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RESEARCH PAPER

Business Process Simulation on Procedural Graphical Process Models

Structuring Overview and Paths for Future Research

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Abstract Business process simulation marks an essential technique for analyzing business processes and for reasoning about process improvement. With first contributions dating back to the mid-1990s, computerized business process simulation has been a continuing research focus and is widely acknowledged as foundational to Business Process Management research and practice. Reviewing contributions to the field published between 1990 and 2018, the authors assess the state of research on business process simulation and develop an organizing overview of research contributions discussing simulation approaches, tool support, results visualization, use context, application purposes, and adoption barriers. Findings inform future research on business process simulation by discussing paths for behavioral research on the use of business process simulation, user requirements, and adoption barriers as well as complementary paths for design science research addressing limitations of present approaches and simulation tool support.

Keywords Business process simulation · Business process modeling · Literature review

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This article extends and revises Rosenthal et al. (2018).

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1 Introduction

Business process simulation (BPS) is described as an essential Business Process Management (BPM) technique for analyzing business processes quantitatively and for reasoning about process improvement (Dumas et al. 2018). With first contributions dating back to the mid-1990s (Gladwin and Tumay 1994), BPS has been a continuing focus in the field of BPM and is widely acknowledged as foundational to BPM (Desel and Erwin 2000; van der Aalst 2015). As an analytic tool in the BPM practitioners' toolkit, BPS enables organizations to scrutinize alternative process designs prior to their organizational implementation to reason about design alternatives, to prevent costly design and implementation flaws, and to identify opportunities for process improvement subsequent to process implementation – without having to actually execute the business process (Neumann et al. 2011; see van der Aalst 2010 for a discussion of practical challenges). Following its instrumental tooling function, research on BPS has taken a theoretical-methodical angle devising simulation approaches and tool support and has studied their use for addressing practical problems (Recker and Mendling 2015).

While recognized as a vital technique at the core of BPM, the body of knowledge on BPS is surprisingly fragmented which obstructs the practitioner's view of the state of the art and impedes cumulative research. The present study contributes to filling this gap by compiling and analyzing prior work on BPS published between 1990 and 2018 to synthesize a structuring and organizing overview of the present state of research on BPS (foundational research objective), and, following, e.g., Rowe (2014), to inform future research on BPS by describing paths for research on practical use, user requirements, and adoption barriers as well as complementary paths for research addressing limitations of present simulation approaches and tool support (constructive research objective). For this purpose, the study targets five analytic dimensions: (1) approaches to BPS – including the construction of simulation models; (2) tool support for BPS; (3) visualization of simulation runs and results; (4) application purposes and use context; and (5) barriers to adopt BPS in organizations. For BPS practitioners, the study contributes to obtaining a concise summary of three decades of research on BPS approaches, simulation tools, modeling languages and simulation visualization in addition to insights into use contexts, application purposes and adoption barriers as discussed in BPS research (pragmatic objective).

Business process simulation is a diverse field utilizing a variety of approaches and starting points to building and running simulations including business process models represented in graphical and textual notations built based on procedural (imperative) as well as declarative process modeling languages (e.g., Fahland et al. 2009; van der Aalst 2015; Dumas et al. 2018). The present study investigates contributions to BPS starting from graphical business process models constructed from procedural process modeling languages. As models of business processes are oftentimes readily available in a procedural graphical representation, e.g., as Business Process Model and Notation (BPMN) diagram, organizations capitalize on their prior investments in business process modeling when building a business process simulation. Graphical procedural process models are widely adopted for communication and organizational design purposes for their wide-ranging understandability and versatile applicability (Davies et al. 2006; Recker et al. 2009; Indulska et al. 2009), and their support by modeling and simulation software tools (Becker et al. 2011; Neumann et al. 2011). Procedural graphical business process models are, hence, seen as a consequential starting point for designing and developing business process simulations (e.g., Barjis 2007, p. 254). Their use as a starting point for BPS is furthered by recent work on extending imperative process modeling languages such as the BPMN for simulation purposes, e.g., by the Business Process Simulation Specification (BPSim, Workflow Management Coalition 2016) (e.g., Bisogno et al. 2016; Cartelli et al. 2016). For these reasons, the present literature review focuses on BPS starting from a graphically represented business process model built on an imperative process modeling language including work that extends procedural process modeling languages with dedicated support for process simulation (e.g., Bocciarelli et al. 2014b; Xie 2008a, b). It excludes BPS starting from mining event logs (e.g., Rozinat et al. 2009a; Liu et al. 2012; Camargo et al. 2020) as they follow a fundamentally different approach to BPS and constitute a review topic in their own right (cf. Martin et al. 2016) as does BPS starting from declarative process modeling languages (e.g., Weber et al. 2009; Fahland et al. 2009; Pichler et al. 2011).

Related literature reviews are few and have different foci, e.g., the use of process mining to support the construction of business process simulation models (Martin et al. 2016; Keith Norambuena 2018) – a research topic addressed in recent research contributions on BPS (Rozinat et al. 2009b; van der Aalst 2010). The review by Bosilj - Vukšić et al. (2017) is restricted to case studies investigating the use of discrete event simulation in BPM projects and focuses on success factors for the implementation of simulation in BPM projects, while Bocciarelli et al. (2017) report on contributions to business process modeling and simulation with a focus on utilized modeling languages and simulation approaches but do not include a comprehensive overview of modeling and simulation approaches. The related literature review in Kloos (2014, pp. 49–59) is based on a selective rather than systematic sampling procedure. Different from prior literature reviews, the present study performs a comprehensive review based on a systematic purposeful sampling of academic publications and builds on a pluralistic search strategy (following, e.g., Webster and Watson 2002, pp. 14–19; vom Brocke et al. 2009, p. 2214). Note that the present study is not restricted to a specific kind of business process as, for example, collaborative business processes (e.g., de Cesare and Serrano 2006), inter-organizational business processes (e.g., Giaglis et al. 1996) or to literature focusing on a specific use context addressed in BPS research as, for example, risk assessment (e.g., Teilans et al. 2011) or life sciences (e.g., Holzmüller-Laue et al. 2013).

The theoretical background and the dimensions of analysis are detailed in the next section (Sect. 2). Section 3 reports the literature retrieval. In Sect. 4, findings are presented following the structure provided by the dimensions of analysis. A discussion of findings and future research directions is provided in Sect. 5. The review concludes by discussing methodical limitations (Sect. 6) and a reflective commentary (Sect. 7).

2 Theoretical Background and Dimensions of Analysis

Computer simulation studies the behavior of systems by imitating them (e.g., Winsberg 2019; Za et al. 2018; Beese et al. 2019). Following Winsberg (2019), computer simulation, in general, builds on a generic 4-step process: (1) Choosing or constructing a model of the system that is to be simulated; (2) implementing this model as an executable model on a computer; (3) calculating output data by simulation runs; and (4) visualizing and analyzing this data. Computer simulation is suggested when other means of investigation (e.g., real-simulation) are not possible, feasible or, for example, are too costly or time-consuming (e.g., Wedekind et al. 1998, p. 269); for a methodological and epistemological contextualization of computer simulation, see Frank et al. (2006) and Becker et al. (2005). Business process simulation, in a nutshell, simulates the execution of instances of a business process (more precisely, a business process type) in a computer simulation to analyze their dynamic, i.e., time-dependent behavior by imitating their execution based on the implementation of an executable model of the process on a computer and by running simulations of process executions (e.g., Tumay 1995; Paul et al. 1999).

2.1 Simulation Design and Execution

The most fundamental decision with respect to designing a BPS relates to the overall approach taken to process simulation. Two principle approaches are the *transformation* approach and the *extension* approach. Closely related to the overall approach is the essential design decision on simulation tool support. An essential step in designing and executing BPS is the visualization of simulation results. Accordingly, we analyze the literature in this review along these three dimensions (in Sect. 4):

1st Dimension of analysis – Overall approach When starting from a conceptual business process model, BPS presupposes enriching the conceptual model with additional information required for simulation (e.g., availability of limited resources and timing of events). Depending on the modeling language used to construct the conceptual process model, the information required for simulation is added to the conceptual process model (provided that precise syntax and semantics are defined by the language) (e.g., Bisogno et al. 2016) or is added during or after a model-to-model or model-to-text transformation to a respective simulation language (e.g., Bocciarelli et al. 2014a; Gruhn and Richter 2009). Thus, approaches to BPS generally fall into two categories (see also, e.g., Kloos 2014, pp. 52–59):

1. Transformation approaches utilize model-to-model or model-to-text transformations to transform a (graphically represented) business process model into a different representation allowing for process simulation. For example, the approach introduced in García-Bañuelos and Dumas (2009) transforms a graphical BPMN 1.x representation extended with information needed for simulation into a Colored Petri net. Likewise, the approach introduced in Xie (2008a, b) extends UML Activity diagrams to enable transformation to General Purpose System Simulation (GPSS) representations (Ståhl et al. 2011). The transformation is followed by the actual simulation (step 3 in the Winsberg's model).
2. Extension approaches do not rely on transformations to general purpose simulation languages such as the GPSS, but define simulation-specific extensions to conceptual business process models and the modeling languages with which they are constructed. For example, the Business Process Simulation Specification (BPSim) 1.0 proposal (Workflow Management Coalition 2013) and the revised BPSim 2.0 proposal (Workflow Management Coalition 2016) specify language extensions to the BPMN 2.x standard for constructing and running process simulations starting from BPMN diagrams based on refined precise semantics for simulating process execution. Similarly, extensions have been proposed for the Petri net-family of formalisms to run process simulation (e.g., Desel and Erwin 2000; Barjis 2007). Moreover, idiosyncratic extensions to process modeling languages have been proposed, typically in combination with proprietary simulation tool support (cf. Gawin and Marcinkowski 2015; Laue and Müller 2016; Pufahl et al. 2018).

We characterize the overall simulation approach further by *simulation properties* commonly used to describe technical details about how the simulation captures the business process to be simulated (cf. Pereira and Freitas 2016, pp. 559–561; Neumann et al. 2011, pp. 377–383, Dumas et al. 2018, pp. 280–282):

Case arrival specifies the number and timing of executions of new instances of the simulated business process – and, hence, is fundamental for configuring a business process simulation. Usually, the mean inter-arrival time and a probability distribution for this time as well as the duration of the simulation or the number of process instances that should be executed during simulation need to be specified (e.g., Dumas et al. 2018, p. 282).

Activity duration specifies the processing time for each process activity (process task) (Camargo et al. 2020, p. 2). An activity duration is assigned to a process task in the simulation model by specifying a fixed processing time, e.g., a fixed value for automated tasks or an estimated mean value, or by specifying a probability distribution for the duration, e.g., an exponential distribution or a normal distribution (Dumas et al. 2018, pp. 280f; Neumann et al. 2011).

Branching probabilities specify a probability for choosing a branch for each conditional branch in the simulation model, i.e., the execution respectively routing logic has to be further specified (Martin et al. 2016, p. 82), e.g., by constant probabilities or by more complex probability distributions such as a Bernoulli distribution (e.g., Lübbecke et al. 2015, p. 869). Simulation software tools typically implement statistical distributions to model non-deterministic decision flows (cf. Cimino and Vaglini 2014, p. 321).

Resource allocation specifies the allocation of resources to process tasks to properly simulate their execution. If an approach to BPS supports the modeling of allocation of resources to process tasks is, hence, a vital aspect to prepare for BPS (e.g., Dumas et al. 2018; van der Aalst 2015) taking a resource perspective on business process models (Russell et al. 2005; van der Aalst 2010). For long, resource allocation mechanisms and resource patterns have been discussed for workflow management tools (Russell et al. 2005), while for BPS the resource perspective is still discussed as a potential source of pitfalls for simulation approaches (van der Aalst 2010). However, in the light of recent research on advanced resource allocation strategies and resource models (e.g., Cartelli et al. 2016), it becomes increasingly important if and how an approach to BPS supports modeling resource allocation.

Resource availability specifies the availability of resources for being allocated to a process task and constitutes a further aspect following a resource perspective on BPS (e.g., Dumas et al. 2018; van der Aalst 2015). Modeling resource availability is discussed with regard to oversimplifying the availability of people, e.g., assuming that people are available continuously and neglecting that people may be involved in different processes (van der Aalst et al. 2008; van der Aalst 2010) – and thus as a further potential source of pitfalls for BPS. Recent research on resource availability patterns (e.g., Rozinat et al. 2009b), modeling of unavailability periods and work schedules or timetables for resources (Pereira and Freitas 2016), and extending BPMN 2 with support for resource modeling, especially modeling of resource availability (Vasilecas et al. 2014), highlights the increasing importance of modeling resource availability for approaches to BPS.

In addition to these simulation properties, we analyze the *use of historic data from event & simulation logs* for preparing a process model for simulation (Martin et al. 2016; Keith Norambuena 2018). Information on process execution that is, for example, available in event logs in process-aware information systems can be used for adding simulation-relevant information to a simulation model (e.g., data from databases, transaction logs) (e.g., van der Aalst 2010). For instance, resource characteristics can be retrieved from event logs assisting in preparing a process model for simulation. Moreover, data from simulation logs – providing information from prior simulation runs – can also be used as input for configuring a simulation model.

Altogether, the first analysis dimension *Overall approach* aims at understanding the principle approach a research contribution to BPS takes, the conceptual modeling language used to construct the underlying business process model, and the construction of the corresponding simulation model.

2nd Dimension of analysis – Tool support for BPS Evidently, each approach to BPS depends on a corresponding simulation software tool. After transforming or extending a business process model with information required for simulation, the actual simulation step is performed: Transformation approaches utilize general purpose simulation tools to run a process simulation. Extension approaches use simulation tools implementing the extensions needed for simulation to run the corresponding process simulation. Idiosyncratic extension approaches to process modeling languages are typically accompanied by proprietary simulation tool support (Laue and Müller 2016; Pufahl et al. 2018).

Following Jansen-Vullers and Netjes (2006), Bosilj - Vukšić et al. (2007) and Pufahl et al. (2018), we differentiate three different types of simulation tools for our analysis: (a) Business process modeling or management tools with simulation support (e.g., ADONIS, ARIS Toolset, Bizagi Modeler); (b) General purpose simulation tools (e.g., Arena, AnyLogic); and (c) Stand-alone business process simulators (e.g., Bimp).

The dimension *Tool support for BPS* aims to identify and compile tools used for performing the actual simulation step in BPS in the reviewed sample.

3rd Dimension of analysis – Visualization of simulation runs and results Visualizing simulation results constitutes one essential step in computer simulation to support purposeful interpretation of simulation results (e.g., Winsberg 2019). The interpretation of simulation results closely relates to the visualization of these results – for example, misleading interpretations of simulation results are associated with pitfalls in representing statistics (e.g., van der Aalst 2015). We categorize visualization techniques used in BPS along three categories following, e.g., Du et al. (2012): (1) static visualization techniques including, for example, tables as well as two- or three-dimensional diagrams; (2) visual animation including the animation of simulation dynamics; and (3) virtual reality visualizations (e.g., Eichhorn et al. 2009) and augmented reality visualizations (e.g., Poppe et al. 2012). In the analysis, we investigate if and how approaches to BPS address the visualization of simulation runs and results, and structure suggested visualization techniques using this categorization.

This third analysis dimension is targeted at achieving insights into how the reported approaches to BPS visualize and evaluate simulation results, and aims to compile an overview of techniques for visualizing simulation runs and results.

2.2 Application of BPS

As analysis technique, the simulation of business processes has been discussed as one focus of the practice of BPM since the mid-1990s (e.g., Tumay 1995; Recker and Mendling 2015). However, a selective review of pertinent literature indicates a limited adoption of business process simulation in practical applications (e.g., van der Aalst 2010; Bocciarelli et al. 2017). To achieve insights into the application of BPS as discussed in the review sample, the analysis is focused on purposes pursued with applying BPS and the use context as well as barriers hampering the adoption of BPS. Hence, analyzing the application of BPS is guided by the following two dimensions:

4th Dimension of analysis – Application purposes and use context Business process simulation as a BPM technique may serve a number of different purposes and pursue a variety of simulation objectives (Dumas et al. 2018, pp. 279–287; van der Aalst 2010, p. 2). From the outset, BPS has been linked to high-level purposes such as gaining competitive advantages through improved process performance (e.g., Gladwin and Tumay 1994; Tumay 1995), and to corresponding objectives such as analyzing resource demands in what-if scenarios. Given the range of practical BPS applications (Dumas et al. 2018, pp. 279–287; van der Aalst and Voorhoeve 2000, p. 2; Greasley 2003, p. 409), a variety of application purposes and simulation objectives is expected to guide their usage. Closely related to the purposes and objectives of simulation is the use context in which business processes are simulated. These contexts can be diverse (e.g., Bosilj Vukšić et al. 2017) as, for example, ranging from the use context of risk assessment (e.g., Teilans et al. 2011) to life science automation (e.g., Holzmüller-Laue et al. 2013). At present, however, literature has not been systematically reviewed about application purposes and use contexts of BPS and, hence, surprisingly little is known about the reasoning behind BPS application.

The dimension *Application purposes and use context* aims to identify and compile purposes and objectives as reported in the reviewed sample and to investigate whether purposes and/or simulation objectives have emerged and whether their mention has increased or decreased over time. In addition, this analysis dimension is targeted at achieving insights into use contexts of BPS as BPM technique discussed in the review sample. This analysis dimension aims at tracing the evolution of intentions and application contexts linked to BPS.

5th Dimension of analysis – Adoption barriers Various barriers are discussed preventing BPS research to transfer to practical applications and limiting the adoption of BPS as, for example, a perceived complexity of applying BPS along with a lack of training for simulation as well as limitations of existing approaches, e.g., limited tool support and missing support for interpreting simulation results and for modeling resources (e.g., van der Aalst 2010, pp. 2f; Bocciarelli et al. 2017, Dumas et al. 2018). In the light of this discussion, questions on underlying rationales and attempts to ease the adoption of BPS as essential technique in BPM raise.

Adoption barriers as analysis dimension is conceptualized as to refer to barriers to the adoption of BPS in practical applications, discussions on rationales behind these barriers and suggestions on how to ease the adoption of BPS approaches. The intention of this dimension of analysis is to achieve insights into adoption barriers of BPS and into remedies that have been suggested to overcome these barriers.

3 Research Design

The present study constitutes a standalone, systematic literature review (e.g., Kitchenham and Charters 2007, p. 3; vom Brocke et al. 2015, p. 207). Following Leidner (2018), the review complements an organizing review with an assessing review. Complementary search strategies are employed to include not only publications in journals and conference proceedings but also in other types of sources such as monographs and anthologies. Therefore, the present review complements database keyword searches (for principle limitations, see, e.g., Levy and Ellis (2006)) with backward and forward searches based on key articles as well as searches in selected journals and conference proceedings. The review process is illustrated in Fig. 1.

3.1 Literature Retrieval

The time frame for database searches as well as for the searches in selected journals and conference proceedings is set to publications from 1990 up to and including May 2018. A first literature retrieval performed in August 2017 covered the time span from 1990 up to and including 2016 (Rosenthal et al. 2018). To provide an updated overview of the field of BPS in the present work, the literature retrieval was extended in May 2018 to also include recent work published between 2017 and May 2018. The choice of the year 1990 as starting year for database and selective searches coincides with increasing interest in process organization and business processes subsequent to Hammer and Champy (1993) and Davenport (1993). For the literature retrieval, we assume that relevant work published before 1990 is cited at least in early publications and, thus, identified by backward searches. The retrieval procedure is limited to publications published in the English and

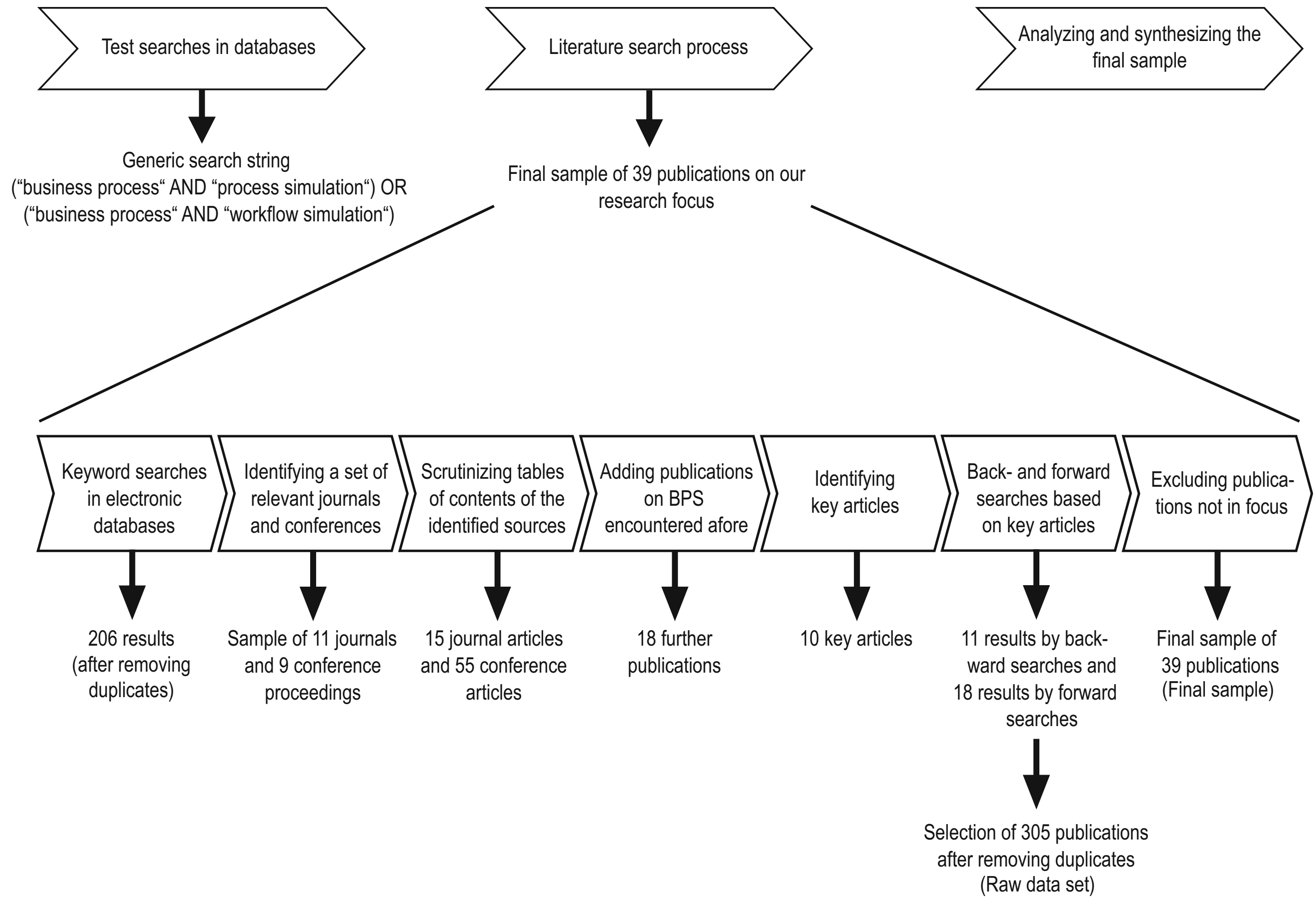

Fig. 1 Review process

German languages while searches in electronic databases use English search terms only.

3.1.1 Searches in Electronic Databases

Initial test searches demonstrated principle limitations with database searches: On the one hand, a search using the phrase "business process simulation" proved too limited with regard to publications deemed as relevant but not indexed by the whole three-word phrase. On the other hand, a search solely using the phrase "process simulation" produced far too many results irrelevant for this literature review including, e.g., results dealing with simulation of manufacturing processes not based on graphical process models. As a solution, the conjunction of the phrases "business process" and "process simulation" was used in database searches. Also, searches using the terms "process automation" and "process execution" led to far too many results from other scientific disciplines (e.g., robot automation) not relating to business process simulation and, hence, irrelevant for the focus of this study. To include approaches using workflow models representing business processes as a starting point for simulation, the phrase "workflow simulation" in conjunction with "business process" was also considered – especially, as the terms *business process* and *workflow* are used synonymously in parts of literature (Frank and van Laak 2003, p. 19). Thus, we arrived at the following generic logical search string that was applied for searches:

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(``business process'' AND ``process
simulation'') OR (``business process''
AND ``workflow simulation'')
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As first step of the literature retrieval, keyword searches were performed in the following electronic databases: EBSCOhost (Business Source Complete), ACM Digital Library (The ACM Guide to Computing Literature) and IEEE Xplore Digital Library. We searched in the fields title, keywords and abstract with the generic logical search string tailored to the search query syntax of each database. Aligned with the aim of an exhaustive review of prior work, the selection of electronic databases comprises core databases on Information Systems (IS) and computer science subjects (ACM Digital Library and IEEE Xplore digital library) as well as a cross-disciplinary database (EBSCOhost) – to cope with the multidisciplinary topic of the present review. The search fields as labeled in the databases and numbers of search results for each database are shown in Table 1. In total, the keyword searches led to 206 results after removing duplicates and results not qualifying as research publications, e.g., a conference summary and an association's members update (a list of the results of database searches is available upon request from the authors).

3.1.2 Selective Searches

As a second search strategy complementing the keyword searches and as suggested by Webster and Watson (2002), we scanned the table of contents of journals and conference proceedings. All eight journals listed in the Senior Scholars' Basket of Journals were considered. The journal Business & Information Systems Engineering (BISE)/ WIRTSCHAFTSINFORMATIK as relevant outlet for the German-language Business Informatics community and two further relevant journals, the Journal of Simulation (JS) and the Business Process Management Journal (BPMJ), were added for which focus and scope comply with the focus of this study. Additionally, proceedings of nine conferences were added to the sample of sources to also account for more recent publications. Seven of the chosen conferences are organized by or affiliated with associations relevant to the disciplines of Information Systems or Business and Information Systems Engineering. The conferences included in the search are the Americas Conference on Information Systems (AMCIS), European Conference on Information Systems (ECIS), Hawaii International Conference on System Sciences (HICSS), International Conference on Enterprise Information Systems (ICEIS), International Conference on Information Systems (ICIS), Internationale Tagung Wirtschaftsinformatik (WI) and the Winter Simulation Conference (WSC). The proceedings of the Conference on Advanced Information Systems Engineering (CAiSE) are added to the sources as they include contributions from the Workshop on Enterprise & Organizational Modeling and Simulation (EOMAS) addressing topics including BPS. Proceedings of the International Conference on Business Process Management (BPM conference series) are also included as the conference directly addresses BPM as research field. The final sample of sources consists of 11 journals and 9 conference proceedings. As a result of manually scanning the table of contents of these sources and viewing titles, abstracts and, in doubt, the full texts of publications, we added 15 journal articles and 55 articles published in conference proceedings to the sample (see Table 2; a list of these publications is available upon request from the authors).

Illustrating the limitations of database searches and selective searches, several publications on BPS that we encountered afore when selectively reviewing the field of research were not yet included in the sample. These publications include journal and conference articles not published in a source in our sample of journals and conference proceedings and not indexed in the queried electronic databases as well as articles published in anthologies and publications published in German. Please note that these publication had to be an original research article to be included in the sample and that, e.g., contributions focusing on (business) process simulation that are published in demo or tool proceedings were not considered (e.g., Burattin 2016). As a third step, we thus added these 18 publications on BPS to the sample (a list of these publications is available upon request from the authors).

3.1.3 Backward and Forward Searches

To obtain additional relevant publications such as monographs and articles published in anthologies, backward and forward searches based on ten articles, identified as key articles for the literature retrieval, were performed (vom Brocke et al. 2015, pp. 215f). Based on reviewing the current sample and requiring a consensus among the authors, the following publications were chosen as key articles: Tumay (1995, 1996), Giaglis et al. (1996), Paul et al. (1999), Desel and Erwin (2000), Greasley (2003), Jansen-Vullers and Netjes (2006), Barjis (2007), Barjis and

Table 1 Search fields and numbers of search results for searches in electronic databases (May 2018)

Database	Search fields	Search results
ACM Digital Library (The ACM Guide to Computing Literature)	acmdlTitle, recordAbstract, keywords.author.keyword	124
IEEE Xplore Digital Library	Document Title, Abstract, Author Keywords	105
EBSCOhost (Business Source Complete)	TI, AB, KW	41
		# (after removing duplicates) 206

Table 2 Sample of journals and conference proceedings with numbers of search results and results included in the final sample

Journals	Search results	Included in final sample
Business Process Management Journal (BPMJ)	11	1
Business & Information Systems Engineering (BISE)/WIRTSCHAFTSINFORMATIK	1	0
European Journal of Information Systems (EJIS)	0	0
Information Systems Journal (ISJ)	0	0
Information Systems Research (ISR)	0	0
Journal of Information Technology (JIT)	0	0
Journal of Management Information System (JMIS)	1	0
Journal of Simulation (JS)	1	0
Journal of Strategic Information Systems (JSIS)	0	0
Journal of the Association for Information Systems (JAIS)	0	0
Management Information Systems Quarterly (MISQ)	1	0
	15	1
Conference proceedings		
Americas Conference on Information Systems (AMCIS)	0	0
Conference on Advanced Information Systems Engineering with Workshop on Enterprise & Organizational Modeling and Simulation (CAiSE with EOMAS)	14	1
European Conference on Information Systems (ECIS)	2	0
Hawaii International Conference on System Sciences (HICSS)	7	1
International Conference on Business Process Management (BPM)	2	2
International Conference on Enterprise Information Systems (ICEIS)	1	1
International Conference on Information Systems (ICIS)	1	0
Internationale Tagung Wirtschaftsinformatik (WI)	0	0
Winter Simulation Conference (WSC)	28	3
#	55	8

Verbraeck (2010) and Liu and Iijima (2015). The selection of key articles is based on two criteria:

(1) A key article is cited multiple times in several articles on BPS and/or
(2) a key article provides an overview of the field of BPS.

To accomplish backward and forward searches, we scrutinized the bibliographies of the key articles respectively the results of forward searches using the search engine Google Scholar for publications on BPS not covered so far by our search strategies – by reason of publication date, type or source – leading to 11 additional results by backward searches and 18 additional results by forward searches in May 2018 (a list of these publications is available upon request from the authors). The literature search process at this stage resulted in a raw data sample of 305 publications – after removing duplicates.

3.2 Filtering Process

As a next step, publications outside of the focus of this study were excluded from the sample. The fulfillment of all of the following criteria was required for a publication to be included in the resulting final sample:

(1) original research contribution;
(2) focus on simulation of business processes starting from a graphical process model;
(3) detailed description of the simulation approach.

Hence, editorials, book reviews, tutorials, textbooks or parts of textbooks as well as education-related publications are excluded. Likewise, publications only marginally referring to BPS are excluded as, for example, publications only briefly mentioning BPS as a functionality of a software tool (e.g., Junginger et al. 2000). Also excluded is prior work on business process redesign not presenting details on performing simulation (e.g., Han et al. 2009a). Also, publications on conceptual and/or process modeling as means for developing simulation models are excluded from the sample if they do not start from a graphical process model (e.g., Wagner et al. 2016; Guizzardi and Wagner 2011; Ryan and Heavey 2007). Moreover, publications discussing the use of historical process instances data for constructing simulation models are excluded (e.g., van der Aalst 2010). The third inclusion criterion refers to the level of detail on the process simulation approach: Only publications are included that provide a traceable presentation of the process modeling language, its use for preparing for a simulation, the transfer to the simulation model and the simulation approach. Also, publications not written in English or German language are excluded. In this pruning process, all 305 publications were reviewed and discarded if they did not meet the inclusion criteria by considering title, abstract and keywords. When in doubt, a review of the full-text was performed. Excluding a publication required a consensus among the authors. The final sample of the remaining 39 publications is shown in Table 3 (classified by publication type). A list of the bibliographical data of the final sample and the raw data sample of 305 publications before excluding publications is available as supplementary material.

3.3 Literature Analysis

The first step of the subsequent analysis educes the publication profile in terms of the numbers of publications per year and per publication type (e.g., journal or conference article, monograph or article in an anthology). As a next step, we purposefully read the publications in the final sample to structure and classify the field with regard to the five dimensions of analysis covering fundamental aspects of approaches to BPS and the application of BPS as discussed in the review sample (see Sect. 2). Therefore, we code the publications in the final sample on the addressed dimensions of analysis: Table 3 shows all publications in the final sample assigned to the addressed dimensions (marked with an X) and grouped by publication type. Next, we develop an insightful synthesis of the identified body of literature on BPS regarding each dimension of analysis – to present, as a whole, an organizing overview of the field contributing to the body of knowledge (Leidner 2018):

Regarding the first dimension of analysis 'Overall approach' (see Sect. 2), we start by categorizing the approaches to BPS with respect to their overall approach to BPS, i.e., extending or transforming a business process model that is to be simulated, and identify the modeling language used to construct the process model as starting point for simulation. For analyzing the final sample on the sub dimensions representing simulation properties and the use of historic data from event logs and simulation logs for preparing a process model for simulation, we introduce four categories distinguishing if and how detailed a contribution addresses the respective aspect: (i) a publication does not address an aspect; (ii) a publication mentions the need to support a certain aspect; (iii) a publication basically explains how to support a certain aspect; (iv) a publication explains how to support a certain aspect in detail. The contributions are assigned to one of these categories for each analyzed aspect (see Fig. 4). For analyzing the second dimension of analysis 'Tool support for BPS' (see Sect. 2), we build on the common differentiation of simulation tools into (a) business process modeling or management tools with simulation support, (b) general purpose simulation tools, and (c) stand-alone business process simulators (cf. Jansen-Vullers and Netjes 2006; Bosilj - Vukšić et al. 2007; Pufahl et al. 2018). The analysis on the third dimension 'Visualization of simulation runs' uses Du et al. (cf. 2012)'s categories of (1) static visualization techniques, (2) visual animation, and (3) virtual reality and augmented reality visualizations. Different from the first three dimensions, analyzing the fourth dimension 'Application purposes and use context' and the fifth dimension 'Adoption barriers' starts with an open coding strategy. The publications in the final sample are systematically assigned to concepts representing application purposes and use contexts of applying BPS respectively adoption barriers of BPS (cf. King and He 2005). Codes are revised and refined until no new codes are identified, i.e., a certain level of saturation has been achieved. This analysis strategy leads us to identify prevalent and emerging application purposes and specific use contexts of BPS as well as adoption barriers of BPS as discussed in the reviewed sample. Subsequently, we identify emerging research gaps and, on that basis, develop suggestions for future research on BPS (following, e.g., Rowe 2014).

4 Findings

The reviewed sample comprises 39 publications published between 1996 and 2018. Analyzing the sample by year of publication suggests that the interest in BPS (as indicated by the number of publications) has increased since the 1990s, in particular, in the past decade (see Fig. 2). Regarding the publication types represented in the final sample, most of the 39 contributions, precisely 27 of 39, are published as conference articles (see Table 3) – besides 6 journal articles, 3 book chapters, 2 doctoral dissertations (Joschko 2014; Kloos 2014) and 1 monograph (Oberweis 1996). We observe that only few publications in the review sample are published in the IS journals and conference proceedings considered for selective searches (see Table 2) and that publications such as monographs and parts of anthologies are represented in the final sample (see Table 3). Both observations confirm our pluralistic search

Table 3 Publications in review sample according to publication type and addressed dimensions of analysis (X marks that a publication addresses a dimension of analysis and is included in the analysis regarding the dimension)

Publications	Dimensions of analysis					
Conference articles	Overall approach	Tool support	Visualization	Purposes & context	Adoption barriers	Outlet
Gladwin and Harrell (1997)	X	X	X	X	X	WSC
Barjis (2007)	X	X	X	X	X	ICEIS
Rozinat et al. (2008)	X	X	X	X	X	BPM
Wynn et al. (2008)	X	X		X	X	ICCASM
Xie (2008a)	X			X	X	ROCOM
Xie (2008b)	X	X	X	X	X	ICAL
Chan et al. (2009)	X	X	X	X		ICEBE
García-Bañuelos and Dumas (2009)	X	X			X	CPnets
Gruhn and Richter (2009)	X	X			X	SIMUL
Kanalici et al. (2009)	X	X		X	X	EMCIS
Kloos et al. (2009)	X	X			X	EMISA
Kloos et al. (2010)	X	X		X		DLM
Bocciarelli et al. (2012)	X	X				WSC
Holzmüller-Laue et al. (2013)	X	X	X	X		BIR
Bocciarelli et al. (2014a)	X	X		X	X	WSC
Bocciarelli et al. (2014b)	X	X		X	X	SpringSim
Bocciarelli et al. (2014c)	X	X		X	X	WETICE
Cartelli et al. (2014)	X	X	X	X		EMS
García et al. (2014)	X	X	X	X	X	ISD
Cartelli et al. (2015)	X	X	X	X		IC3K
Lübbecke et al. (2015)	X	X	X	X	X	HICSS
Antonacci et al. (2016)	X	X	X	X	X	WETICE
Cartelli et al. (2016)	X	X	X	X		EOMAS
D'Ambrogio et al. (2016)	X	X		X		TMS-DEVS
D'Ambrogio and Zacharewicz (2016)	X			X		SummerSim
Stankevicius and Vasilecas (2016)*				X		EStream
Pufahl et al. (2018)	X	X		X	X	BPM
# 27						
Journal articles	**Overall approach**	**Tool support**	**Visualization**	**Purposes & context**	**Adoption barriers**	**Outlet**
Han et al. (2009b)	X	X	X	X	X	WSEAS
Rozinat et al. (2009b)	X	X	X	X		DKE
Kloos et al. (2011)	X	X		X		EMISAJ
Vasilecas et al. (2013)	X	X			X	BJMC
Cimino and Vaglini (2014)	X	X	X	X	X	Information
Bisogno et al. (2016)	X	X	X	X		BPMJ
# 6						
Others	**Overall approach**	**Tool support**	**Visualization**	**Purposes & context**	**Adoption barriers**	**Outlet**
Oberweis (1996)	X	X	X	X		Monograph
Desel et al. (1999)	X	X		X		Anthology
Desel and Erwin (2000)	X	X		X		Anthology
Desel and Erwin (2003)	X	X	X	X		Anthology
Joschko (2014)	X	X	X	X		Monograph
Kloos (2014)	X	X				Monograph

Table 3 continued

Others	Overall approach	Tool support	Visualization	Purposes & context	Adoption barriers	Outlet
# 6						

Abbr.: ICCASM (International Conference on Computer Application and System Modeling), ROCOM (International Conference on Robotics, Control and Manufacturing Technology), ICAL (International Conference on Automation and Logistics), ICEBE (International Conference on e-Business Engineering), CPnets (Workshop and Tutorial on Practical Use of Coloured Petri Nets and the CPN Tools), SIMUL (International Conference on Advances in System Simulation), EMCIS (European and Mediterranean Conference on Information Systems), EMISA (Workshop on Enterprise Modelling and Information Systems Architecture), DLM (Dienstleistungsmodellierung), BIR (International Conference on Perspectives in Business Informatics Research), SpringSim (Spring Simulation Conference), WETICE (International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises), EMS (European Modelling Symposium), ISD (International Conference on Information Systems Development), IC3K (International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management), TMS-DEVS (Symposium on Theory of Modeling & Simulation), SummerSim (Summer Computer Simulation Conference), EStream (Open Conference of Electrical, Electronic and Information Sciences), WSEAS (Transactions on Information Science and Applications), DKE (Data & Knowledge Engineering), EMISAJ (Enterprise Modelling and Information Systems Architecture – International Journal of Conceptual Modeling), BJMC (Baltic Journal of Modern Computing)

* Please note that including the article Stankevicius and Vasilecas (2016) in the final sample was a borderline decision. The short paper of four pages introduces a preliminary approach to simulate long running business processes starting from graphically represented event-based process models and, hence, is included in the review sample. However, the article is not included in the analysis regarding the first dimension 'Overall approach' as detailed information for an analysis based on the present conceptualization of this analysis dimension (Sect. 2) is missing in the article

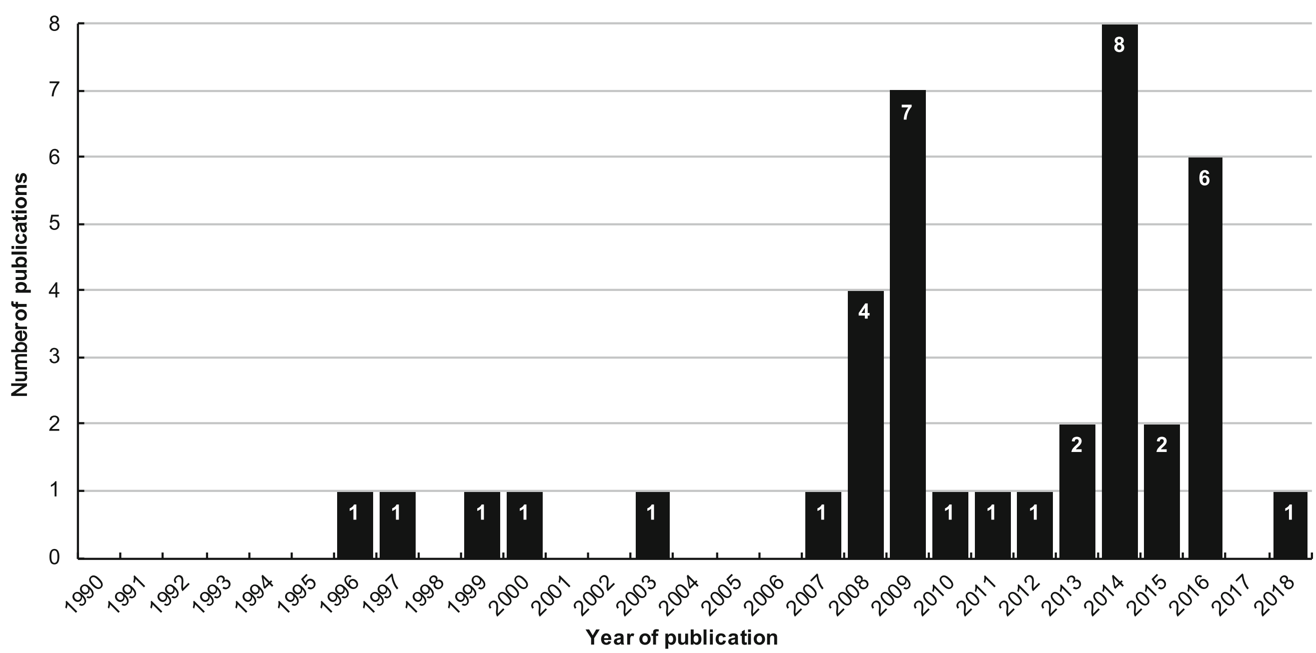

Fig. 2 Development over time of numbers of publications in the final sample from 1990 to May 2018

strategy combining searches in electronic databases as well as backward and forward searches in addition to selective searches.

In the following, findings are presented along the five dimensions of analysis beginning with the analysis regarding simulation design and execution and continuing with the application of BPS (see Sect. 2). For each dimension, prior work in the review sample addressing the respective dimension is structured and summarized.

4.1 Simulation Design and Execution

4.1.1 Overall Approach

Analyzing approaches to BPS suggests that, broadly, three categories of simulation approaches deserve distinction extending our initial categorization (e.g., Kloos 2014, pp. 52–59): (1) 'direct simulation approaches' directly simulating (extended) graphical process models (e.g., Oberweis 1996; Desel and Erwin 2003; Barjis 2007); (2) 'direct transformation approaches' providing a direct transformation of a business process model into a simulation model (e.g., Bocciarelli et al. 2014a, c; Xie 2008a, b); and (3) 'indirect transformation approaches' requiring an intermediate transformation model that is, subsequently, transformed into a simulation model (e.g., Kloos et al. 2011; Kloos 2014). In categorizing the approaches, we do not consider extending a business process model, e.g., annotating a model by use of PyBPMN (e.g., Bocciarelli et al. 2012; D'Ambrogio and Zacharewicz 2016), as a transformation because the underlying modeling language used to construct the process model is not changed, but an extension of this language is used (e.g., Antonacci et al. 2016). Table 4 shows the categorization of the approaches to BPS reported in the final sample into the three categories.

As starting point for simulation, we find conceptual business process models constructed with different modeling languages: Petri nets, BPMN, UML, EPC and a number of unrelated, idiosyncratic approaches referred to as "Others" in Table 5. Related to Table 5, Fig. 3 adds a time axis and counts the number of publications per year. As to be expected, more recent approaches to BPS build on BPMN 2.x as modeling foundation whereas early contributions rely on Petri nets and later on the EPC and on UML Activity diagrams. Despite standardization attempts, curiously, only one approach in the sample builds on the proposed BPSim 1.0 standardization attempt (Bisogno et al. 2016).

We observe considerable differences regarding simulation properties (case arrival; activity duration; branching probabilities, resource allocation, resource availability) and the use of historic data from event logs and simulation logs for preparing a process model for simulation (see Fig. 4 for an overview).

The specification of case arrival is addressed in only a third of the reviewed publications. Only seven publications basically explain how to specify case arrival for BPS (Gladwin and Harrell 1997; Rozinat et al. 2008; Wynn et al. 2008; Chan et al. 2009; Rozinat et al. 2009b; Cimino and Vaglini 2014; Pufahl et al. 2018), while six publications only mention the need to support this simulation property (Desel and Erwin 2003; García-Bañuelos and Dumas 2009; Kanalici et al. 2009; Holzmüller-Laue et al. 2013; Joschko 2014; Bisogno et al. 2016). It is remarkable that not a single reviewed publication explains how to support case arrival in detail. Particularly, explanations are very scarce on how the number and timing of executions of process instances can be derived (e.g., Rozinat et al. 2008, p. 199).

The simulation property of activity duration is discussed in the vast majority of reviewed publications, only seven publications do not mention this property. However, only about a quarter of the contributions comprises detailed explanations on how to specify activity durations (Oberweis 1996; Desel et al. 1999; Desel and Erwin 2000, 2003; Chan et al. 2009; Cimino and Vaglini 2014; Joschko 2014; Cartelli et al. 2015, 2016). The majority of approaches uses a fixed time value for the duration of activities, which in several cases is determined by assuming or calculating the mean value of the process execution time (e.g., Desel and Erwin 2003; Chan et al. 2009; Holzmüller-Laue et al. 2013). Further approaches use probability distributions, in particular, if the duration varies or is unknown, e.g., a normal or exponential distribution (Xie 2008a, b; García-Bañuelos and Dumas 2009). We find the use of historical data to specify the duration of activities only in three publications, e.g., by aggregating values from historic data to derive a probability distribution (Rozinat et al. 2008, 2009b; Wynn et al. 2008).

Branching probabilities for process alternatives are also addressed in the vast majority of reviewed publications with only six publications not mentioning this simulation property. Branching probabilities are introduced with regard to extending branches with constant probabilities or stochastic approaches such as the roulette wheel method (Cimino and Vaglini 2014, p. 336) or based on a Gaussian distribution (Lübbecke et al. 2015, p. 869). We find more detailed explanations on preparing process alternatives for simulation by extending branches only in eight reviewed publications (e.g., Desel and Erwin 2003; García-Bañuelos and Dumas 2009; Gruhn and Richter 2009; Kloos et al. 2009; Cimino and Vaglini 2014; Kloos 2014; Cartelli et al. 2015, 2016). Moreover, many publications do not mention if and how XOR- or OR-operators are executed when simulating the business process – this may be a more technical part of the simulation tool, but it directly affects the simulation and, for XOR-gateways, it is important to ensure that exactly one of the process branches is executed in each process instance (cf. Neumann et al. 2011, p. 381).

The resource perspective on BPS regarding resource allocation is addressed in about three quarters of the reviewed publications, while there are seven publications that do not mention the allocation of resources to process tasks. It is remarkable that 15 publications addressing

Table 4 Approaches to BPS according to simulation approach

Publications	Direct simulation	Direct transformation	Indirect transformation
Oberweis (1996)	X		
Gladwin and Harrell (1997)	X		
Desel et al. (1999)	X		
Desel and Erwin (2000)	X		
Desel and Erwin (2003)	X		
Barjis (2007)	X		
Rozinat et al. (2008)		X	
Wynn et al. (2008)		X	
Xie (2008a)		X	
Xie (2008b)		X	
Chan et al. (2009)		X	
García-Bañuelos and Dumas (2009)		X	
Gruhn and Richter (2009)		X	
Kanalici et al. (2009)		X	
Han et al. (2009b)		X	
Rozinat et al. (2009b)		X	
Kloos et al. (2009)			X
Kloos et al. (2010)			X
Kloos et al. (2011)			X
Bocciarelli et al. (2012)			X
Vasilecas et al. (2013)		X	
Holzmüller-Laue et al. (2013)		X	
Bocciarelli et al. (2014a)		X	
Bocciarelli et al. (2014b)		X	
Bocciarelli et al. (2014c)		X	
Cimino and Vaglini (2014)	X		
Joschko (2014)		X	
Kloos (2014)			X
Cartelli et al. (2014)		X	
García et al. (2014)		X	
Cartelli et al. (2015)		X	
Lübbecke et al. (2015)		X	
Bisogno et al. (2016)	X		
Antonacci et al. (2016)		X	
Cartelli et al. (2016)		X	
D'Ambrogio et al. (2016)		X	
D'Ambrogio and Zacharewicz (2016)		X	
Pufahl et al. (2018)		X	

resource allocation explain how to support this simulation property in detail (Oberweis 1996; Chan et al. 2009; Gruhn and Richter 2009; Kloos et al. 2009, 2010, 2011; Vasilecas et al. 2013; Cimino and Vaglini 2014; Joschko 2014; Kloos 2014; Cartelli et al. 2014, 2015, 2016; D'Ambrogio et al. 2016; D'Ambrogio and Zacharewicz 2016). A few publications propose extensions for modeling languages enabling the allocation of resources, e.g., for BPMN 2.0 via text annotations (Bocciarelli et al. 2014a, p. 3015) as well as for the extended Event-Driven Process Chain (eEPC) (e.g., Kloos 2014). Other approaches suggest resource models to enrich and extend a simulation model for BPS (e.g., Cartelli et al. 2015).

Besides resource allocation, resource availability as further vital aspect of the resource perspective is also addressed in about three quarters of the reviewed

Table 5 Modeling languages as foundation for BPS and respective publications in the final sample (multiple assignments allowed)

Process modeling language	Publications
Petri net	Oberweis (1996), Desel et al. (1999), Desel and Erwin (2000, 2003), Barjis (2007)
BPMN 1.x	García-Bañuelos and Dumas (2009)
BPMN 2.0	Bocciarelli et al. (2012), Vasilecas et al. (2013), Holzmüller-Laue et al. (2013), Bocciarelli et al. (2014a, b, c), Cartelli et al. (2014), Cimino and Vaglini (2014), Joschko (2014), Kloos (2014), García et al. (2014), Cartelli et al. (2015), Antonacci et al. (2016), D'Ambrogio and Zacharewicz (2016), Bisogno et al. (2016), Cartelli et al. (2016), D'Ambrogio et al. (2016), Pufahl et al. (2018)
UML (Activity diagrams)	Xie (2008a, b), Han et al. (2009b), Gruhn and Richter (2009), Kloos (2014)
EPC	Chan et al. (2009), Kloos et al. (2009, 2010, 2011), Kloos (2014), Lübbecke et al. (2015)
Others	Gladwin and Harrell (1997), Wynn et al. (2008), Rozinat et al. (2008, 2009b), Kanalici et al. (2009)

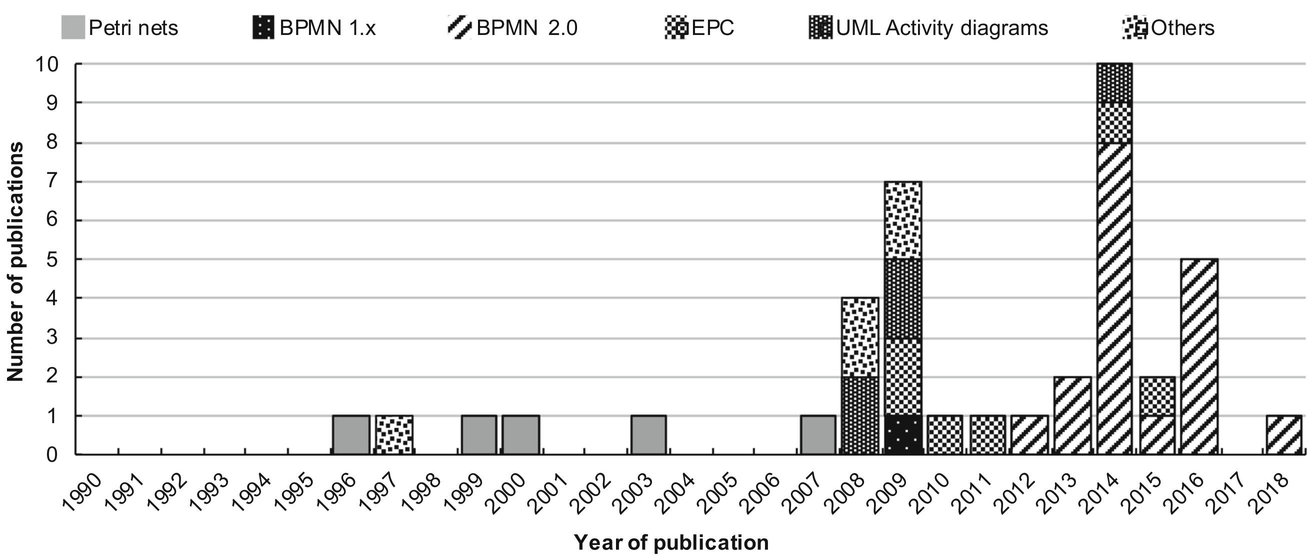

Fig. 3 Development over time of numbers of approaches to BPS in the final sample differentiated by modeling language used as foundation (multiple assignments allowed)

publications, while eight publications do not mention this simulation property. However, only eight contributions explain resource availability in detail (Gruhn and Richter 2009; Vasilecas et al. 2013; Kloos 2014; Cartelli et al. 2014, 2015, 2016; D'Ambrogio et al. 2016; D'Ambrogio and Zacharewicz 2016). Several different approaches for modeling resource availability for BPS have been suggested. For example, Cartelli et al. (2016, pp. 27–29) propose a resource model defining a resource concept focusing on costs and process related information in which resource availability is modeled by defining calendars representing a set of time intervals in which a resource is available. Schedules used as shift plans for the resource availability of, e.g., human resources, as well as to control the timing of a resource respectively activity are only barely discussed (e.g., Kloos 2014; Joschko 2014). The availability of non-human, stationary resources, e.g., costs, is discussed in more detail (e.g., Cimino and Vaglini 2014; Cartelli et al. 2016). In addition, availability patterns of resources are suggested that are based on extracting historical information from event logs that contain information on the actual execution of cases (e.g., Rozinat et al. 2009b, p. 836). However, inter-case dependencies between instances of the simulated process or multiple instance tasks are only mentioned in very few publications (e.g., Vasilecas et al. 2013; Pufahl et al. 2018).

Only ten publications in the final sample mention the use of historic process data for preparing process models for simulation. We only identify three publications that explain the use of historic data from event logs and simulation logs as input for simulation in detail (Rozinat et al. 2008, 2009b; Wynn et al. 2008). Besides, we only observe a few publications mentioning the need to support the use of historic data from event logs for extending process

	Simulation properties					Use of historic data	
Publications	Case arrival	Activity duration	Branching probabilities	Resource allocation	Resource availability	from event logs	from simulation logs
Oberweis (1996)	—	●	◐	●	◐	—	—
Gladwin & Harrell (1997)	◐	○	○	◐	○	—	—
Desel et al. (1999)	—	●	○	—	—	—	—
Desel & Erwin (2000)	—	●	◐	—	—	—	—
Desel & Erwin (2003)	○	●	●	○	◐	—	—
Barjis (2007)	—	—	—	—	—	—	—
Rozinat et al. (2008)	◐	◐	○	◐	◐	●	●
Wynn et al. (2008)	◐	◐	◐	◐	◐	●	●
Xie (2008a)	—	○	◐	○	—	—	—
Xie (2008b)	—	○	◐	○	—	—	—
Chan et al. (2009)	◐	●	◐	●	◐	—	—
García-Bañuelos & Dumas (2009)	○	○	●	◐	○	—	—
Gruhn & Richter (2009)	—	—	●	●	●	—	—
Kanalici et al. (2009)	○	—	◐	—	—	○	—
Han et al. (2009b)	—	—	○	○	○	—	—
Rozinat et al. (2009b)	◐	◐	○	◐	◐	●	●
Kloos et al. (2009)	—	◐	●	●	◐	—	—
Kloos et al. (2010)	—	◐	◐	●	○	○	—
Kloos et al. (2011)	—	◐	◐	●	○	○	—
Bocciarelli et al. (2012)	—	◐	—	—	○	—	—
Vasilecas et al. (2013)	—	—	—	●	●	○	—
Holzmüller-Laue et al. (2013)	○	◐	—	○	—	—	—
Bocciarelli et al. (2014a)	—	○	○	○	○	—	—
Bocciarelli et al. (2014b)	—	○	○	◐	◐	—	—
Bocciarelli et al. (2014c)	—	○	○	○	○	—	—
Cimino & Vaglini (2014)	◐	●	●	●	◐	—	○
Joschko (2014)	○	●	◐	●	◐	—	—
Kloos (2014)	—	◐	●	●	●	○	—
Cartelli et al. (2014)	—	○	—	●	●	—	—
García et al. (2014)	—	—	○	○	○	—	—
Cartelli et al. (2015)	—	●	●	●	●	—	—
Lübbecke et al. (2015)	—	—	◐	—	—	○	—
Bisogno et al. (2016)	○	○	—	—	○	—	—
Antonacci et al. (2016)	—	○	◐	○	○	—	—
Cartelli et al. (2016)	—	●	●	●	●	—	—
D'Ambrogio et al. (2016)	—	○	○	●	●	—	—
D'Ambrogio & Zacharewicz (2016)	—	○	○	●	●	—	—
Pufahl et al. (2018)	◐	○	◐	◐	◐	—	—

— marks that a publication does not address an aspect; ○ marks that a publication mentions the need to support a certain aspect; ◐ marks that a publication basically explains how to support a certain aspect; ● marks that a publication explains how to support a certain aspect in detail

Fig. 4 Simulation properties and use of historic data for preparing a process model for simulation as discussed in the final sample

models for simulation (Kanalici et al. 2009; Kloos et al. 2010, 2011; Vasilecas et al. 2013; Kloos 2014; Lübbecke et al. 2015) and one further publication mentioning to use data from simulation logs for this purpose (Cimino and Vaglini 2014).

The following paragraphs introduce the approaches to BPS suggested in the review sample. For each modeling language used to prepare business process models for simulation, we firstly give a short overview of corresponding simulation approaches before, secondly, each approach is briefly described along the three categories of simulation approaches – starting with (1) 'direct simulation approaches', continuing with (2) 'direct transformation approaches' and concluding with (3) 'indirect transformation approaches'. Please note that this first dimension of analysis is closely intertwined with the second analysis dimension *Tool support for BPS*. Hence, the description of the overall approaches comprises information on corresponding tool support as necessary for understanding. A systematic overview regarding tool support for BPS suggested in the review sample is given further below.

Approaches starting from a Petri net Petri net-based approaches are unsurprisingly among the earliest proposals to BPS (e.g., Oberweis 1996). The Petri net-based approaches in the final sample represent a business process as Petri net and, without further transformation, simulate by generating runs of the Petri net (Oberweis 1996; Desel et al. 1999; Desel and Erwin 2000, 2003). Hence all Petri net-based approaches in the review sample fall into the category of 'direct simulation approaches'. In the following, the approaches are briefly outlined.

A simulation approach for business processes represented as Nested-Relation/Transition nets, a class of higher Petri nets, including a graphical query language facilitating the interpretation of simulation runs is presented in Oberweis (1996, pp. 210–230). In this context, the term simulation means generating a sequence of markings for a Petri net starting with an initial marking of the net. Following this approach, the simulation step can be performed interactively by a user, automatically by a simulation engine or semi-automatically (Oberweis 1996, pp. 214f).

In Desel et al. (1999) and Desel and Erwin (2000, 2003), an approach to BPS, called VIP Project (Desel and Erwin 2000, p. 237), is suggested. Starting from a Place/Transition net, a class of Petri nets representing a business process, a representative set of concurrent runs of the net is selected with the aim of including standard cases and regular exceptions. As a subsequent step, simulation properties such as time and cost values are added to the selected runs followed by performance analysis of the business process. Additionally, integration of resources into this approach has been suggested in Desel and Erwin (2003).

An approach based on the Design & Engineering Methodology for Organizations (DEMO) for applying BPS is developed in Barjis (2007): For a graphical representation of a business process constructed in an extended Petri net notation, the simulation step is performed using a Petri net tool providing simulation functionalities.

Approaches starting from a BPMN model Almost half of the publications in the final sample recommend BPMN 2.0 models as a starting point for simulation. In the following, we firstly outline one (1) 'direct simulation approach' using BPMN 1.x (García-Bañuelos and Dumas 2009) and continue with the further approaches referring to BPMN 2.0. The latter split into two (1) 'direct simulation approaches' (Cimino and Vaglini 2014; Bisogno et al. 2016), a majority of approaches utilizing (2) 'direct transformation' (e.g., Vasilecas et al. 2013; García et al. 2014) and two (3) 'indirect transformation approaches' (Bocciarelli et al. 2012; Kloos 2014).

Prior to the release of BPMN 2.0 in the year 2011, a 'direct transformation approach' to BPS based on BPMN 1.x is reported that is based on transforming a BPMN 1.x process model into a Colored Petri net (García-Bañuelos and Dumas 2009). In a first step, the process model is extended with further information needed for simulation (García-Bañuelos and Dumas 2009, p. 202). In the next step, the extended BPMN model is transformed into a Colored Petri net that is simulated (García-Bañuelos and Dumas 2009, p. 200).

Building on BPMN 2.0 and the BPSim 1.0 standard, Bisogno et al. (2016) suggest a modeling and simulation method called Simulation-based Process Performance Analysis (SimPPA). Following the BPSim 1.0 standard (see Workflow Management Coalition 2013), a BPMN 2.0 process model is supplemented by information needed for simulation (Bisogno et al. 2016, p. 63) – hence, constituting a 'direct simulation approach'. One further approach to BPS using direct simulation is proposed in Cimino and Vaglini (2014): The approach uses interval-valued parameters instead of conventional single-valued or probability-valued parameters. A BPMN 2.0 model is extended with interval-valued data and, for the simulation step, a genetic algorithm computes the interval-valued output in a standalone business process simulator (Cimino and Vaglini 2014, pp. 338–341).

Other approaches starting from BPMN 2.0 models suggest the direct transformation of process models into simulation models: García et al. (2014) introduce an approach to automatically generate executable simulation models from BPMN 2.0 models by extending the business process models with information needed for simulation followed by a transformation step into a tool-independent discrete event simulation model (García et al. 2014, pp. 310f). The approach provided in Vasilecas et al. (2013) focuses on concurrency aspects of business processes. A BPMN 2.0 process model is extended by a Real-time UML collaboration diagram with extensions for concurrency and a resource model. These models are transformed into a simulation model (Vasilecas et al. 2013, pp. 234f).

Further approaches starting from BPMN 2.0 models propose the development and application of research prototypes of business process simulators. A recent approach suggests transforming a BPMN 2.0 model integrated with a context model into a Colored Petri net that is simulated (Cartelli et al. 2014, 2015, 2016). The context model comprises a resource model for representing human and non-human resources as well as an environment model referring to features of the specific process environment (Cartelli et al. 2016, pp. 26–30).

Furthermore, a procedure starting from BPMN 2.0 process models with the aim to generate executable simulation code utilizing the domain-specific language eBPMN is suggested in Bocciarelli et al. (2014a, b, c). In more detail, a business process model is extended with additional information needed for simulation by including text annotations specified according to the syntax of the lightweight BPMN extension Performability-oriented BPMN (PyBPMN) (Bocciarelli and D'Ambrogio 2011). Transformation of such an extended BPMN model is performed resulting in code in the domain-specific language eBPMN implementing BPMN 2.0 execution semantics. For the actual simulation, this simulation code is executed in a research prototype. In D'Ambrogio et al. (2016), the aforementioned approach to BPS is extended aimed at supporting continuous refinement of business processes by dynamically adapting processes based on simulation results and actual process data. For this, PyBPMN is extended to annotate BPMN models with results provided by simulation in addition to input parameters for simulation. Adapting the approach suggested in Bocciarelli et al. (2014a, b, c) to health care processes is discussed in Antonacci et al. (2016): For BPMN 2.0 models annotated using the PyBPMN extension specifying performance properties of the model, an automated transformation into eBPMN simulation code is performed.

Pufahl et al. (2018) introduces an approach to BPS by proposing an open business process simulator to perform BPS starting from BPMN 2.0 models. More specifically, a BPMN model is transformed into a discrete event simulation model that is, subsequently, simulated using the suggested tool support (Pufahl et al. 2018, p. 5). Joschko (2014) introduces an approach starting from BPMN 2.0 models and integrating partial domain-specific simulation models. For that purpose, an extension of BPMN 2.0 is developed that links model elements of the BPMN to domain-specific models. For the actual simulation, the approach includes prototypical tool support (Joschko 2014, pp. 99f, 109). Aimed at supporting the development of a BPM-based process automation approach in the field of life science, BPS is investigated in Holzmüller-Laue et al. (2013). A BPMN 2.0 model is extended with information needed for simulation and transformed into a machine-readable representation as input for a simulator (Holzmüller-Laue et al. 2013, pp. 53–60).

Another approach starting from BPMN 2.0 models proposes annotating the BPMN 2.0 models by using PyBPMN (D'Ambrogio and Zacharewicz 2016).

According to the suggested automated transformation, a BPMN 2.0 model is, in a first step, annotated by using PyBPMN and, subsequently, transformed into a Discrete Event Systems Specification (DEVS) model using the Atlas Transformation Language (ATL) (D'Ambrogio and Zacharewicz 2016, pp. 2f). In the simulation step, the DEVS model is executed.

In contrast to the aforementioned approaches, Kloos (2014) suggests an approach transforming business process models into simulation models by introducing an intermediate transformation model, i.e., an 'indirect transformation approach'. The approach is specified for different process modeling languages used to construct the starting point for simulation and for different general purpose simulation tools utilizing the same intermediate transformation model. The approach called Process to Simulation Transformation (ProSiT) is specified for BPMN 2.0 models as a starting point as well as for eEPC models and UML Activity diagrams (Kloos 2014, pp. 25f). Starting from a business process model, an automatic transformation into an idiosyncratic sequence diagram, denoted as ProSiT sequence diagram, is provided followed by an automated transformation into a simulation model as input for the actual simulation step (Kloos 2014, p. 62). The approach extends previous work, see Kloos et al. (2009, 2010, 2011).

Also relying on indirect transformation, Bocciarelli et al. (2012) propose a two-step procedure starting from a BPMN 2.0 model annotated following the BPMN extension PyBPMN. After transformation into a UML Activity diagram as an intermediate transformation model, the second transformation step results in an Extended Queueing Network (EQN) model as simulation model. This approach has been a preliminary starting point for the 'direct transformation approaches' suggested by Bocciarelli et al. that have been explained above (Bocciarelli et al. 2014a, b, c).

Approaches starting from a UML Activity diagram The sample comprises five contributions starting from UML Activity diagrams. Four UML-based approaches in the review sample propose the direct transformation of UML Activity diagrams into a simulation model (Xie 2008a, b; Han et al. 2009b; Gruhn and Richter 2009) while Kloos (2014) suggest an 'indirect transformation approach' requiring an intermediate model. In the following, we briefly describe the approaches.

Two of the proposed UML-based approaches propose a transformation into Petri nets. Following the approach suggested in Han et al. (2009b), workflows are modeled as UML Activity diagrams and, subsequently, transformed into Petri nets based on the developed A2P Petri net building block structure (Han et al. 2009b, pp. 1251f). Verification builds on the analysis of reachability trees using the Petri net representation of the workflows. A two-step approach for simulation of business processes is suggested in Gruhn and Richter (2009). In a first step, reusable models of a business domain are created as Colored Petri nets by domain experts. Because of the perceived complexity of modeling Petri nets (Gruhn and Richter 2009, p. 132), business process models are created by business analysts as UML Activity diagrams in a second step. Integrating the UML Activity diagrams with the domain models is followed by transformation into executable Colored Petri nets (Gruhn and Richter 2009, pp. 134–137).

In Xie (2008a, b), UML Activity diagrams are extended for process simulation using UML profiles including stereotypes resulting in extended UML Activity diagrams that can be transformed into executable simulation models in the process-oriented discrete event simulation language GPSS. It is claimed that the transformation can be carried out automatically (Xie 2008b, p. 2935).

As only 'indirect transformation approach' starting from a UML Activity diagram, the transformation approach ProSiT (Kloos 2014), that has already been explained in more detail for BPMN models as a starting point, requiring an intermediate transformation model is also specified for UML Activity diagrams as starting point.

Approaches starting from an EPC model The approaches in the final sample based on EPC or extensions of the EPC split into (2) 'direct transformation approaches' (Chan et al. 2009; Lübbecke et al. 2015) and (3) 'indirect transformation approaches' suggested by Kloos et al. (Kloos et al. 2009, 2010, 2011; Kloos 2014). Below, these approaches are explained briefly.

One approach suggests, as first step, to extend an EPC model as a starting point with further information needed for simulation followed by a transformation into a discrete event simulation model, e.g., a Colored Petri net, as second step (Chan et al. 2009). Subsequently, the resulting model is simulated applying existent software tools. A further approach starting from an EPC model is suggested in Lübbecke et al. (2015). An EPC model representing a business process is directly transformed into a simulation model based on predefined transformation rules (Lübbecke et al. 2015, p. 871). The approach emphasizes to measure the energy consumption of process steps considered relevant for the specific use context of Green BPM (Lübbecke et al. 2015, p. 871).

The transformation approach ProSiT (Kloos 2014) requiring an intermediate transformation model is also specified for starting from an eEPC model representing a business process (Kloos et al. 2009, 2010, 2011).

Other approaches The review sample includes several approaches that we subsume under the denominator "Other approaches" as they do not build on one of the aforementioned modeling languages but employ other, partly idiosyncratic process modeling language (Gladwin and Harrell 1997; Wynn et al. 2008; Rozinat et al. 2008, 2009b; Kanalici et al. 2009). In the following, these approaches are outlined splitting into one (1) 'direct simulation approach' (Gladwin and Harrell 1997) and further (2) 'direct transformation approaches' (Wynn et al. 2008; Rozinat et al. 2008, 2009b; Kanalici et al. 2009)

Gladwin and Harrell (1997) present a 'direct simulation approach' starting from Flowcharts representing business processes. With the aim of a quantitative analysis of process performance, these flowcharts are constructed with the front end FlowChart. However, details on arriving at the simulation models are not reported. The simulation step is performed with the business process simulator ProcessModel (Gladwin and Harrell 1997, p. 600).

A proposed architecture for a business process simulation environment suggests a modeling and analytical phase as well as a simulation phase (Wynn et al. 2008, pp. 70–73). In the first phase, a simulation model is generated considering a non-empty state of a business process using historical data, e.g., from recent simulation runs as well as data on the current state of the process instances, e.g., from execution logs (Wynn et al. 2008, p. 71). In the second phase, simulation experiments are performed, and simulation outputs are generated. An instantiation of this architecture based on Petri nets is realized (Wynn et al. 2008, pp. 73f): The Yet Another Workflow Language (YAWL) workflow environment, which is based on Petri nets, is used for modeling business processes and analyzing simulation outputs, while the simulation is performed with CPN Tools. For the simulation step, the YAWL workflow models are transformed into Colored Petri nets as input for a simulation tool, which is assessed to be straightforward and, for a case study, performed manually. Transformation is necessary following this approach because directly modeling business processes as Colored Petri nets is assumed to be unsuitable for users (Wynn et al. 2008, p. 74). The approach is extended with incorporating process mining techniques and the use of the process mining framework ProM to construct simulation models in Rozinat et al. (2008) and further refined in Rozinat et al. (2009b). A further approach aimed at integrating simulation functionalities in a BPM tool is proposed in Kanalici et al. (2009). In particular, an interface transforming process models from the BPM tool Netflow into executable simulation models is introduced. The approach and the introduced transformation are tool specific because Netflow uses an idiosyncratic process modeling notation.

4.1.2 *Tool Support for BPS*

This second dimension of analysis targets tool support for BPS. Reviewing the final sample, it becomes clear that there is no standard tool for BPS utilized in the analyzed approaches but that a variety of tools from all categories is employed. A structuring overview of tool support for BPS is presented in Table 6 (see Sect. 2 for an explanation of the categorization of tools): Several approaches propose the application of general purpose simulation tools, precisely suggested in 16 publications in the review sample, whereas only two approaches suggest a business process modeling or management tool (respectively a workflow management system included in the category of BPM tools). This is surprising in the light of the dissemination of business process modeling or management tools, many of which provide simulation functionalities (see Jansen-Vullers and Netjes 2006; García-Bañuelos and Dumas 2009; Pufahl et al. 2018). The largest group in the review sample with 19 publications reports on the development of research prototypes of business process simulators. However, these simulators partly use simulation engines of general purpose simulation tools as, for example, of CPN Tools (e.g., García-Bañuelos and Dumas 2009) or the Renew tool (e.g., Cartelli et al. 2014, 2015, 2016) as a component. Hence, in these cases, the simulation algorithms of general purpose simulation tools and their implementations are utilized.

In the following, we present an overview of tool support for BPS suggested in the review sample. We begin with a summary of (a) business process modeling or management tools with simulation support, continue with (b) general purpose simulation tools and conclude with (c) stand-alone business process simulators.

Business process modeling or management tools Software tools falling in this category are only utilized as tool support for BPS in two approaches in the review sample, one early Petri net-based approach (Oberweis 1996) and a recent BPMN 2.0-based approach (Bisogno et al. 2016):

The simulation approach starting from business processes represented as Petri nets, more precisely Nested-Relation/Transition nets, presented in Oberweis (1996) is accompanied by the suggestion of the architecture of a research prototype of a workflow management system incorporating simulation functionalities as tool support for BPS (Oberweis 1996, pp. 231–248).

A business process modeling tool is utilized in the direct simulation approach starting from BPMN 2.0 process models presented in Bisogno et al. (2016). The Bizagi Modeler is used for supplementing a BPMN 2.0 process model with information needed for simulation following the BPSim 1.0 standard (see Workflow Management

Table 6 Tools applied in publications in the final sample for simulating business processes (X marks that a publication suggests to apply a tool for the simulation step in BPS, see Sect. 2 for an explanation of the categorization of tools)

Publications	Tool support for BPS											
	Business process modeling or management tools		General purpose simulation tools						Business process simulators			
	Bizagi Modeler	Other BPM tools	AnyLogic	Arena	CPN Tools	ExtendSim	HPSim	Plant simulation	IBimp simulator	ProcessModel 9000	VIPtool	Other prototypes
Oberweis (1996)		X										
Gladwin and Harrell (1997)										X		
Desel et al. (1999)											X	
Desel and Erwin (2000)											X	
Desel and Erwin (2003)											X	
Barjis (2007)							X					
Rozinat et al. (2008)					X							
Wynn et al. (2008)					X							
Xie (2008b)												X
Chan et al. (2009)					X							
García-Bañuelos and Dumas (2009)												X
Gruhn and Richter (2009)					X							
Kanalici et al. (2009)				X								
Han et al. (2009b)						X						
Rozinat et al. (2009b)					X							
Kloos et al. (2009)				X								
Kloos et al. (2010)				X								
Kloos et al. (2011)				X								
Bocciarelli et al. (2012)												X
Vasilecas et al. (2013)			X									
Holzmüller-Laue et al. (2013)												X
Bocciarelli et al. (2014a)												X
Bocciarelli et al. (2014b)												X
Bocciarelli et al. (2014c)												X
Cimino and Vaglini (2014)									X			
Joschko (2014)												X
Kloos (2014)			X	X								
Cartelli et al. (2014)												X
García et al. (2014)			X									

Table 6 continued

Publications	Tool support for BPS											
	Business process modeling or management tools		General purpose simulation tools						Business process simulators			
	Bizagi Modeler	Other BPM tools	AnyLogic	Arena	CPN Tools	ExtendSim	HPSim	Plant simulation	IBimp simulator	ProcessModel 9000	VIPtool	Other prototypes
Cartelli et al. (2015)												X
Lübbecke et al. (2015)								X				
Bisogno et al. (2016)	X											
Antonacci et al. (2016)												X
Cartelli et al. (2016)												X
D'Ambrogio et al. (2016)												X
Pufahl et al. (2018)												X

Coalition 2013). The tool is also used as simulation software (Bisogno et al. 2016, p. 63).

General purpose simulation tools General purpose simulation tools are applied for performing the simulation step in 16 publications in the review sample spanning one approach based on Petri nets (Barjis 2007), approaches based on BPMN 1.x and BPMN 2.0 (Vasilecas et al. 2013; García et al. 2014) and on UML Activity diagrams (Han et al. 2009b; Gruhn and Richter 2009) as well as all EPC-based approaches in the review sample (e.g., Chan et al. 2009) and the vast majority of approaches summarized as "Other approaches" (e.g., Rozinat et al. 2008, 2009b).

The approach suggested in Barjis (2007) utilizes general purpose simulation tools, more specifically a Petri net tool providing simulation functionalities that carries out the simulation step. As an example, a tool called HPSim is used that implements a graphical user interface for constructing a Petri net simulation model (Barjis 2007, p. 263).

Also approaches starting from BPMN 2.0 models suggest using general purpose simulation tools: For the approach provided in Vasilecas et al. (2013), that extends an BPMN 2.0 process model by a Real-time UML collaboration diagram and transforms these models into a simulation model, the general purpose simulation software AnyLogic is utilized as simulation software in a case example. AnyLogic is also utilized for a case example illustrating the simulation approach provided in García et al. (2014) that automatically generates simulation models from BPMN 2.0 models by transformation into tool-independent discrete event simulation models.

Two of the UML-based approaches in the review sample propose using a general purpose simulation tool after transforming a business process model into a Petri net: The approach suggested in Han et al. (2009b) performs the simulation of Petri net representations of workflows using the tool ExtendSim. The two-step approach reported in Gruhn and Richter (2009) applies CPN Tools to simulate executable Colored Petri nets that are the result of transformation of the business process model that is to be simulated (Gruhn and Richter 2009, pp. 134–137).

CPN tools is also applied within a case example illustrating the approach suggested in Chan et al. (2009): The software tool is used for simulating a Colored Petri net that results from transforming an extended EPC model. A further approach starting from an EPC model representing a business process generates a simulation model as input for the simulation software Plant Simulation (Lübbecke et al. 2015, p. 871). This general purpose simulation tool originates from the field of industrial manufacturing and was chosen for providing the needed functionality for the specific use context of Green BPM (Lübbecke et al. 2015, p. 871).

Subsumed under the denominator 'Other approaches", several approaches apply general purpose simulation tools: CPN Tools is used to perform the simulation step following the approach proposed in Wynn et al. (2008) that has been extended in Rozinat et al. (2008, 2009b). After modeling a business process as YAWL workflow model in the YAWL workflow environment, the model is transformed into a Colored Petri net as input for CPN Tools that carries out the actual simulation. Using the general purpose simulation tool Arena is suggested in Kanalici et al. (2009): Process models constructed in Netflow are transformed into simulation models as input for Arena that performs the simulation step.

Furthermore, the 'indirect transformation approach' suggested in Kloos et al. (2009, 2010, 2011), Kloos (2014) utilizes general purpose simulation tools for performing the simulation step: The simulation approach transforms a business process model into an idiosyncratic sequence diagram followed by an automated transformation into a simulation model – specified for BPMN 2.0 models as a starting point as well as for eEPC models and UML Activity diagrams (Kloos 2014, pp. 25f). This simulation model serves as input for the general purpose simulation tools AnyLogic and Arena (Kloos 2014, p. 62).

Stand-alone business process simulators The largest group of publications in the review sample, i.e., 19 publications, report on using a business process simulator for performing BPS. Business process simulators are applied in one Petri net-based approach (e.g., Desel and Erwin 2003), in the vast majority of BPMN-based approaches (e.g., Bocciarelli et al. 2014c; Pufahl et al. 2018) as well as in one UML Activity diagram-based approach (Xie 2008b) and one approach in the category "Other approaches" (Gladwin and Harrell 1997).

A business process simulator called VIPtool is developed and applied within the VIP Project (Desel et al. 1999; Desel and Erwin 2000, 2003). The software tool allows to simulate business processes by generating concurrent runs of the Place/Transition net representing a business process (Desel and Erwin 2003, pp. 232f): As first step, a graphical editor allows to create and edit the business process specification. As second step, the simulation component of the tool Vipsim generates runs that a browser component visualizes.

Based on BPMN 1.x models, the approach in García-Bañuelos and Dumas (2009) presents an open and extensible business process simulator called OXProS. After constructing BPMN 1.x process models using the Oryx Editor 3, an extension called BPMNSim is introduced that allows to extend these process models with further information needed for simulation (García-Bañuelos and Dumas 2009, p. 202). The transformation of extended BPMN models into Colored Petri nets by OXProS is determined by templates that can be modified and extended by developers. For the simulation step, the engine of CPN Tools is utilized (García-Bañuelos and Dumas 2009, p. 200).

Building on BPMN 2.0, several approaches in the review sample propose the development and application of research prototypes of business process simulators as tool support for BPS. The 'direct simulation approach' proposed in Cimino and Vaglini (2014) presents a business process simulator called Interval Bimp (IBimp) using interval-valued parameters. By extending the simulator Bimp, the Java-based tool incorporates a genetic algorithm computing the interval-valued output. For the simulation step, the engine of the simulator Bimp is utilized (Cimino and Vaglini 2014, p. 339).

A further business process simulator is proposed in Holzmüller-Laue et al. (2013): The simulation of a BPMN 2.0 model transformed into a machine-readable representation is performed in a browser-based simulation tool called Laboratory Business Process Execution Simulation (Lab-BPESi) (Holzmüller-Laue et al. 2013, pp. 53–60).

The simulation approach suggested by Bocciarelli et al., that utilizes the BPMN extension PyBPM, develops and refines a business process simulator for performing the simulation step (Bocciarelli et al. 2012, 2014a, b, c). The simulation code as result of transforming a BPMN 2.0 model is executed in a research prototype built on top of a layered software architecture called SimArch that provides a general-purpose and event-based simulation infrastructure for distributed discrete event simulation (Gianni et al. 2011). Antonacci et al. (2016) build on the approach suggested in Bocciarelli et al. (2014a, b, c) and propose to perform simulation by executing eBPMN simulation code in a research prototype, also built on top of SimArch.

Also based on annotating the BPMN 2.0 models by using PyBPMN, the approach suggested in D'Ambrogio and Zacharewicz (2016) executes DEVS models as result of transforming BPMN 2.0 models. As tool support for performing the simulation step, DEVS simulators are suggested, but this is not specified further.

The recent approach proposed and refined in Cartelli et al. (2014, 2015, 2016) builds on transforming an extended BPMN 2.0 model into a Colored Petri net. Based on prior work (see Cartelli et al. 2014), a research prototype is developed integrating the third party simulation engine of the Renew tool to perform the actual simulation (Cartelli et al. 2015, p. 309).

The DESMO-J framework is utilized as basis for business process simulators in two approaches: Joschko (2014) realizes a prototypical software framework building on the .NET software development plugin-framework Empinia and DESMO-J (Joschko 2014, pp. 99f, 109) to perform BPS starting from BPMN 2.0 models. The design and architecture of a proof-of-concept implementation of an open business process simulator building on the DESMO-J framework and starting from BPMN 2.0 models are introduced in Pufahl et al. (2018): The simulator offers a plug-in concept for extensions and accounts for the simulation of multiple concurrent business processes.

Furthermore, the approach in Xie (2008b) performs the simulation step, after extending and transforming a UML Activity diagram into a GPSS model, utilizing an idiosyncratic business process simulator (Xie 2008b, p. 68). Another business process simulator called ProcessModel is proposed in Gladwin and Harrell (1997): Flowcharts representing business processes are constructed with the front end FlowChart and simulated with the business process simulator ProcessModel.

4.1.3 Visualization of Simulation Runs and Results

This analysis dimension refers to visualizing simulation runs and results aimed at supporting the results' interpretation. A number of approaches to BPS in the final sample suggest visualizing simulation runs and results obtained in the simulation step in different ways. However, the majority of the reviewed approaches to BPS does not address this aspect (see Table 3) – despite starting from a graphical process model. In the following, suggestions for visualizing simulation results in the review sample are summarized and distinguished according to the categorization of visualization techniques introduced in Sect. 2 (see Table 7 for an overview): (1) static visualization, i.e., representation of simulation results through, e.g., two-dimensional graphical diagrams (e.g., Bisogno et al. 2016, p. 67) and (2) dynamic visualization, i.e., visualizing the time-dependent behavior of process instances, e.g., through token game animation (e.g., Barjis 2007, p. 263). The last category, (3) virtual reality and augmented reality visualization is not discussed in the review sample.

Static visualization (1) is suggested as one means to support the interpretation of quantitative simulation results in about a third of the publications in the final sample. For example, tables showing quantitative measures as results of simulating a business process are utilized in several approaches (e.g., Bisogno et al. 2016; Antonacci et al. 2016; Cartelli et al. 2016, 2015, 2014; Chan et al. 2009; Cimino and Vaglini 2014; García et al. 2014; Gladwin and Harrell 1997; Joschko 2014; Lübbecke et al. 2015; Xie 2008b). The approaches differ, particularly, in the representation, e.g., in the form, arrangement and graphical representation of tables, as well as in the use of graphical diagrams. For example, simulation results are complemented by two-dimensional diagrams that visualize quantitative results, in most cases comparing simulation results of different simulation runs representing different scenarios (e.g., Antonacci et al. 2016; García et al. 2014; Bisogno et al. 2016; Gladwin and Harrell 1997; Han et al. 2009b; Joschko 2014; Rozinat et al. 2008, 2009b). In contrast to the graphical representation of two-dimensional diagrams, Desel and Erwin (2003) chose a three-dimensional diagram as representation visualizing quantitative simulation results for different runs with the particular aim to enrich the representation with detailed information, i.e., throughput times for all runs and stochastic configurations (Desel and Erwin 2003, p. 239).

Surprisingly, only five articles in the final sample refer to a dynamic visualization (2) of simulation runs and results primarily suggesting the use of visual animations (e.g., Oberweis 1996; Gladwin and Harrell 1997). The earliest approach in the sample suggests to graphically visualize a sequence of markings of a Petri net representing a business process as dynamic representation (Oberweis 1996, pp. 214f). Token game animation is utilized in order to assist in understanding the behavior of process models represented as Petri nets in the approach proposed in Barjis (2007, p. 263). As related dynamic visualization technique, Holzmüller-Laue et al. (2013, p. 54) suggest a time-based animation by highlighting the control flow of a running process with a colored token and by color coding (elements of) subprocesses pursuing the aim of making the control flow transparent and traceable. A further Petri net-based approach suggests to graphically display executions of a business process, each represented as a causal net, a specific class of Petri nets (Desel and Erwin , 2003).

4.2 Application of BPS

4.2.1 Application Purposes and Use Context

This analysis dimension refers to purposes of BPS and its use contexts reported in the review sample. The majority of publications mentions purposes of applying BPS or concrete simulation objectives (see Table 3) while use contexts of BPS are only rarely specified in the review sample (see Table 8). In the following, our findings regarding this analysis dimension are presented, starting with prevalent and emerging purposes (see Fig. 5 for an overview), and continuing with insights regarding use contexts of BPS.

Several publications presume that a common purpose of BPS is to evaluate the performance of business processes and objectives concerning quantitative measures – the so-called ex-ante evaluation of business processes – for example, regarding process cycle time, waiting time, process costs or bottlenecks in processes (e.g., Oberweis 1996; Desel et al. 1999; Desel and Erwin 2000, 2003; Kanalici et al. 2009; Cartelli et al. 2014; Bocciarelli et al. 2014b;

Table 7 Publications in the final sample addressing visualization of simulation runs and results according to category of visualization techniques

Publications	Static visualization	Dynamic visualization
Oberweis (1996)		X
Gladwin and Harrell (1997)	X	X
Desel and Erwin (2003)		X
Barjis (2007)		X
Rozinat et al. (2008)	X	
Xie (2008b)	X	
Chan et al. (2009)	X	
Han et al. (2009b)	X	
Rozinat et al. (2009b)	X	
Holzmüller-Laue et al. (2013)		X
Cimino and Vaglini (2014)	X	
Joschko (2014)	X	
Cartelli et al. (2014)	X	
García et al. (2014)	X	
Cartelli et al. (2015)	X	
Lübbecke et al. (2015)	X	
Bisogno et al. (2016)	X	
Antonacci et al. (2016)	X	
Cartelli et al. (2016)	X	

Bisogno et al. 2016; Cartelli et al. 2016; Pufahl et al. 2018). Additionally, the objective of quantifying effects of randomness, uncertainty and interdependencies of resources is pursued (e.g., Gladwin and Harrell 1997). Recent contributions aim to perform reliability analysis considering uncertainty, inaccuracy, variability and dynamicity inherent to a process (e.g., Cimino and Vaglini 2014).

A further common purpose is applying BPS to serve as basis for "What-if" analyses for testing the impact of process improvements, for example, on organizational performance (Barjis 2007; Xie 2008a, b; Kloos et al. 2010, 2011; Cartelli et al. 2014; D'Ambrogio et al. 2016; Stankevicius and Vasilecas 2016). For instance, D'Ambrogio and Zacharewicz (2016) focus on analyses taking into account possible failures of resources. Related to this topic is the objective of predicting the behavior of business processes before their implementation (e.g., Han et al. 2009b; Bocciarelli et al. 2014a, c; Cartelli et al. 2015; D'Ambrogio et al. 2016). Along with this, approaches in the reviewed sample emphasize applying BPS to support decisions, in particular, design decisions between alternatives, and to reduce the risk of making wrong decisions (Desel et al. 1999; Desel and Erwin 2000; Cimino and Vaglini 2014). For example, García et al. (2014) have a focus on applying BPS to support strategic decisions – tactical and operational.

Another purpose pursued in the review sample with applying BPS is graphically displaying the dynamic behavior of business processes. Executions of process instances are animated as means for discussing business processes, fostering understanding of the processes and validating their representations as models involving stakeholders (e.g., Oberweis 1996; Kanalici et al. 2009; Holzmüller-Laue et al. 2013).

As additional application purpose of BPS, the support of operational decision making for already implemented processes with approaches characterized by starting from a non-empty starting state of a business process are reported (Wynn et al. 2008; Rozinat et al. 2008, 2009b). These approaches use historical information, e.g., data from former simulation runs, and information on the current state of process instances, e.g., data from execution logs, as basis for simulation. The aim is to achieve an understanding of the short-term behavior of the simulated business processes. However, the underlying idea of simulating already implemented processes with the aim to evaluate alternatives can be traced back to the 1990s as one possible application of workflow simulation (e.g., Oberweis 1996).

Only very few publications in the final sample specify a particular use context for the suggested BPS approach – the vast majority of the reviewed publications introduces approaches to BPS as BPM technique, but does not further specify a particular use context. It is noticeable that several approaches consider BPS and its application in the context of Business Process Reengineering (BPR), particularly earlier publications (Desel and Erwin 2000, 2003; Desel et al. 1999; Gladwin and Harrell 1997; Gruhn and Richter 2009; Xie 2008a, b). However, no particular use context is specified in these approaches.

Table 8 Specific use contexts of BPS in the final sample

Use context	Publications
Green BPM	Lübbecke et al. (2015)
Health care	Antonacci et al. (2016)
Life sciences	Holzmüller-Laue et al. (2013)
Service processes	Kloos et al. (2010, 2011)

In Joschko (2014), an approach to BPS is reported that fosters the application of BPS in use contexts in which business processes are characterized by a strong dependence on system environment factors. Therefore, the approach integrates domain specific partial simulation models into BPS to consider the interaction of business processes with other systems at run-time. However, no specific use context is addressed, but a case study from the use context of the offshore wind farms industry is reported.

We observe only four particular use contexts for BPS specified for approaches to BPS in the final sample, starting in the 2010s (see Table 8). The approach reported in Lübbecke et al. (2015) aims to support decision making in the specific use context of Green BPM that focuses on energy consumption and carbon footprints of business processes. In health care, applying BPS serves the purpose of improving health care processes by reducing costly reworks (Antonacci et al. 2016), and in life sciences, Holzmüller-Laue et al. (2013) report on a BPM-based process automation approach utilizing BPS. In addition, Kloos et al. (2010, 2011) focus on simulating service processes based on service process models.

4.2.2 Adoption Barriers

This analysis dimension refers to barriers preventing research on BPS to transfer to practical applications and remedies to overcome these barriers. Contrary to the development of publication numbers indicating increasing research efforts, low adoption of applying BPS to practical problems is claimed for a number of different reasons. In this section, we summarize our insights into adoption barriers of BPS starting with barriers referring to the complexity of applying BPS and missing expertise and continuing with barriers relating to tool support for BPS (see Fig. 6 for an overview).

The complexity of performing simulation studies and missing expertise, especially technical expertise of users, are assessed as reasons for low usage of approaches to BPS in practice (Gladwin and Harrell 1997; Xie 2008a, b; Bocciarelli et al. 2014c). Especially, constructing and implementing simulation models is described as challenging in practical applications of BPS, acknowledging that business process models are in several cases created for purposes other than simulation resulting in a lack of required information (e.g., Kloos et al. 2009; Bocciarelli et al. 2014b). Relating thereto, Bocciarelli et al. (2014c) and Bocciarelli et al. (2014b) report a 'semantic gap' between business process models and the operational semantics of simulation engines as one issue concerning the use of BPS. Further challenges in constructing simulation models emerge regarding the efforts and costs to gather and prepare data needed for simulation models (e.g., Cimino and Vaglini 2014; Bocciarelli et al. 2014b, c; Antonacci et al. 2016).

As a further adoption barrier, an 'expertise gap' between business users and simulation experts possibly resulting in inconsistencies in simulation studies is presumed (García et al. 2014). Especially, Petri net-based models are assessed to be difficult to understand and unsuitable by prospective users (e.g., Barjis 2007; Wynn et al. 2008; Gruhn and Richter 2009; Han et al. 2009b). To mitigate barriers with regard to missing expertise, an increasing use of animation has been suggested (Barjis 2007).

Furthermore, adoption barriers relating to tool support for BPS are discussed since the 2000s. García-Bañuelos and Dumas (2009) assess that many commercial business process modeling tools provide tool support for simulation with limitations regarding the import of models and tool extensibility – recently criticized again in Pufahl et al. (2018). However, Kanalici et al. (2009) presume improvements in business process modeling tools and their user interfaces that allow users to apply simulation with no or only few experience. So far, several business process or management tools provide integrated support for simulation but are limited in capabilities, e.g., concerning

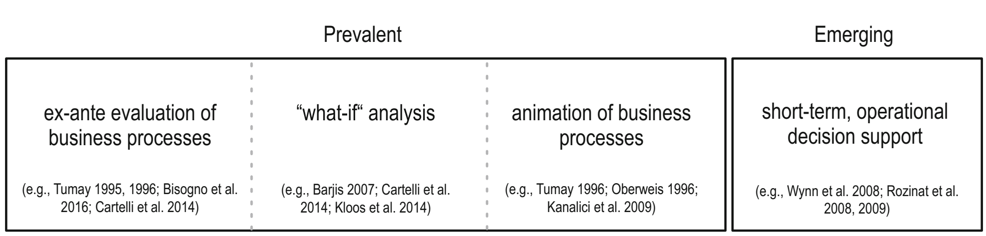

Fig. 5 Prevalent and emerging application purposes of BPS as discussed in the review sample

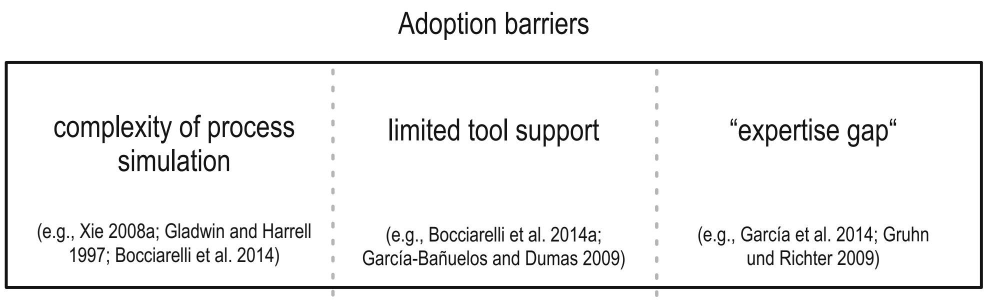

Fig. 6 Adoption barriers of BPS identified in the review sample

customization or configuration and merely implement animation of (graphical) simulation models (e.g., Kanalici et al. 2009; Bocciarelli et al. 2014a, b). Interestingly, Vasilecas et al. (2013) report on missing support for the BPMN in the general-purpose simulation tool AnyLogic – though the BPMN is seen as de facto standard for business process modeling (e.g., Kocbek et al. 2015). More generally, a missing integration between process modeling and simulation tools is criticized (García et al. 2014). In recent work, business process modeling tools and simulation tools are contrasted with regard to their suitability for BPS (García et al. 2014; Lübbecke et al. 2015): Tools originating from business process modeling are assessed to have limited simulation capabilities and functionalities (Bocciarelli et al. 2014a, b), whereas general simulation tools are assessed to not provide a direct import and processing of business process models created with a modeling language such as BPMN or EPC.

5 Discussion and Future Research Directions

Based on a search strategy including not only general IS outlets but also specific outlets including conference proceedings, monographs and anthologies, 305 unique publications between 1990 and 2018 were identified in the literature search – giving an idea of the size of the body of knowledge in the field of BPS by approximation (subject to the limitations of the search strategy outlined in Sect. 6). The subsequently reviewed subset of prior work reduces the sample by concentrating on 39 contributions presupposing a procedural graphical model representation as a starting point for business process simulation and, thus, tying in with work on business process modeling. In the following, our findings are discussed along the five dimensions of analysis.

5.1 Simulation Design and Execution

5.1.1 Overall Approach

Reviewing approaches to BPS in the final sample led us to an organizing overview structuring prior work. Figure 7 illustrates this organizing overview of the approaches to BPS reported in the final sample combining the segmentation into the three broad categories of simulation approaches (direct simulation, direct transformation, indirect transformation, see Sect. 4), according to the process modeling language used to construct the starting point for simulation and including the suggested tool support for BPS.

It becomes apparent that, starting from (1) direct simulation approaches proposed in the 1990s, (2) direct transformation approaches came to the fore. In the past decade, few (3) indirect transformation approaches have been reported additionally. Furthermore, transformations of BPMN models and extensions to the BPMN have been increasingly discussed (e.g., Bocciarelli et al. 2014c; Bisogno et al. 2016) where approaches to automatically transform BPMN models into simulation models is observed to have progressed continually (e.g., Bocciarelli et al. 2014b; Pufahl et al. 2018). It is surprising that only two approaches propose a direct simulation starting from BPMN 2.0 models, whereas the majority of BPMN-based approaches requires a transformation step (see Fig. 7). Furthermore, it is notable that the standard BPSim 1.0 is only considered by Bisogno et al. (2016) and BPSim 2.0 is not yet mentioned. Although BPSim 1.0 and BPSim 2.0 have been published only recently (in 2013 respectively 2016), it is surprising that even the more recent publications in the final sample starting from BPMN models do not refer to these standards for BPS. Hence, this provides an anchor point for future research on interoperability with regard to standard conformity.

Reviewing approaches to BPS in the final sample with respect to modeling languages used to prepare for simulation led us to observing an unsurprising shift from Petri nets as a foundation for BPS to EPC models, UML Activity diagrams and, especially, to models constructed with BPMN 2.0, which has since its publication in 2011 been predominantly employed as modeling language to prepare for process simulation.

Regarding simulation properties (case arrival; activity duration; branching probabilities, resource allocation, resource availability) and the use of historic data from event logs & from simulation logs, it is striking that some aspects affecting how well a simulation allows to capture a business process are only discussed very briefly in several publications in the final sample. Regarding case arrival, it is surprising that about two thirds of the reviewed publications do not even mention the number of process instances, their arrival rates and the availability of data input for specifying these parameters – although specifying these parameters is decisive for the execution and traceability of the simulation (Cimino and Vaglini 2014, p. 321). It is also surprising that only one quarter of the reviewed publications addresses the use of historic process data for preparing process models for simulation – with only three publications explaining details on how to use the data in BPS. This is especially striking as this simulation-relevant information is oftentimes available, e.g., in process-aware information systems (e.g., Rozinat et al. 2009b; van der Aalst 2015). Other simulation properties are addressed in the majority of publications, i.e., activity duration, branching probabilities for process alternatives as well as resource allocation and resource availability. However, for the simulation properties of activity duration and branching probabilities it is surprising that we observe publications that do not even mention these essential properties of preparing for simulation. For activity duration, detailed and traceable explanations for the specification are missing in several contributions as is information on how to determine the values for the duration of activities. Also, the majority of publications lacks detailed explanations on how to specify branching probabilities and on how XOR- or OR-operators are executed in the actual simulation step. Resource allocation and the closely related availability of resources are addressed in the majority of publications in the final sample, whereby resource allocation is discussed more comprehensively than resource availability. However, for both simulation properties of the resource perspective, several publications lack detailed explanations or perform the allocation of resources as well as the specification of their availability in a rather simplified manner, e.g., regarding inter-case dependencies between instances – confirming that current approaches to BPS are confronted with the pitfall to oversimplify the modeling of resources (van der Aalst 2010; Vasilecas et al. 2014).

One major research gap emerges from reviewing approaches to BPS in detail: First, only few approaches to BPS address obstacles accompanying the construction of simulation models and only few contributions (e.g., Wynn et al. 2008; Cimino and Vaglini 2014) aim at overcoming limitations identified and discussed for existing simulation approaches as, for example, regarding the reliability of simulation results, modeling of resources and process alternatives performed in a rather naive manner and the neglect of simulation-relevant information as input for simulation, e.g., historical process execution data (e.g., van der Aalst 2010, 2015; Dumas et al. 2018, p. 287). Hence, discussing how to overcome these limitations and to address simulation properties in future approaches to BPS opens a fruitful research direction as, for example, by elaborating resource availability patterns or by further developing the use of historic data for preparing process models for simulation.

5.1.2 Tool Support for BPS

Analyzing the final sample regarding tool support for BPS, it becomes apparent that the approaches suggested in the review sample do not indicate a clear development and no standard tool for BPS is discernible. Rather, we can observe that several different tools – spanning all three categories, i.e., (a) business process modeling or management tools, (b) general purpose simulation tools and (c) stand-alone business process simulators – are utilized in the reviewed approaches. A focus is on research prototypes of business process simulators and general purpose simulation tools.

A further major research gap emerges from analyzing tool support for BPS in the review sample: Insights into simulation algorithms utilized for simulating business processes in the reviewed approaches are scarce – apart from a few exceptions as, for example, Cimino and Vaglini (2014). This is in line with observations indicating that simulation algorithms have become a rather practical topic – for example, proprietary simulation algorithms used in BPM tools – than a theoretical topic in the scientific discourse (see Gawin and Marcinkowski 2015; Pufahl et al. 2018). In addition, insights into the use of business process modeling or management tools for simulating business processes in the final sample are very limited. For an investigation into simulation capabilities of tools starting from BPMN models, see Pereira and Freitas (2016). However, an overview and understanding of the algorithms used for BPS and further insights into simulation functionalities of tools are required to extend the knowledge base on BPS furthering future research, specifically construction-oriented research on BPS tools.

Fig. 7 Approaches to BPS in final sample grouped by simulation approach, modeling language used as foundation and tool support (multiple assignments allowed)

Modeling language	Tool support	Direct simulation	Direct transformation	Indirect transformation
Petri nets	BPM tools	Oberweis (1996)		
Petri nets	GPS tools	Barjis (2007)		
Petri nets	BP simulators	Desel et al. (1999) Desel & Erwin (2000) Desel & Erwin (2003)		
BPMN 1.x	BP simulators		García-Bañuelos & Dumas (2009)	
BPMN 2.0	BPM tools	Bisogno et al. (2016)		
BPMN 2.0	GPS tools		Vasilecas et al. (2013) García et al. (2014)	Kloos (2014)
BPMN 2.0	BP simulators	Cimino & Vaglini (2014)	Holzmüller-Laue et al. (2013) Bocciarelli et al. (2014a) Bocciarelli et al. (2014b) Bocciarelli et al. (2014c) Cartelli et al. (2014) Joschko (2014) Cartelli et al. (2015) Antonacci et al. (2016) Cartelli et al. (2016) D'Ambrogio et al. (2016) Pufahl et al. (2018)	Bocciarelli et al. (2012)
BPMN 2.0	No tool support		D'Ambrogio & Zacharewicz (2016)	
UML Activity diagrams	GPS tools		Gruhn & Richter (2009) Han et al. (2009b)	Kloos (2014)
UML Activity diagrams	BP simulators		Xie (2008b)	
UML Activity diagrams	No tool support		Xie (2008a)	
EPC	GPS tools		Chan et al. (2009) Lübbecke et al. (2015)	Kloos (2009) Kloos (2010) Kloos (2011) Kloos (2014)
Others	GPS tools		Rozinat et al. (2008) Wynn et al. (2008) Kanalici et al. (2009) Rozinat et al. (2009b)	
Others	BP simulators	Gladwin & Harrell (1997)		

5.1.3 Visualization of Simulation Runs and Results

Reviewing the final sample shows that less than half of the reviewed publications offer suggestions on how to visualize simulation runs and results (see Table 3). This is surprising in the light of the presumed relevance of graphically representing simulation results to support the interpretation of these results (see Sect. 2), and as limitations discussed for existing approaches to BPS refer to the interpretation of simulation results as critical step in performing BPS (e.g., Dumas et al. 2018, p. 287). Prior work addressing the visualization of simulation results points at (1) static visualization by means of tables and diagrams as prevalent way to visualize simulation results and (2) animating business processes as dynamic visualization suggested in a few contributions. It is remarkable that the use of (3) virtual reality and augmented reality techniques to visualize simulation runs and results is not mentioned in the review sample. This is especially surprising with regard to the development in the last years characterized by increasing development and dissemination of hardware and tools suitable for the representation of complex virtual and augmented environments – already applied for business process modeling (e.g., Betz et al. 2008; Brown et al. 2011; Poppe et al. 2012; Metzger et al. 2017).

Hence, a further research gap turning up from this study is that remarkably few publications in the final sample explicitly address the interpretation of simulation results (e.g., Oberweis 1996; Joschko 2014; Lübbecke et al. 2015) and that suggestions for visualizing simulation results only in very few cases go beyond a representation of quantitative measures in a table (e.g., Barjis 2007; Desel and Erwin 2003). A potential path for future research, hence, lies in exploring further techniques to support the interpretation of simulation results by providing purposeful visualizations of simulation results – considering static and dynamic visualization and, especially, virtual reality and augmented reality based environments. We deem such three dimensional representations, e.g., three dimensional animation, and environments enriched with augmentations, e.g., with videos, to have the potential to support the interpretation of simulation results by reducing complexity and providing an intuitive, immersive representation (e.g., Eichhorn et al. 2009). Following this path will inform future research on extending or designing approaches and tools for BPS that support users with helpful graphical representations of results.

5.2 Application of BPS

5.2.1 Application Purposes and Use Context

Reviewing application purposes produces the expected and unsurprising three prevalent purposes mentioned in pertinent literature: (1) ex-ante evaluation of business processes in conjunction with (2) "What-if"-type sensitivity analyses and (3) animation of business processes, especially aimed at fostering an understanding of simulation runs. Moreover, the review indicates that another purpose has emerged: (4) Short-term, operational decision support for already implemented business processes using historical data to construct simulation models (Wynn et al. 2008; Rozinat et al. 2008, 2009b), see Martin et al. (2016) for a recent literature review. Apart from this discovery, the review confirms the three typical, yet very high-level application purposes conveyed, e.g., in textbooks (Dumas et al. 2018, pp. 279–287).

Regarding the use context of BPS, it is remarkable that only very few publications in the final sample focus on a particular use context that, in these cases, is Green BPM, health care, life sciences and the use context of service processes. This is especially surprising as a particular use context for BPS is associated with specific simulation purposes and objectives as well as specific requirements for approaches to BPS. An example is the specification of simulation objectives in Lübbecke et al. (2015) to reducing the energy consumption of business processes and the accompanying requirements for BPS, e.g., regarding the simulation-relevant information on the energy demand of activities of the business process.

Overall, reviewing purposes and contexts of applying BPS in the final sample made us recognize that – besides assignments to specific application purposes and simulation objectives for the suggested approaches – insights into the use of BPS in practice, particularly intended use contexts, are scarce constituting one of the major research gaps turning up in our study. For investigations into the use of business process simulation in practical applications that do not focus on graphical process models as a foundation for simulation, see Melão and Pidd (2003), who report on a survey among potential business process simulation users, and Bosilj Vukšić et al. (2017) reviewing case studies on the application of discrete event simulation in BPM projects. However, a current structured inquiry into the adoption and diffusion of BPS in practice and prevalent application purposes and use contexts is not available at present. A further differentiated and detailed understanding of these purposes, objectives and corresponding functional and non-functional requirements thus is required to better understand existing and possible future application scenarios of BPS.

Hence, a potential path for future research lies in surveying practical applications of BPS, especially with regard to application purposes, simulation objectives and user requirements, and in cumulatively compiling a knowledge base that informs future research on BPS. Moreover, future research on approaches to BPS focusing on specific use contexts provides the opportunity to address needs and requirements specific to a domain and, hence, to support the ease-of-use of BPS for users and their productivity (cf. the advantages of domain-specific modeling languages, e.g., Frank 2010) – in contrast to current approaches to BPS that mostly do not address a particular use context.

5.2.2 Adoption Barriers

Reviewing prior work on BPS suggests that principle barriers prevent BPS research to transfer to practical applications. Prior work points at (1) the complexity of purposeful process simulation and the corresponding difficulty to design and carry out meaningful simulations, (2) the lack of ease-of-use of software tools, and (3) postulates the need to bridge the 'expertise gap' between simulation experts, modeling experts and business users.

Two research gaps emerge from reviewing adoption barriers: First, a systematic investigation into barriers to adopting BPS is missing – besides insights into open issues in the adoption of modeling and simulation in BPM based on a selective review of pertinent literature reported in Bocciarelli et al. (2017). Moreover, the reasoning about the underlying rationale for the barriers preventing practical applications of BPS remains mainly anecdotal in the review sample. Second, suggestions on how to overcome barriers to adopting BPS remain only marginally addressed in the reviewed work (e.g., Barjis 2007). This constitutes another anchor point for future research: As a first step to mitigate barriers to adoption, gaining an in-depth understanding of those barriers appears as a fruitful avenue for future research. Along this path, it should be clarified whether there is a discrepancy between the barriers purported in literature and those expressed by (prospective) users. Moreover, inquiries into user requirements contribute to the scientific knowledge base that in turn informs future construction-oriented research on approaches to BPS and on BPS tools.

6 Limitations

Scope of the literature review and dimensions of analysis: The scope of this literature review limits findings in different respects: First, this review is restricted to prior work on BPS starting from a conceptual business process model represented as procedural graphical model (see Sect. 1 for an explanation of reasons for the restriction). Hence, prior work starting, for example, from declarative process models or directly creating a simulation model based on mining event logs is not reviewed in this study – representing review topics in their own right and possible starting points for research following-up this literature study. Second, the review is limited to academic literature in line with the primary objective to present a state of research as well as the further objective to identify research gaps and suggest future research directions. Non-academic literature and non-research contributions on commercial BPS tools are excluded from the present study. Thus, this study reflects the current state of research on BPS as discussed in academic literature – a state of the art of the application practice of BPS is not presented. A potential path for future research, hence, lies on reviewing non-academic literature on BPS as well as commercial tools implementing BPS approaches with the aim to broaden the overview of the field of BPS. Also, the present work is limited to analyzing prior work regarding the five dimensions of analysis. Other dimensions of analysis are not addressed in detail in this research as, for example, inter-case dependencies between executed process instances of a business process (e.g., van der Aalst 2010) and the underlying simulation algorithms utilized in process simulation engines (e.g., Gawin and Marcinkowski 2015) – representing review topics in their own right. Hence, research following-up this literature study can build on the present raw data set to review and structure prior work on these aspects of BPS to achieve in-depth insights into those specific aspects.

Literature retrieval Even though the search strategy outlined in Sect. 3 employs several measures to include all pertinent prior work, an exhaustive literature review does not necessarily lead to a complete census of relevant literature due to the vast number of sources and publications (vom Brocke et al. 2009, p. 2207). Moreover, our sampling and filtering process entails the risk of misleading decisions, i.e., to have overlooked relevant sources or to have erroneously misjudged an excluded publication. For example, the literature retrieval resulted in only two doctoral dissertations on BPS included in the review sample – though probably others were written. We report the selection of publications in detail to render the search procedure including our decisions transparent and intersubjectively traceable to make them accessible to a critical evaluation.

Categorization of approaches to BPS and tools The segmentation of approaches to BPS in (i) 'direct simulation approaches,' (ii) 'direct transformation approaches' and (iii) 'indirect transformation approaches' is a broad distinction extending prior work (see Sect. 4). We deem the categories reasonable to achieve an organizing overview of the field of BPS. However, clearly assigning the approaches into one category can not succeed in all cases. For instance, extending a BPMN 2.0 model by use of the extension PyBPMN is not assessed as a transformation in this study – though denoted as model-to-model transformation (e.g., Bocciarelli et al. 2014b, p. 5). In order to make the extension and transformation steps within the approaches and, hence, their categorization traceable, a comprehensible way of reporting the approaches is pursued as a solution (Sect. 4). For research following-up this study, a potential path lies in refining the categorization by, for example, further subdividing the developed categories by considering different extension steps adding information needed for simulation to a graphical process model.

Assigning contributions in the final sample to one of the four categories distinguishing if and how detailed a contribution addresses a simulation property or the use of historic data from event logs and simulation logs (see Fig. 4) is subject to limitations, too. Clearly assigning an approach to BPS to one category may not succeed in all cases. We guarded against categorization errors by having two researchers cross check the assignments and by requiring an agreement between the researchers involved.

A further limitation applies to the segmentation of tools in (a) business process modeling or management tools offering simulation functionalities, (b) general purpose simulation tools and (c) stand-alone business process simulators (see Sect. 2). We did not include other possible categorizations, for instance, by distinguishing between business process modeling tools and business process management tools (e.g., Jansen-Vullers and Netjes 2006). However, this category of tools is only referred to in very few cases in the review sample. Hence, we consider the categories as helpful to structure tool support suggested for BPS (Sect. 4).

7 Conclusion

Spanning a time frame of 28 years from 1990 to mid-2018, the present literature study arrives at a total of 305 publications characterizing the body of knowledge in the field of business process simulation. Focusing on procedural graphical process models as a foundation for business process simulation, 39 publications are identified and reviewed in detail. We deem both findings as surprisingly low considering that BPS marks an essential BPM technique.

As expected, our findings highlight the multidisciplinary character of the field involving disciplines such as mathematics, statistics, (computer) simulation, conceptual modeling and, in particular, business process modeling. Interestingly, however, cross-disciplinary exchange, fertilization and/or collaboration appear not particularly characteristic of BPS research given that referencing across groups is rare and author groups seem stable. For example, we find one group starting from BPMN 2.0 models and utilizing eBPMN as well as PyBPMN (e.g., Bocciarelli et al. 2014a, c; Antonacci et al. 2016; D'Ambrogio et al. 2016) and another group also starting from BPMN 2.0 models but transforming the models into timed Colored Petri Nets (Cartelli et al. 2014, 2015, 2016) – despite the common starting point for simulation these groups do not refer to each other.

The present work structures the discussed body of literature along five dimensions of analysis: Overall approach to BPS; tool support for BPS; visualization of simulation results; application purposes and use context; and adoption barriers. Our findings lead us to outline four major suggestions for future research on BPS:

(1) Surveying practical applications of BPS: Our findings suggest to further investigate application purposes, simulation objectives and requirements of (prospective) users, for example, by combining large-scale studies aiming at a structuring overview with in-depth investigations contributing to a detailed understanding of practical applications and use contexts of BPS. (2) Inquiries into barriers to adopting BPS and discussions of remedies: To foster transfer of research on BPS to practical applications, it is important to investigate barriers for adoption. A particular focus should be on underlying rationales for the identified barriers to conceive means to overcome those barriers. (3) Studying simulation visualization: To facilitate the interpretation of simulation results and, hence, decision making based on such results, further research has to design, build and evaluate simulation visualization for process simulation in the light of the requirements of different groups of prospective users. An obvious choice is to base this design science research on visual language theory (e.g., Narayanan and Hübscher 1998) and data visualization research (e.g., Cleveland and McGill 1984; Wilkinson and Wills 2005), and to further explore virtual and augmented reality visualizations. (4) "From expert discipline to common practice": Following Sandkuhl et al. (2018), future research on approaches and tools for BPS should address current obstacles of wide adoption, and, thus, identify barriers and limitations, rethink current approaches and develop creative and innovative solutions to overcome these obstacles by, e.g., focusing on specific use contexts and domain requirements and by addressing the crucial aspects of resource availability and inter-case dependencies. Moving to a common practice is a challenging task likely to benefit from further cross-disciplinary collaboration in recognition of the multidisciplinarity of the field of BPS.

The present findings suggest further research efforts in which behavioral research and construction-oriented research would jointly advance our knowledge on business process simulation and its applications: A first step could be to jointly build a common knowledge base on application purposes, requirements and user needs regarding BPS as well as barriers to the adoption of BPS by surveying practical applications. This would then form a basis from which to engage in further construction-oriented research on approaches to BPS and on BPS tools – which aim to overcome limitations of existing BPS approaches. These research efforts will also benefit BPM practitioners by furthering the development of new approaches and tools for simulating business processes that jointly account for user requirements and current limitations.

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