performed validation.

Overview

In the following, there will be a brief overview of the found papers about simulation models. Table 1 shows all papers which were separated in three simulation model types: discrete event (DES), agent based and hybrid. This separation was done to get a possible overview of whether there are any differences between the simulation model types. Some papers which did not mention their simulation type were assigned to DES because their description came closest to this. Below, Table 2 shows the allocation of types per publication.

Table 1: All found articles separated into their simulation model types.

DES	Agent Based	Hybrid
82 %	10 %	8 %

Table 2: All found articles classified by simulation model per publication.

	DES	Agent Based	Hybrid
WSC	76 %	11 %	13%
SIMULTECH	73 %	17 %	1 %
IBPSA	97 %	3 %	0 %
TOMACS	95 %	5 %	0 %

Information about validation

This section addresses the research question 1, the extent to which there was evidence of validation in the development of simulation models in the reviewed articles.
From all reviewed papers, 62 percent mentioned validation in their development of simulation models. Table 3 shows how many articles mentioned validation and in which publisher. On the one hand, authors described their realization of validation within the development of the simulation model, which will be discussed in further detail in the next section. On the other hand, the validation of simulation models was not specifically dealt with. This means that some authors suggested that they validated their simulation model, but they did not provide evidence how they validated their simulation model (cf. Cox and Rossetti (2017), Kai Kruppa et al. (2017), Feldkamp et al. (2020), W. A. Boyd and H. S. Sarjoughian (2020),Yifu Shi and Godfried Augenbroe (2019), Macal et al. (2018) and S. Das et al. (2021)).
However, other authors referenced other sources where the validation is supposed to have carried out (cf. MaayanTardif.2019, A. Ninh et al. (2019) and N. D. Bastian et al. (2019)).
Furthermore, some authors mentioned that they are going to validate their simulation model in the future (cf. K. Gutenschwager et al. (2019), G. Lugaresi and A. Matta (2020), Balakrishnan et al. (2021), H. Le and X. Hu (2020), J. J. Green et al. (2017), Abbas (2017a) K. Gutenschwager et al. (2019), G. Lugaresi and A. Matta (2020), Balakrishnan et al. (2021), H. Le and X. Hu (2020), J. J. Green et al. (2017) and Abbas (2017a)).
Also, in some articles, it was suggested how to validate their simulation model but it was not written whether it has been validated (cf. Hardwick and Panella (2017), Kai Kruppa et al. (2017), Reyes et al. (2017), Yifu Shi and Godfried Augenbroe (2019), Feldkamp et al. (2020), G. Lugaresi and A. Matta (2020), (D. M. Aleman et al. 2021), Jean Le Fur and Moussa Sall (2018), Viana et al. (2017) and M. Farhan et al. (2020)).

In addition, there were articles indicating that validation should not be performed because it would be too difficult or unnecessary (cf. G. Lugaresi and A. Matta (2020), Maayan Tardif et al. (2019), S. Nambiar et al. (2018) and Hu and Wu (2019)).
All in all, the answer to research question 1 would is: More than half of the reviewed articles mentioned validation in their articles.

Table 3: Details of validation among the articles per publication.

WSC	SIMULTECH	IBPSA	TOMACS
68 %	59 %	48 %	57%

Validation methods

Table 4: Frequency of validation method statements in publications.

WSC	SIMULTECH	IBPSA	TOMACS
43 %	45 %	29 %	38 %

This section deals with the research question 2 and 3 which are about the use of validation methods and whether information from a real system was used.
Altogether in only 40 percent of the reviewed articles are mention the use of any validation methods or techniques. In table 4 is shown, in percent, which article in which publisher mentioned any validation method or technique. The article from the conference SIMULTECH mentioned the most use of a validation method or technique. In comparison to that, he articles from IBPSA mentioned at least information of the use of any validation method or technique.
Table 5 shows which paper from which publisher mentioned which validation method or technique. The most mentioned validation techniques out of all reviewed articles were *face validation, historical data validation, event validation* and also the method in which the output behavior of the simulation model is compared with that of another model. In addition, they mentioned the use of *confidence interval, kpi* and the validation techniques *animation, internal validation, extreme condition test, structured walkthrough* and also undefined methods which are not generally known. The method *black- and white-box-validation* was also mentioned, especially for agent-based simulations. In contrast to that, the articles from the IBPSA conference mentioned the fewest percentages (29 %) about validation methods or techniques of their simulation models, while the articles from SIMULTECH (45 %) mentioned the most.
The third research question addressed whether the information from a real system was used and the results were actually implemented in reality or the prediction of the simulation model was validated. For this question the validation technique *event validation* helps to give the answer, because in this technique the result of the simulation is compared with the real system. Besides, the validation techniques historical data validation and the use of confidence interval also refer to the real system but in contrast, these methods do not compare the events of the simulation with the real system after the fact, but collect the data before the simulation model is developed. In summary, only four percent of all reviewed articles used the validation technique *event validation*. The highest number was found in the articles from the conference IBPSA (10 %). But in the articles from TOMACS were not mentioning the use of this technique.
All in all, many validation methods or techniques were used for their simulation model but just few compared it to the real system.
(The following are papers that incorporate the above validation methods or techniques:

- *face validation* cf. A. Alban et al. (2020), Troy et al. (2017), P. Url et al. (2018), Inanc et al. (2017a), M. Cherkesly and Y. Maïzi (2020), Ruiz-Martin et al. (2021), Diviš and Kavička (2022), (R. De la Fuente et al. 2019), L. R. de Groot and A. Hübl (2021), M. E. A. E. Abdellaoui et al. (2020), Y. Li et al. (2020), Pereira and Chwif (2018), W. J. Marrero et al. (2019); Aros and Gibbons (2018), Barri et al. (2020); W. Abohamad et al. (2017), Viana et al. (2018), Sall et al. (2019) and J. Viana et al. (2021)

- *historical data validation* cf: Lucas Verschelden et al. (2017), S. Gupta et al. (2021), D. Kilinc et al. (2020), B. Sandıkçı et al. (2019), K. Konrad (2020), Kitora et al. (2019), Takashi Momonoki et al. (2017), Pierce et al. (2018), Y. Li et al. (2019), Aien and Mahdavi (2019); Hesham and Wainer (2021), Kaium et al. (2019); W. Abohamad et al. (2017), Mielczarek and Zabawa (2018), Viana et al. (2018), J. Viana et al. (2021), Oleghe and Salonitis (2018) and J. Werling et al. (2020)

- *event validation* cf. Ž. Letonja et al. (2021), Hossain et al. (2019), Estacio et al. (2019), Jakubiec et al. (2019), Markus Wirnsberger et al. (2019), E. Nemethova et al. (2017) and Busby and Carter (2017) Comparison with model cf. :Sormaz and Malik (2017), Plagge et al. (2018), Cassidy et al. (2013), Wolfe et al. (2018), Kathareios et al. (2015), Martin Hauer and David Geisler-Moroder (2019), Lee et al. (2019), Bozalp et al. (2021)

- *confidence interval* cf. N. Suhaimi et al. (2017), M. Golz et al. (2018), Inzillo et al. (2018)

- *kpi* cf.: Mosinski et al. (2021), Gaku and Takakuwa (2017), L. R. de Groot and A. Hübl (2021), M. E. A. E. Abdellaoui et al. (2020); W. Abohamad et al. (2017)

- *animation* cf. Y. Maïzi et al. (2019), N. Suhaimi et al. (2017), M. Golz et al. (2018), Greasley (2020)
- *internal validation & extreme condition test* cf.: I. J. Samuel et al. (2019)
- *structured walkthrough* cf. J. Viana et al. (2021)
- *black-box- & white-box-validation* cf. Gerrits et al. (2017), Berry Gerrits et al. (2018)
- undefined methods cf.: Bo et al. (2019), Xavier Centelles, J. Ramon Castro, Luisa F. Cabeza (2019), B. Wang et al. (2019), Lienert et al. (2018), Y. Pan et al. (2021), Riegl and Gaull (2018))

Table 5: Distribution of validation method statements per publication.

	WSC	SIMULTECH	IBPSA	TOMACS
Face validation	14 %	11 %	0 %	15 %
Historical data validation	12 %	7 %	10 %	8 %
Event validation	2 %	7 %	10 %	0 %
Confidence interval	2 %	3 %	0 %	0 %
KPI	4 %	0 %	0 %	0 %
Animation	2 %	3 %	0 %	0 %
Internal validation & Extreme condition test	1 %	0 %	0 %	0 %
Stucutred Walkthrough	1 %	0 %	0 %	0 %
Black- & White-box	2 %	0 %	0 %	0 %
Comparison with model	1 %	7 %	3 %	15 %
Undefined methods	2 %	7 %	6 %	0 %
Without validation methods	57 %	55 %	71 %	62 %

Weight of validation

This section deals with the research question 4. To answer this question, the following four issues must be considered.

Why was validation performed?
The first issue was the question: why was validation performed.
Some authors said it would give full control about data generation and therefore no wrong or missing data would occur in the simulation model (e.g. cf. Feldkamp et al. (2020)). Also, other authors mentioned that a validation would be a basis for further studies (cf. Markus Wirnsberger et al. (2019)). Besides, some authors specifically stated that their objective was to develop a valid simulation model (cf. E. Nemethova et al. (2017), Troy et al. (2017), Aros and Gibbons (2018), Berry Gerrits et al. (2018)).

Meaning of validation
The second issue which was considered was the meaning of validation.
Some authors mentioned that the validation of a simulation model is seen as a traditional approach in development. That means the validation is a part in the development of a simulation model (cf. Hardwick and Panella (2017)). Moreover, it was mentioned that the implementation of simulation experiments in validation was of crucial importance in order to facilitate their creation, reuse and reproduction (cf. Pierce et al. (2018)). Also, the validation is said to be one of the most important steps in the development of a simulation model because it would prove that the simulation model successfully reproduce the real system and it would be directly related to the objectives of the analyzed study (cf. D. Kilinc et al. (2020), (Gonsiorowski et al. 2017)).

Advantages
The third issue is about the stated advantage from the reviewed articles.
One advantage was mentioned to be that the validation helped to understand and improve the operation of the simulation model (cf. Gaku and Takakuwa (2017)). Also, for the development of agent based simulation model was mentioned that the validation helped to understand the function and limits of their model as well as being able to deduct an appropriate scope of validity from the logic of the modelled processes (cf. Jean Le Fur and Moussa Sall (2018)). Additionally, some authors said the comparison of simulation results and real system would show the performance and reliability (cf.Hossain et al. (2019)). It was also said to validate small part modes was practical and had the advantage that it could be handled with a manageable complexity by single or few scientists and changes to the simulation model would also be easier to implement (cf. (Pierce et al. 2018),(Sormaz and Malik 2017)). Furthermore, these authors said that sematic validity of large models could be ensured by systematic reuse of validation experiments (cf. (Pierce et al. 2018)).

Problems
The last issue is about the stated problems of validation which were fond in the articles.
One the one hand, it was said the validation was more difficult than the verification due to the lack of data (cf. Troy et al. (2017)). On the other hand, some authors claimed the validation to be complex and expensive which means that some authors validate their simulation in the small area (cf. Ruiz-Martin et al. (2021), Jakubiec et al. (2019)). In addition to that, the use of tools for validation is limited because this tool has its own limitations and the hardware-based environment makes reproducibility impossible (cf. Liu et al. (2017)). Besides, for some authors was the validation the hardest aspect of development of their agent-based simulation. They claimed it to be a challenge in context of model development (cf. Hesham and Wainer (2021)). Moreover, it was said that due to the hybrid nature of the hybrid simulation model, validation of the interface between the paradigms presents an additional challenge (cf. J. Viana et al. (2021)).
All in all, validation has a high priority in the development of simulation models, but it also poses some problems due to time and financial constraints.

Evaluation of validation

This section concludes with an evaluation of the reviewed articles to what extent validation has been implemented. For this purpose, four quality criteria were chosen to evaluate these articles. The criteria are sorted from negative to positive: None validation (D), poor validation (C), sufficient validation (B) good validation (A). The results of the reviewed articles are presented below and summarized in the Table 6.

None Validation (D)
The majority (49 Percent) gets the quality criterion none validation. That means that none of these reviewed articles make mention of validation or its realization.
On the one hand, some articles claimed that they did not validate their simulation model. Some reason was said to be time intesitivity, they did not finished their model or planned it for the future (e.g. cf. Barring et al. (2018), K. Gutenschwager et al. (2019), G. Lugaresi and A. Matta (2020)). On the other hand, some articles did not mention any word of validation (e.g. cf. van Kenhove et al. (2019)). Because of the missing validation in the articles it is assumed that the simulation models were not validated. In comparison the articles from conference IBPSA and SIMULTECH received the largest shares with 55 and 52 percent each of the quality criterion D.
From this follows, the half of the reviewed articles did not see validation as important and did not mentioned it. Consequently, these simulation models have no relation to the real world and therefore could not fulfil their real purpose.

Poor Validation (C)
Quality criterion C was given if in an article mentioned validation but the authors did not provide any information on the implementation, nor any justification of what and how they implemented the validation of their simulation model.
Overall, twelve percent received quality criterion C, which is the minority in the overall comparison of quality criteria. For example some authors mentioned that they validated their simulation model but did not explain what or how they did that. This means that the evidence of validation is missing and it could be assumed they did not validate their simulation model at all (e.g. cf. W. A. Boyd and H. S. Sarjoughian (2020), Choi (2019), S. Das et al. (2021)). Besides, some articles received the criterion C because it was written that assumptions were just validated and not the simulation model itself (e.g. cf. S. Das et al. (2021)). In comparison of the publications, the articles of the TOMACS have the most articles with poor validations with 19 percent, which is also more than the total value of twelve percent.
Altogether, there are some articles where validations were poorly performed or justified and thus cannot give a valid reference to the real world. The consequence could be that poor validation can be rated almost the same as none validation. This is because the less validation has been done, the less likely it is that the simulation model will validly represent the real system.

Sufficient validation (B)
This section deals with quality criteria B. To comply with this, a validation must be specified in the article and must be sufficiently reasoned. That means that there is at least little information about how the model was validated.
In total 26 percent of all reviewed articles accomplished this quality criteria. On the one hand, some articles did not mention how exactly the validation was performed and generated the results (e.g. cf. Barri et al. (2020)). To show that a simulation model represents the real model it is needed to use more validation methods and the use of real data. Besides, there are also articles which used data sets for validation that do not reflect the complete real system or are not realistic enough (e.g. cf. Jakubiec et al. (2019) or Greasley (2020)). But to get a truly valid model it is necessary to use real data sets. When comparing all articles, the articles from TOMACS accomplished at most (33 %) the quality criteria and also in percentage terms more than the total value (26 %).
All together these articles accomplished the quality criteria because although validation was mentioned, it did not provide enough detail or was incomplete and thus did not yet reflect a good reference to the real system. What follows is that these articles still have room for improvement and validate simulation model much more so that they represent the real system even better and more comprehensibly.

Good validation (A)
This quality criterion was awarded if the article describes a satisfactory validation of the simulation model by reproducing the relation to the real system in a good and comprehensible way.
Of all the reviewed articles, only 13 percent accomplished this quality criterion. These articles described a detailed validation of their simulation model so that one can see from their execution and results that their model could be a valid model. For example one article detailly described what validation methods and techniques were used and it was also justified what purpose they should serve. It has also used a comparison to a data set from the reals system (e.g. cf. Berry Gerrits et al. (2018)). In addition, there were articles that described using validation to discover errors, fix them, and re-validate. (e.g. cf. L. R. de Groot and A. Hübl (2021)). With the detailed information of their failures and optimization, it is much easier to understand that their model is a valid

model. In comparison to all reviewed articles, SIMULTECH accomplishment the largest proportion (17 %) of the quality criteria A which is also more than the total value (13 %).
It can be concluded that only a small fraction of the total reviewed articles had performed good and convincing validation in the development of their simulation model, so that their simulation models achieved a valid relation to the real system.

Summary of evaluation
The lesson is clear: More than half of the reviewed articles mentioned none or a poor validation in the development of the simulation model and under 40 percent of the total article described sufficient to good validation of their simulation model. That means, the majority did not validate their simulation model and thus could not give any reference to the real word. Consequently, these simulation models could be unusable if not validated.

Table 6: Publication split according to goods criteria.

	WSC	SIMULTECH	IBSPA	TOMACS	total
A	15 %	17 %	10 %	5 %	13 %
B	28 %	21 %	19 %	33 %	26 %
C	9 %	10 %	16 %	19 %	12 %
D	48 %	52 %	55 %	43 %	49 %

CONCLUSION

This paper has given an overview of the current state of validation methods over the last five years and their use in simulation modeling. It has used a systematic literature review according to Kitchenham and Charters (2007) and the reviewed articles are from WSC, SIMULTECH, IBPSA and TOMACS. The result of this review is the answer of the research question and an evaluation of the validation information which is summarized in the following.
More than half of the reviewed articles addressed the issue of validation of simulation models in their articles (RQ1). Also, different validation methods or techniques were used. The most common method was the comparison of the behavior of the simulation model with the behavior of the system (RQ2). There was little data on a real system and the prediction of the simulation model was validated against it (RQ3). But it was also mentioned that the use of validation in model development has a high priority (RQ4). The result of the evaluation is that more than half of all reviewed articles described none to poor validation of their simulation model. And under 40 percent described sufficient to good validation of their simulation model.
In conclusion, the vast majority did not perform validation due to time and financial constraints, although they were aware of its importance. This has the consequence that more than half of the simulation models and simulations developed provide no reference to the real world.

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