

Software Process Simulation Modeling: An Extended Systematic Review

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Abstract. Software Process Simulation Modeling (SPSM) research has increased in the past two decades, especially since the first ProSim Workshop held in 1998. Our research aims to systematically assess how SPSM has evolved during the past 10 years in particular whether the purposes for SPSM, the simulation paradigms, tools, research topics, and the model scopes and outputs have changed. We performed a systematic literature review of the SPSM research in two subsequent stages, and identified 156 relevant studies in four categories. This paper reports the review process of the second stage and the preliminary results by aggregating studies from the two stages. Although the load of SPSM studies was dominated in ProSim/ICSP community, the outside research presented more diversity in some aspects. We also perceived an immediate need for refining and updating the reasons and the classification scheme for SPSM introduced by Kellner, Madachy and Raffo (KMR).

1 Introduction

Software Process Simulation Modeling (SPSM) research has increased in the past two decades, especially since the first ProSim¹ Workshop held in 1998 and Kellner, Madachy and Raffo's (KMR) paper addressed the fundamental "*why, what and how*" questions of process simulation in software engineering. After 10 years (1998-2007) progress, there is a need for a timely review of the research done in SPSM, to update the current state-of-the-art, to summarize the experiences and lessons, and to portray a full overview of SPSM research.

In ICSP 2008, we reported the first stage of our Systematic Literature Review (SLR) on SPSM [1], which focused on the research published through ProSim/ICSP channels over the decade (1998-2007). Nevertheless, a broader view of SPSM research in software engineering will make this systematic literature review more valuable to the software process community, which is the

¹ International Workshop on Software Process Simulation Modeling.

motivation for the second stage of this review. During this review stage, another relevant SLR [2] on the role of SPSM in software risk management was conducted and reported, which focused a special use of SPSM based on the 27 studies from a sub-scope of our review.

This paper reports the process and the preliminary results of the second stage SLR, which searched and aggregated evidence from the publication channels outside ProSim/ICSP to address our original research questions. As the continuous work of our former stage, the results derived from this stage also serves as a validation of the ‘*facts*’, ‘*trends*’, and ‘*directions*’ identified in our first stage [3], as well as the latest update and enhancement to the topics discussed in KMR’s paper [4]. Additionally, our staged SLR enables a comparison of the research characteristics and preferences within and outside ProSim/ICSP community.

2 Method: The Extended Systematic Review

The Stage 2 of this systematic review continuously followed Kitchenham’s guidelines [5]. As the method and process of Stage 1 of this SLR was reported in [1], this paper instead only reports the difference between the two stages.

In order to maintain the consistency, integrity and comparability between the two stages of SLR, there were no significant change to the original six research questions [1]. Thus, the second stage of this systematic review also addresses the following research questions:

- Q1.** *What were the purposes or motivations for SPSM in the last decade?*
- Q2.** *Which simulation paradigms have been applied in the last decade, and how popular were they in SPSM?*
- Q3.** *Which simulation tools are available for SPSM and have been in use in the last decade?*
- Q4.** *On model level, what were research topics and model scopes focused by process simulation models?*
- Q5.** *On parameter level, what were the output variables of interest when developing process simulation models?*
- Q6.** *Which simulation paradigm is the most appropriate for a specific SPSM purpose and scope?*

The three researchers involved in the first stage continued to work in their roles during the second stage. In addition, one more researcher was invited to join in the expert panel to ensure the review quality.

2.1 Search Strategy

In the first stage review, we employed manual search on ProSim/ICSP related publication channels only. The search scope was extended in the Stage 2 by including more conference (workshop) proceedings and journals that are relevant to software process research and empirical software engineering. In addition, the automated search method [5] was employed in this stage as a complement to the

Table 1. Search sources for Stage 2 of the SLR

Source	Period	Method
<i>Conference proceedings</i>		
Proceedings of ICSE (incl. Workshops, excl. ProSim)	'98-'07	Manual
Proceedings of PROFES Conference	'99-'07	Manual
Proceedings of ISESE/METRICS/ESEM conference	'02-'07	Manual
Proceedings of SEKE conference	'98-'07	Manual
<i>Journals</i>		
IEEE Transactions on Software Engineering (TSE)	'98-'07	Manual
ACM Transactions on Software Engineering & Methodology (TOSEM)	'98-'07	Manual
Journal of Systems & Software (JSS)	'98-'07	Manual
Journal of Software Process: Improvement & Practice (SPIP)	'98-'07	Manual
Journal of information and software technology (IST)	'98-'07	Manual
International Journal of Software Engineering and Knowledge Engineering (IJSEKE)	'98-'07	Manual
<i>Digital Libraries</i>		
IEEE Xplore	'98-'07	Automated
ACM digital library	'98-'07	Automated
ScienceDirect	'98-'07	Automated
SpringerLink	'98-'07	Automated

manual search in order to identify as many SPSM studies as possible. Table 1 summarizes the sources searched in Stage 2.

By following the systematic literature search process suggested in [6], the search terms for automated search were elicited based on observation of the studies found by the manual search in the both stages. Then we combined the terms to form the following search string, which was further coded into the equivalent forms to match the search syntax of different digital libraries. The string was searched in the fields of *title-abstract-keyword*. Note that ‘system dynamics’ was explicitly designated in the search string because ‘simulation’ does not appear in the search fields of some relevant studies using SD.

((software process) OR (software project) OR (software product)
OR (software evolution)) AND (simulation OR simulator OR simulate
OR (dynamic model) OR (system dynamics))

2.2 Study Selection

The studies retrieved through the literature search were further screened and selected. The entire selection process was performed by the principal researcher. The initial selection (after literature search) applied the same criteria in [1] to identify and exclude the irrelevant studies. The *title-abstract-keyword* and *conclusion* of each paper were read as the evidence for inclusion/exclusion. Any selection difficulties were escalated to the expert panel for final decision.

When the full-text of each paper was read in data extraction, more duplicate publications and irrelevant studies were identified and excluded (see Section 3).

2.3 Study Classification

The first stage SLR identified four categories of SPSM study [1]. These four types of studies focus on different aspects of software process simulation research, and

may give answers to the research questions from different points of view. Category B studies introduce and provide effective paradigms, methods and tools for constructing process simulation models or simulators (Category A studies). These simulation models can be further adopted for different purposes in industrial context by following the practical solutions or guidelines (Category C studies). The experience (Category D studies) collected from modeling and adoption can be used as feedback to iteratively improve SPSM research [3].

- A. Software process simulation models or simulators;
- B. Process simulation modeling paradigms, methodologies, and environments;
- C. Applications, guidelines, frameworks, and solutions for adopting process simulation in software engineering practice;
- D. Experience reports and empirical studies of SPSM research and practice.

Due to some minor disagreements experienced between the principal and the secondary researchers in the classification on a small number of studies (between Category B and C), we further specified a set of concrete criteria (questions) to facilitate the effective identification of each study's category (in Table 2). If a 'yes' answer applies to any question related to one study type, this study was allocated the corresponding (one or more) category.

Table 2. Questions for study classification

Category	Question
A	<ul style="list-style-type: none"> - Was a new process simulation model or simulator presented in the study? - Was a process simulation model or simulator applied in a new SE domain or a new practical context?
B	<ul style="list-style-type: none"> - Compared with previous studies, was a new simulation modeling paradigm introduced into SPSM? - Was a new process simulation environment or tool developed and described? - Was a methodology or framework proposed or developed for improving SPSM? - Were any factors associated to SPSM discussed in the study?
C	<ul style="list-style-type: none"> - Was a new application of SPSM introduced to SE domain? - Was a guideline or framework of directing SPSM solution to one specific problem or context proposed or developed?
D	<ul style="list-style-type: none"> - Did the study report any experience (qualitative or quantitative) of applying SPSM in industry? - Did the study report how a process simulation model or simulator has been built or calibrated with empirical data? - Did the study report an empirical study related to SPSM?

2.4 Data Extraction and Quality Assessment

Data extraction and quality assessment were performed by the principal and the secondary reviewer independently. The former was responsible for reviewing all primary studies, extracting data, and assessing study quality. The other selected and reviewed approximately 15% studies for validation of the extraction and assessment. When there were disagreements could not be resolved, the final decision was made by the principal researcher.

The study attributes for *data extraction* and questions for *quality assessment* can be found in [1]. Due to the abovementioned considerations, we did not propose any changes in these activities in Stage 2.

3 Results

3.1 Primary Studies

After literature search and initial study selection, 79 relevant studies were uploaded into the online system (<http://systematicreviews.org>) for more careful selection and data extraction. By reading the full-text, 19 studies were further excluded because they are 1) duplicate publications; 2) not simulation studies on *software process* (e.g., simulation of software systems); or 3) research proposals without implementation.

Finally, the second stage included 60 relevant studies in addition to those found by the first stage review. In total, 156 (S1:96/S2:60) primary studies² on SPSM research were identified from 1998 to 2007. They form a comprehensive body of research of software process simulation.

Table 3 shows the number of SPSM studies published during the decade, which are grouped by two review stages. The number of published studies per year was between 15 and 19 after Y2K, and stabilized at 18 or 19 after 2004. This stability applies to all papers during the period, irrespective of whether or not they were ProSim related papers. The overall number of conference publications (77) is very close to the journal publications (79) over the period.

Table 3. Identified as primary studies in the staged SLR

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Sum
Stage One											
- ProSim/ICSP	2	0	2	n/a	n/a	11	6	7	4	8	40
- JSS/SPIP special issues	0	11	9	12	7	0	5	4	6	2	56
Stage Two											
- Conference/workshop	2	3	2	3	6	1	3	7	3	7	37
- Journal	0	0	4	3	2	3	4	1	5	1	23
Total	4	14	17	18	15	15	18	19	18	18	156

Table 3 also shows that the number of SPSM studies significantly increased after the first ProSim workshop (ProSim'98), which demonstrates the positive effect of ProSim series workshops to software process simulation research.

Table 4 lists the top conferences and journals where the researchers published their SPSM studies in the decade. Apart from ProSim/ICSP venues (including SPIP and JSS), IST and PROFES also have dominated outside publications.

It is worth noticing that most primary studies cited either [7] or [4], which are the seminal work and landmark paper on SPSM.

3.2 Classification

The second stage review confirmed the classification from Stage 1 is appropriate. Each included primary study was classified into one or more of the four categories. Figure 1 shows the distribution of study categories over the decade. It is clear that Category A studies (simulation models) were dominant in every single year during the period.

² The full study list will be online for public access at <http://systematicreviews.org>

Table 4. Top conferences & journals publishing SPSM studies

Rank	Journal	#Studies(S1/S2)	Rank	Conference	#Studies(S1/S2)
1	SPIP	36(33/3)	1	ProSim	32(32/0)
2	JSS	25(23/2)	2	ICSP	8(8/0)
3	IST	6(0/6)	3	PROFES	5(0/5)
4	IJSEKE	4(0/4)	4	ICSE/EWSPT/ASWEC	3(0/3)

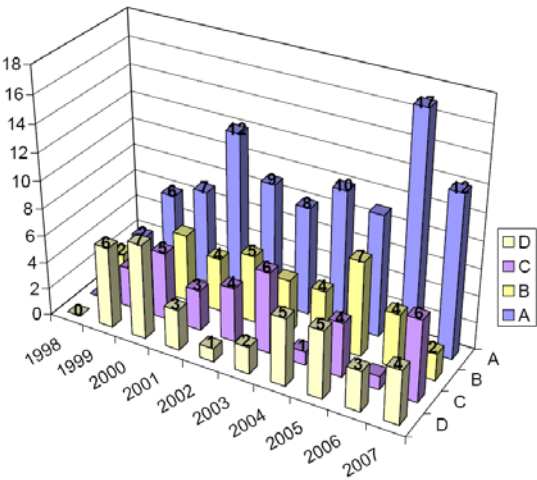


Fig. 1. Study category distribution over years

In total, 92 Category A studies (59%) describing software process simulation models (simulators) were found from literature, 56 from Stage 1 and 36 from Stage 2. Most studies of Category B discussed methods of constructing process simulation model more correctly, effectively and efficiently. Some papers introduced either novel simulation paradigms or simulation environments. The classification found 37 (24%) studies falling into two categories, and 5 studies that were identified as combinations of three categories.

3.3 Quality Assessment

The quality of the included studies was assessed using the checklist in [1]. Fig. 2 shows the average quality score after normalization. Fig. 2-a depicts the varying study quality from both stages per paper type over the decade. The overall study quality was not stable till 2003. Since then, the quality of the journal articles has been better than the conference/workshop papers.

Fig. 2-b compares the average study quality from each stage. From 2002, the quality of studies published in ProSim/ICSP (from Stage 1) was better than the studies published in other venues (in Stage 2) in most cases by paper type, particularly journal publications. This was probably because ProSim/ICSP encouraged more researchers to publish their quality research on SPSM.

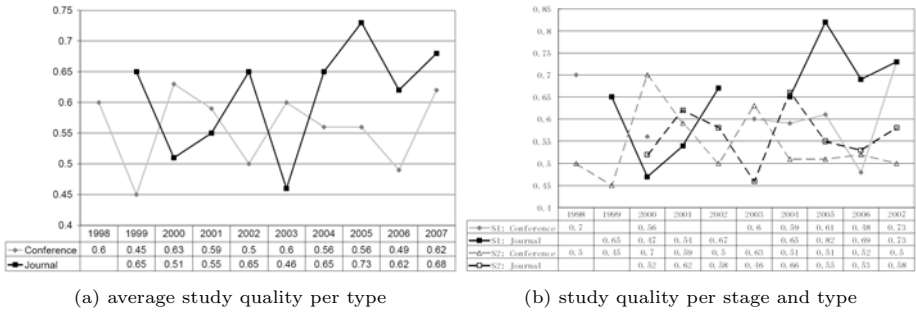


Fig. 2. Study quality assessment over years

4 Discussion

Following up our discussion in [1], this section focuses on the preliminary answers to the first five research questions (Q1-Q5), but provides a broader view by synthesizing the results from the both stages.

4.1 Research Purposes (Q1)

In the first ProSim Workshop (1998), KMR presented a wide variety of reasons for undertaking simulations of software process models [4]. Primarily, process simulation is an aid to decision making. They identified six specific purposes for SPSM. Our first stage SLR extended and restructured them to be ten purposes [1] based on the observation of SPSM studies.

The second stage SLR confirmed that these ten purposes for SPSM research identified in Stage 1. After minor refinements, these research purposes were grouped in three levels (i.e. *cognitive level, tactical level, strategic level*). Table 5 reports the categories and relationships.

4.2 Modeling Paradigms (Q2)

The diversity and complexity of software processes and the richness of research questions (concluded into simulation purposes in Table 5) determine the different capabilities of simulation paradigms needed.

Overall, 15 simulation modeling paradigms were found in our two-staged SLR. Table 6 shows the paradigms used by more than one applied study. The rightmost column indicates the number of studies (not limited to Category A) using or addressing the corresponding paradigm (the leftmost column). The first number in the bracket denotes the study number from Stage 1 (S1), and it is followed by the number from Stage 2 (S2) for comparison.

System Dynamics (SD, 47%) and Discrete-Event Simulation (DES, 31%) are the most popular technologies in SPSM. Other paradigms include State-Based Simulation (SBS), Qualitative (or semi-quantitative) Simulation (QSIM),

Table 5. SPSM purposes, levels, and model scopes

Purposes	Cognitive	Tactical	Strategic
Understanding	✓		
Communication	✓		
Process investigation	✓		
Education (training & learning)	✓		
Prediction & planning		✓	✓
Control & operational management		✓	✓
Risk management		✓	✓
Process improvement		✓	✓
Technology adoption		✓	✓
Tradeoff analysis & optimising		✓	✓

Role-Playing Game (RPG), Agent-Based Simulation (ABS), Discrete-Time Simulation (DTS), Knowledge-Based Simulation (KBS), Markov Process (MP), Cognitive Map (CM). These paradigms provide modelers with a number of options for modeling software processes at different abstraction levels, and enrich the modeling technologies (SD, DES, SBS and KBS) discussed by KMR [4].

Our first stage review identified 10 simulation paradigms for SPSM research. Compared to Stage 1, however, more paradigms (12) were employed by the fewer studies from the second stage, 5 of which are new to ProSim community. They are MP, CM, Specification and Description Language (SDL), Dynamic System Theory (DST), and Self-Organized Criticality (SOC). Most of these are not the conventional simulation paradigms.

Table 6. Modeling paradigms and simulation tools

Rank	Paradigm	Simulation tool or package	#Studies(S1/S2)
1	SD	Vensim(12/4), iThink(3/3), PowerSim(0/1)	74(47/27)
2	DES	Extend(11/4), DSOL(1/0), QNAP2(1/1), DEVSim++(1/0), DEVJava(1/0), MicroSaint(0/1), SimJava(0/1)	48(30/18)
3	SBS		9(6/3)
4	QSIM	QSIM(2/1)	6(5/1)
5	RPG	SESAM(1/0)	6(3/3)
6	ABS	NetLogo(1/0), RePast(1/0)	5(3/2)
7	DTS		5(2/3)
8	KBS	PML(1/0)	4(4/0)
9	MP		2(0/2)
10	CM		2(0/2)

4.3 Simulation Tools (Q3)

Simulation toolkits and packages provide computer-aided environments (compilers, engines, or workbenches), with which modelers can develop and execute their simulation models. Our staged SLR found 15 tools or packages explicitly specified in Category A studies. Table 6 shows them and their application frequencies (in bracket). Considering the number of Category A studies, however, this information was difficult to extract because in many cases that the authors did not mention the tools they used in their papers. Some of them programmed their simulators from scratch.

Compared to the other paradigms, it seems that DES offers more tool options for its modelers in SPSM. Note that though Extend provides both *continuous* and *discrete* simulation capabilities, it was seldom used for *continuous* simulation alone in SPSM studies.

It is interesting that although Vensim and Extend are two popular simulation tools in ProSim community, their dominance was not found outside that community. Our review shows that most studies using them but published outside are also from the active researchers in ProSim/ICSP community. Instead, the researchers outside the ProSim/ICSP community seemed to prefer programming their models themselves.

4.4 Research Topics and Model Scopes (Q4)

Research Topic identifies the topics (problems) in software engineering that researchers choose investigate. It also determines the model's structure, input parameters, and output variables. In both stages of our SLR, we found 21 different research topics from Category A studies (as shown in Table 7), of which '*software maintenance*' and '*COTS-based development*' were added after analysis of the studies from Stage 2. 'Project', again, was the most studied model scope, particularly for 'generic development' (e.g., waterfall process model).

Model Scope specifies the boundary of a simulation model in two dimensions: time span and organisational breadth. To more properly differentiate and classify the model scopes of the published simulation models, their scopes were extended from 5 (defined by KMR [4]) to 7.

- **single phase** (e.g. some or all of design or testing phase)
- **multi-phase** (more than one single phase in project life cycle)
- **project** (single software project life cycle)
- **multi-project** (program life cycle, including multiple, successive or concurrent projects)
- **product** (software product life cycle, including development, deployment, and maintenance.)
- **evolution** (long-term product evolution, including successive releases of software product, i.e. software product line)
- **long-term organisation** (strategic considerations or planning spanning releases of multiple products over a substantial time span)

4.5 Simulation Outputs (Q5)

By carefully examining the simulation models described in Category A studies from the both stages, 15 output variables were identified (shown in Table 8), 12 of them from Stage 1 and 13 from Stage 2. The third column indicates the number of studies including the leftmost output variable, and the rightmost column shows their corresponding percentage in Category A studies (divided by

Table 7. Process simulation research topics vs. model scopes

Topic	single phase	multi-phase	project	multi-project	product	evolution	long-term	unknown	Sum (S1/S2)
generic development			9/10				1/2		22(10/12)
software evolution			1/0		7/1				9(8/1)
software process improvement	1/0	1/0				1/0	3/1		7(6/1)
requirements engineering	2/0		1/1	0/1	1/0		1/0		7(5/2)
incremental & concurrent development	1/0	2/0	1/2				1/0		7(5/2)
inspection & testing	1/2	0/2	0/1	0/1					7(1/6)
open-source development	1/0		0/1	1/0	2/0				5(4/1)
global development			1/0		3/0				4(4/0)
agile development			1/2				1/0		4(2/2)
software maintenance	0/1			0/3					4(0/4)
software economics	1/0		1/1	1/0					4(3/1)
acquisition & outsourcing		1/0	0/1				1/0		3(2/1)
software product-line				1/0		1/0			2(2/0)
quality assurance		1/0					1/0		2(2/0)
COTS-based development	0/1	0/1							2(0/2)
software engineering education			2/0						2(2/0)
software design	1/0								1(1/0)
software services				1/0					1(1/0)
risk management			1/0						1(1/0)
productivity analysis			1/0						1(1/0)
software reliability							1/0		1(1/0)
Total	7/3	4/3	19/20	1/0	2/5	8/1	2/0	9/3	92(56/36)

Table 8. Summary of simulation outputs

Output	Description	#Studies(S1/S2)	Percent
time	project schedule or elapsed time	44(20/24)	47.8%
effort	effort or cost	29(16/13)	31.5%
quality	product quality or defect level	23(11/12)	25%
size	requirement size or functionality	15(11/4)	16.3%
resource	resource utilization or staffing level	12(7/5)	13%
productivity	team or personal development productivity/competency	6(1/5)	6.5%
ROI or revenue	return on investment or cost/benefit analysis	4(2/2)	4.3%
plan	project or development plan (e.g. task allocation)	4(3/1)	4.3%
progress	project progress to completion by percent	4(0/4)	4.3%
market share	product market share	2(1/1)	2.2%
behavior	behavior patterns	2(1/2)	1.1%
index	nominal index	1(1/0)	1.1%
flow	process/work flow	1(1/0)	1.1%
change requests	requested changes to product	1(0/1)	1.1%
human exhaustion	level of people or team's exhaustion	1(0/1)	1.1%

92 - the number of Category A studies). Note that there are many simulation studies (models) with multiple outputs of interest.

In terms of Table 8, it is evident that *time*, *effort*, *quality*, *size* are the most common drivers for simulation studies of software process. There are 71% studies (65 out of 92) including either one of them or their combination as model outputs. This finding confirms that SPSM research focuses mainly on factors of interest to software project managers.

5 Conclusion

We conducted a two-staged systematic literature review of software process simulation modeling by systematically searching and aggregating studies published within and outside the ProSim/ICSP community from 1998 to 2007. The results and in-depth findings from the first stage were reported in [1] and [3]. As a continuation of previous research, this paper presents the process and the updated results of our second stage review. To be specific, this research contributes to software process research in the following aspects.

- A two-staged SLR which identified most SPSM studies and classified them into four categories builds a basis for future secondary studies in SPSM.
- A broad state-of-the-art of SPSM research is portrayed from diverse aspects: purposes, paradigms, topics, scopes, outputs, and so on.
- Updates to KMR's landmark paper based on the evolution over the decade since ProSim'98.
- An initial comparison between the SPSM related research reported within and outside the ProSim/ICSP community.

Some limitations still exist in the current study and need further improvements: 1) the study categorization was mainly determined by the principal reviewer's final judgment, which may need further examination; 2) the impact of study quality needs to be considered in data analysis, particularly for the inclusion of low quality studies.

As our SLR is also a kind of mapping study, which provides groups of studies in this domain, it can be used as a precursor to future more detailed secondary research. In particular, this work will be enhanced by including a more detailed analysis of the studies of Categories B, C and D.

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