Technical report

Nr.: FIN-009-2010

Post Execution Analysis of Business Processes: Taxonomy and Challenges

Azeem Lodhi, Veit Köppen, and Gunter Saake

Arbeitsgruppe Datenbanken

Fakultät für Informatik
Otto-von-Guericke-Universität Magdeburg

Nr.: FIN-009-2010

Post Execution Analysis of Business Processes: Taxonomy and Challenges

Azeem Lodhi, Veit Köppen, and Gunter Saake

Arbeitsgruppe Datenbanken

Technical report (Internet)
Elektronische Zeitschriftenreihe
der Fakultät für Informatik
der Otto-von-Guericke-Universität Magdeburg
ISSN 1869-5078

Fakultät für Informatik
Otto-von-Guericke-Universität Magdeburg

Impressum (§ 5 TMG)

Herausgeber:
Otto-von-Guericke-Universität Magdeburg
Fakultät für Informatik
Der Dekan

Verantwortlich für diese Ausgabe:
Otto-von-Guericke-Universität Magdeburg
Fakultät für Informatik
Azeem Lodhi
Postfach 4120
39016 Magdeburg
E-Mail: azeem.lodhi@ovgu.de

http://www.cs.uni-magdeburg.de/Technical_reports.html

Technical report (Internet)
ISSN 1869-5078

Redaktionsschluss: 15.12.2010

Bezug: Otto-von-Guericke-Universität Magdeburg
Fakultät für Informatik
Dekanat

Post Execution Analysis of Business Processes: Taxonomy and Challenges

Azeem Lodhi, Veit Köppen, Gunter Saake
azeem.lodhi@ovgu.de
veit.koeppen@ovgu.de
gunter.saake@ovgu.de

Technical Report

Department of Technical and Business Information Systems,
Faculty of Computer Science,
Otto-von-Guericke University,
Magdeburg, Germany

Post Execution Analysis of Business Processes: Taxonomy and Challenges

Abstract

Business process modeling is used for better understanding and communication. Mostly, business process modeling is discussed from information system development perspective. After execution of business processes, various objects become important and have to be represented in business process models. The process models conceived for information system development are not sufficient for the post execution analysis because different focus of conception for these models. In this report, we discuss the characteristics of business processes and provide a classification of involved objects and their attributes. We also identify the limitations of modeling languages for the post execution phases and discuss the characteristics of an analytical modeling language. Therefore, the purpose of this report is to provide motivation for further research on business process models, which can be effectively used in business process analysis and improvement.

Keywords: Business process modeling, analysis, evaluation, improvement

Contents

List of Figures

List of Tables

1 Introduction

Business processes (BP) are often represented in a graphical way for easy communication between stakeholders. The intuitive nature of models and explicit representation of business objects improve the overall understanding of business processes. Different past developments in enterprises and information technology triggered the development of different sets of models [57]. Business process analysis aims toward the improvement of business processes and their efficiency at a company wide level. Many papers demand an accurate and complete representation of business processes for analysis [1, 13], improvements [14, 56], and for reengineering [29].

Different phases of process management (from initial setting to optimization) require different models [1, 30, 36]. Phalp and Shepperd distinguish the usage of business process models into two types [35]. On the one side software development is in focus, whereas on the other side, restructuring of business processes is the priority. Diagrammatic notations are used for software development where a focus is on a certain perspective. Different models and views are required for restructuring and analysis of business processes [1]. Most of the modeling methods address only the needs of information system development purposes.

Process Mining techniques [51] provide excellent opportunities to extract knowledge from business process executions. Process mining fits between the business process models and business executions. Most of the research in process mining is focused on alignment of information technology and business processes. It also provides different statistics for analyses. Limited research is carried out to represent process knowledge through business process models for improvement. Currently, information is represented with key performance indicators (KPIs), statistics, or visualizations (e.g., pie charts or histograms) which is too abstract and does not provide process details to business analysts. Business process modeling has to be investigated for adequate representations of business processes especially after execution.

This technical report reviews the limitations of modeling languages in post execution analysis context and shows the need of research in process modeling for business process improvement. Furthermore, a classification of involved business objects and their attributes is also provided for including them in business process models.

1.1 Motivation

Availability of analytical data and records of business objects in business process execution provide the means to analyze processes more carefully. In process mining [51],

logs of business processes (after execution in systems) are taken and analyzed in different ways like delta analysis [47] or organizational analysis [50]. In the coming years, a big market share will be taken by analyses of business processes and its tool as indicated by Gartner research report [3].

Different notational approaches are required for different modeling purposes and audiences as stated in [36]. Most of the modeling languages are designed for the development of information systems. Some articles in business process analysis use business process models in post execution analysis phases. However, using these modeling languages for analyses of business processes is not appropriate, especially after execution, as these models are not designed for this purpose. Some challenges of modeling languages for post execution analysis are mentioned in Sect. 5.

There are some approaches for analysis of business processes and its models; however, they address only the correctness of business processes before execution. These approaches attempt to address the challenge of identifying the structural deficiencies in models like studies in evaluating event process chains (EPC) business models [31, 55] or Petri nets [2, 46]. However, syntactically and semantically correctness of business models does not guarantee the execution in reality as planned [17].

Different business process models address certain perspectives of business processes. Models of different perspectives have to be consulted before a decision is made. These models may exist at different abstraction levels and therefore, consulting such models may create ambiguities. A consistent and integrated view of business processes has to be represented in business process models. For business process improvement (BPI), such models should have focus on post execution analysis of business processes and address the challenges in post execution context.

Similarly, current business process models (and analyses) do not give directions what exactly should be done to improve results and profits. In [49], authors demand that analysis of business processes should result the instructions or guidelines as in case of navigation system. For example, for reaching a destination, directions like take 300m right and then 200m left are very helpful. Similarly, in case of business processes, what action and operations should be taken to make improvements in business processes? How this can be achieved is a challenging task and needs further investigation. Business process analyses with descriptive graphical methods can answer such questions and provide substantial results in business process improvement and optimization [14].

A motivating example is introduced in the following which is taken as a case study to explain the concepts of this technical report.

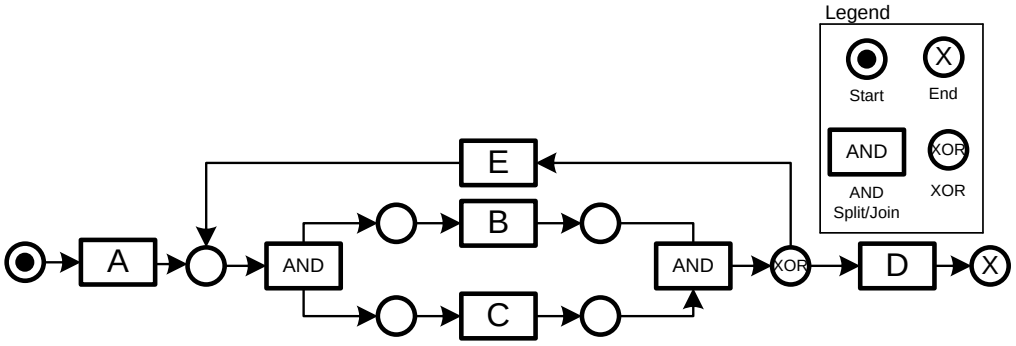

Figure 1: Product manufacturing example

1.2 Motivating Example

Consider a small and simplified business process given in Fig. 1 where five activities are executed to manufacture a product. Here, we used Petri nets to represent the business process because of their formalism and abundance of analysis techniques [44]. In this process, first the *parts are collected* in activity A followed by activity B and activity C which are executed in parallel. These parallel activities *assemble the specific parts* of product independently from one another. After completion, the quality of assembled parts is checked (not represented in the model because of abstract representation). If the assembled parts meet the quality requirements, then *product is packed* in activity D and the process is completed. If the assembled parts do not fulfill a desired level of quality, then activity E is executed which *disassembles the parts.* Assuming that there is no loss during disassembly process, some part of the process has to be repeated again. Therefore, activity B and activity C will be executed again. In Table 1, the log of some case executions is shown with respect to their occurrence in simulation, reality, and conformance between them.

Assume that in activity C parts are not assembled according to standard and caused the part of the process to repeat. This means that activity B should not be repeated again. However, because of *AND* construct(parallel), the simulation software will generate the log containing activity B and activity C as well, and thus indicates that activity B and C are carried out again. However, in reality only activity C will be repeated. This is shown in Case 2 of Table 1.

This scenario shows the problem of right level of detail (granularity) in the model. A more detailed model would check that in case of an *AND* split and iteration which parallel activities are already performed with the satisfied level of quality. Therefore, operations are performed only on those activities which are not at the desired quality level, i.e. activity C in the presented example. When the model is extended with attributes and

Table 1: Simulation and reality log with conformance

Cases	Simulation Log	Reality	Conformance
Case 1	ABCD	ABCD	Yes
Case 2	ABCEBCD	ABCECD	No
Case 3	ABCEBCD	ABCEBCD	Yes
Case 4	ABCEBCD	ABCEBD	No

their values, then it is possible to infer which activity will be executed again. Workflow management systems based on the process model of Fig. 1, will allocate the resources to activities (like activity B) which may not execute in case of iterations. Moreover, the model represented in Fig. 1 does not give any information about the rationale for decisions and involved objects. With such motivation in mind, we investigate the challenges of business process modeling in the post execution phases and characteristics of analytical modeling language that will help in business process analysis.

The structure of the report is as follows: First, business process management (BPM) lifecycle and modeling are discussed in Sect. 2. Post execution analysis phases and its representation are discussed in Sect. 3. We also provide a classification of involved business objects to build models for improvements in Sect. 4. Several challenges of modeling in post execution analysis perspective are mentioned in Sect. 5. Section 6 discusses some anticipated characteristics of an analytical modeling language. In Sect. 7, these characteristics are explained with the help of a case study. We also discuss the importance of the anticipated characteristics and models for business process improvement in Sect. 8 by providing examples of the analytical queries. Section 9 mentions related work in this domain, followed by the Sect. 10 which summarizes this report and presents the future work.

2 Business Process Management Lifecycle & Modeling

To achieve goals and objectives of enterprises, business operations are carried out in a defined way. This specific way is called business process and defined as an ordered set of activities performed by organizational resources to transform inputs into outputs. Business Process Management (BPM) is used for effective management of business processes (BPs). Depending on the granularity of details and area being addressed, BPM is divided into different phases. An abstract view of business process management phases is shown in the Fig. 2.

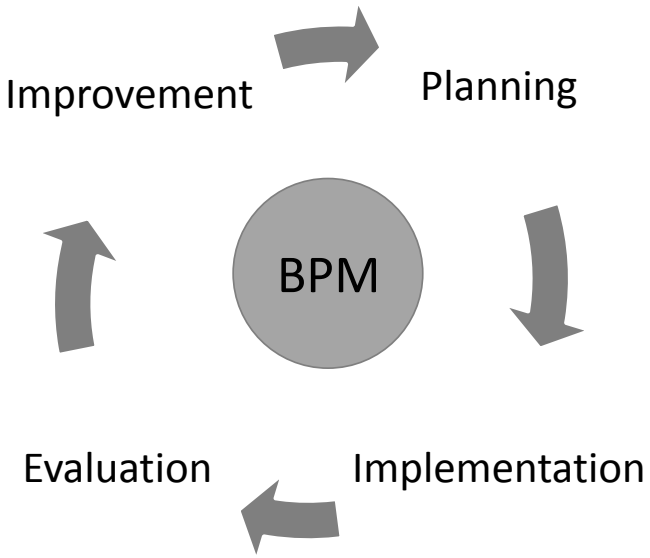

Figure 2: Business process management lifecycle adopted from [18]

Business process modeling is considered as the first and the most important step in BPM [52]. Graphical business process models are used as a tool for the communication between stakeholders. Business process modeling has increased the ability to understand business processes and to make rational decisions for organizing activities in a best possible way [11]. Business process modeling is used in different phases of the BPM lifecycle, like, from identification of business processes to implementation in information system, and improvement after its execution.

Different starting points are possible in the BPM lifecycle depending on the context of discussion. A new enterprise starts from defining its objectives and then to planing phase; which is a starting point for business process reengineering (BPR) [19]. In planning phase analysts conceptualize the operations of enterprises that describe how enterprise goals can be achieved? Domain experts design a detailed model of business processes which defines how company's operations will be carried out. EPC models [41], Flowcharts [20], and other models are used for communication during this phase.

Once business processes are designed then these are implemented in an organization. For efficiency, business processes are supported with information technology (IT). The implementation phase of business processes with IT can have similar phases like BPM phases, because business needs and requirements have to be mapped into IT services to provide the IT support. So activities of BPM phases can also be carried out in the implementation phase like first plan and design of IT services, and then their automation. Different business process models are used during these activities of phases

Table 2: Models in business process lifecycle

Phase	Activities	Stakeholders	Models
Planning	Identification and designing	Business analysts and domain experts	Flow charts, EPCs, and Use cases
Implementation	IT phases, simulation, deployment, and execution	IT team	UML, ER diagrams, BPMN, Petri nets
Evaluation	Performance analysis	Executives, managers	Statistics (different charts, KPIs)
Improvement	Optimization and reengineering	Business analysts, process owners	Same models which are conceived for earlier phases

like object oriented UML[1] diagrams [39] or BPMN[2] [5]. Before implementation, business processes and models are validated using simulation, e.g., Petri nets are used to simulate the business process.

Business process instances are initiated by a defined event, for instance, order sent by a customer. Resources carry-out operations on inputs with the help of information systems and transform the input into outputs. In this way, business processes are executed in information systems.

After execution, the operations of business processes are analysed for performance and other analyses. Different measurements are carried out to measure the performance of business processes like the actual values of business objects are compared with the target values. The post execution analysis indicates deficiencies in the current systems and areas where business processes have to be improved. These deficiencies are tried to be avoided in improvement phase and in subsequent phases of business processes. Therefore, the company's goals are achieved efficiently in the future. Models used in different phases of a business process lifecycle are conceived to fulfill requirements of these phases. Table 2 shows different models with respect to their focus of development for activities of phases in a business process lifecycle.

Several gaps occur in BPM lifecycle due to lack of communication, especially during the transition from one phase to another phase. The gap of communication in re-

[1] www.omg.org

[2] Business Process Modeling Notation, see www.bpmn.org

quirement phase of software engineering is tried to overcome with different models, e.g., for object oriented UML diagrams, as addressed in literature of software engineering [4]. Similarly, the gap exists between implementation of the business processes in IT as discussed in [24]. Due to these gaps, business processes are not executed as the way they are planned as discussed and addressed in process mining literature [48, 51].

3 Post Execution Analysis and Representations

Information systems record the interaction between resources, business objects and applications during business process execution. Post execution analysis of a business processes uses these records to provide quantitative (like processing time) and qualitative (like structure, customer's and employees' satisfaction) measurements for performance evaluation. Data about the involved objects and their attributes can be collected from log files and database tables. Different analysis methods are used during this phase.

Business process analysis after execution attempts to provide answers of several questions like what is actually happening in the system? Which are the business objects involved in execution? How are the processes executed? Where are the deficiencies/problems? What are the reasons of problems? Whether business rules are completely followed or not?

Different analytical techniques provide statistics about business process executions. Process mining is an analysis technique in which logs of information systems are used for analyses. Process mining technique aims at identifying the quality of process model and adequacy of execution environment [8]. The focus of process mining is on process structure itself rather than data perspective [53]. Currently, the knowledge in post execution analysis is represented at abstract level using charts and other models. For a better support in business process improvement, knowledge should be represented along the process structure with more details within business process models. By doing so, models provide further insights to processes and enable analysts to carry-out improvements at the process structure level.

In the Fig. 3, the business process lifecycle is divided into two parts, the part on right-hand is before execution and the part on left-hand is after execution. This figure is adapted from earlier work [18] where the difference between approaches of business process re-engineering (BPR) [19] and continuous process improvement (CPI) [21] is explained. The evaluation phase is the entry point for continuous process improvement where an existing system is evaluated and analysed for improvement.

The right-hand part has more focus on the implementation of business processes. The right-hand part is considered for business process re-engineering (BPR) and their

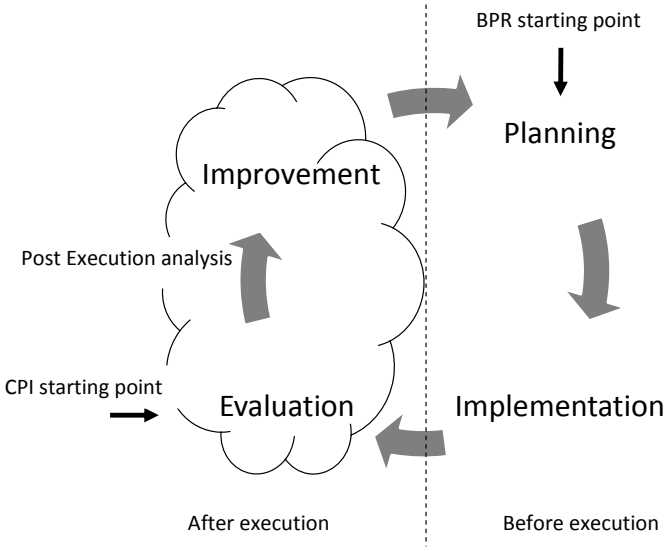

Figure 3: BP lifecycle with focus of modeling adopted from [18]

management. Most of the existing modeling methods are strongly influenced from the right-hand part only i.e., software development [12, 56]. The left-hand part focuses on process evaluation, analysis, and improvement. The process modeling has to be further investigated for the left-hand part because existing models are conceptualized only for the right-hand part.

Models for right-hand part, have different focus and level of detail to model. For example, abstraction is required for activities of right-hand phases and certain details are not considered during modeling (like implementation details, execution). Whereas for the activities of left-hand part phases, detailed representation is required to find out the deficiencies for optimization and improvement. For post execution phases, we need models which have more focus on business domain and at the same time also support details from IT domain.

Figure 4 positions different models with respect to their focus of development with regard to BP phases. Two dimensions are shown in Fig. 4 where different phases of a business process lifecycle are represented in horizontal axis and vertical axis represent the focus (Business and IT). In Fig. 4, we do not give precedence to any model within a phase and focus. Figure 4 shows that statistical techniques are used for evaluation and lack of models for evaluation and improvement phases. We found that graphical models for evaluation and improvement phases is still an open issue and need to be addressed. We also recommend that the anticipated analytical modeling language should have more focus in a business domain rather than information technology.

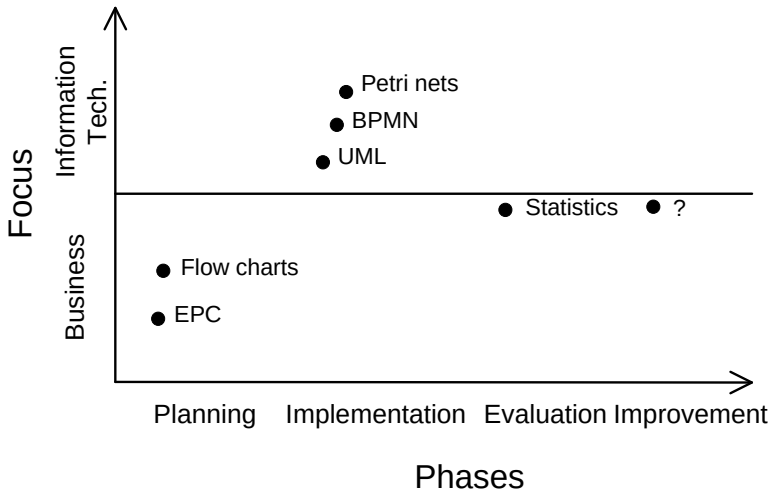

Figure 4: Phases of BP lifecycle and modeling languages

The gap will occur when existing models are used for evaluation and improvement as these models will not provide complete details. Therefore, there is a need to fulfill this gap and provide models for continuous process improvement (CPI) and for overall business process improvement. This representational gap in post execution context is further explained in the following Sect. 5 where we explain several limitations of modeling languages.

4 Characteristics of Business Processes

Business processes are characterized by involved business objects, their characteristics, and flow of activities. Different business objects are involved in business process executions. The operations of business processes are carried out on these business objects according to a specific set of rules. The business objects are characterized by their attributes (characteristics). These attributes are modified during business process execution which drives the flow of instances in execution. Analyzing the processes with involved objects, their attributes, and rules are considered as breaking down the process into details that provide the opportunity to think creatively and to perform individual analysis. This helps to improve existing processes and services for customers.

Which objects and their attributes should be represented in models by an analytical modeling language is a challenging question. To overcome this challenge, we provide a classification of business objects, their attributes, and rules (flow of business processes). Objects are classified based on their participation in execution and type of the element

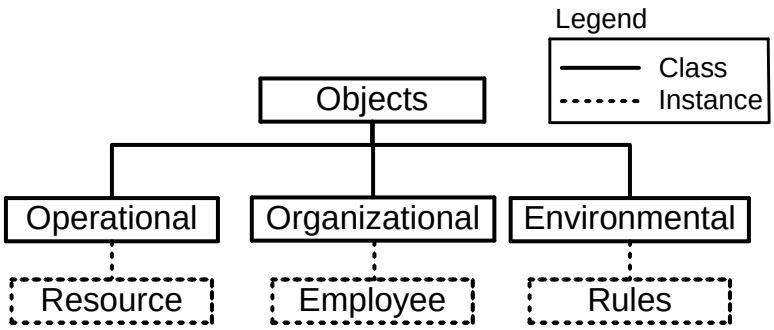

Figure 5: Classification of business objects

itself. We classify attributes of objects based on their contribution or role in analyses. In the following sections, we provide further details on this classification.

4.1 Classification of Objects

Business objects are classified based on their participation in operations. A classification of business objects helps analysts to understand which kind of objects are involved in the execution. Mostly, the concept of business objects is used in the software development lifecycle like objects discovered in analysis phase and then converted into classes in design and implementation phases. Therefore, these are discussed in software development perspective in the literature [16, 43]. Four kinds of business objects (people, places, things, and events) are described for business object modeling purposes in [33] where authors also presented the collaboration patterns for a clear communication of business requirements about the product. In Fig. 5, we provide the classification of business objects based on their participation in the executions.

4.1.1 Operational Objects

Operational objects are involved in executions of tasks in business processes. Different operational objects interact with one another to complete the execution. These object types are highlighted in following.

Resources perform operations on **inputs** and transform them into **outputs** which can be further taken as input for other operations or as a final output of the process.

Functional objects are the objects which are related with the operation of tasks, these objects help in transforming input into output like operational guidelines, checklists, and invoice of products.

Derived objects are informational objects derived from other objects and fulfill information need of the processes, for example, quantity in stock, total quantity, invoice total, customer history profile, and available capacity. These are dependent on execution of business processes which modify the objects from where these objects are derived.

Categories of operational objects are flexible because one object can belong to different categories depending on participation in a business process. Like outputs of one process is input for another process, e.g., order is output of order receiving process and input for production department.

4.1.2 Organizational Objects

Organizational objects perform operations in business processes by making interactions with other objects. Resources discussed in Sect. 4.1.1 are also organizational objects and further classified in different types. Examples of organizational objects are humans (employees), machines (operating machines, vehicles), and organizational units (buildings, departments, and organizational roles).

4.1.3 Environmental Objects

These objects are related with the environment of a business process where executions take place. These objects may reside outside the control of enterprise. We classify the objects based on their perspective under which it occurs. Different objects affect the execution and operations of a business process. Some examples of such factors are business markets (changes in customers' demands, technologies, currency rates, shipping rates), governmental issues (taxes and legislation rules), and natural conditions (weather and disasters).

4.2 Classification of Attributes

Attributes of objects are classified based on their participation in a different analysis. Attributes of objects from one kind of analysis can be combined with other attributes and objects that provide the basis for new analyses. In this way process of creative analysis evolves. Some analyses consider attributes of objects while other focuses on the attributes of a process after an instance is executed. Some kinds of analysis are described below with examples of attributes analyzed in analyses. Figure 6 shows the classification of attributes and the following sections discuss them in detail.

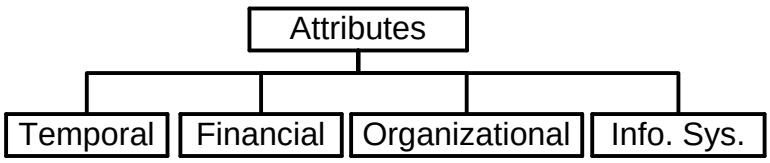

Figure 6: Classification of attributes

4.2.1 Temporal Analysis

Business processes are analyzed with respect to time for measuring the efficiency and performance of involved objects. Examples of attributes involved in such analyses are total manufacturing time, operational time of tasks/activities (time in execution), waiting time, customer negotiation time, and other temporal metrics for performance evaluation.

4.2.2 Financial Analysis

In this type of analysis monetary characteristics of objects are analyzed and their participation in business processes. These are critical identifiers for business processes as it have a major effect on overall cost and business. These attributes can be further classified based on their participation in business analysis like stock and flow. Stock is referred as quantity (money and goods) of a company at a particular time while flow is the transactions of objects occurred over a time period. Examples of attributes of business objects are money, quantities of products, purchase invoice, and receipts of payment (flow of money). Activity based costing is an example of such analysis.

4.2.3 Organizational Analysis

Different characteristics of organizational objects are included in an analysis to measure efficiency and effectiveness of organizational resources (employees/machines) like to determine the usage/performance of resources (machines) in business processes. Such analyses also used to see the interaction between different organizational resources (employees) like social groups as described in [50]. Such an analysis provides answers to questions how resources collaborate with each other to carry-out the task or which employees are involved in task execution.

4.2.4 Information System Analysis

In this analysis different objects and attributes related with IT system are analyzed like status of different components, their performances, and other details. In such analysis, users are concerned with the information system because other systems fall in organizational resource category. Therefore, program views/screens, executed functions, and elements/information accessed during execution are considered in this analysis. Such analysis helps to answer the question like how well IT systems are aligned with business operations? In which areas this alignment can be further improved?

4.3 Classification of Rules

Enterprises define their policies according to which operations of organization are carried out. These policies are further specified into a set of business rules. Business rules are also implemented as conditions. Conditions are evaluated and based on this result certain activities are executed in business processes. Conditions are of different types like **pre-conditions** and **post-condition**.

Before performing any operation, an activity of a process checks whether the pre-conditions are fulfilled or not. Examples of pre-conditions are completion of previous activity in sequence and availability of resources. Once pre-conditions are fulfilled, then operations of activity are carried out. Conversely, post-conditions ensures that system is in a stable state and all related attributes of elements are updated. Pre-condition and post-condition concepts can be applied to any granularity level of detail like at an abstract level or detailed level. Depending on the context, pre and post conditions can be optional for activities.

Several other types of business rules and conditions also exists like logical, event or time-specific, and probabilistic. For example, if weight of product is greater than a certain value, then a particular shipping method is used. An example of an event oriented rule is like that when customer payment is received then the product is dispatched to the customer. In time specific example, a salary is transferred at the end of a month or insurance deducted from an account on certain time. Rules and conditions are applied and sometimes relaxed based on events and characteristics of instances. For example, handling of vip customers in which certain conditions are relaxed for a certain time like confirmation of payment.

4.4 Business Process Flow

Business rules, events, and involved business objects affect the flow of business processes. Flow of business processes is investigated under various perspectives like control flow, organization flow, and information (data) flow. Control flow focuses on execution of activities and addresses what activities should be performed and in which order (for example, sequential, parallelization, and iteration). Organizational flow investigates which organizational objects perform actions over activities and where these activities will be carried out. Information (data) flow focuses which information (data) elements are consumed or produced in activities and what are their interrelationship.

4.5 Data Collection, Computation, and Representation

Data about business process characteristics like involved business objects and their attributes can be collected from an information system's log files, tables, companies documents, and other resources. Afterwards, this data is computed to provide different statistics and details about execution. Some of the measurements are very common in practice and can be collected from an information system. Details on data collection and computation of business objects are out of scope of this paper and will be addressed in future work.

Mostly attributes are represented with involved business objects. Sometimes attributes are applicable for overall process rather to a specific instance or business object. In this case, they are represented with a process itself. Similarly, business rules and conditions are represented where they are applied to provide the rationale for decisions. For post execution analysis, descriptive models are required and all details are needed to be represented in models for analysis.

5 Representational Challenges of Modeling in Post Execution Phases

Several surveys [1, 22, 42, 56] and comparisons [13, 28, 38] discuss the limitations of modeling languages and current challenges in the business process modeling domain. Their findings show that user's demands are not satisfied and require further research in business process modeling [22]. When business processes are modeled for current status analysis and improvement, then their requirements are more as compared with simple representation of processes for understanding [1, 13]. This requires the enrichment of business process models with details and requires new constructs to represent

reality. Focusing particularly on the evaluation and improvement phase after execution, the representational challenges are discussed in the following subsections.

5.1 Environment of Business Processes

In a recent survey of modeling techniques [38], authors found that only few modeling techniques represent a business process environment in their models using some constructs. The absence of environment factors from models makes analysis difficult for analysts to understand the execution of business processes and their performance. This is because of external factors (time, weather, market's condition, employee's skills, and others) which have a direct effect on business operations.

5.2 Elements and Attributes

Most of the business process models do not represent the elements and attributes involved in business process executions. The involved elements and attributes are implicitly assumed as present before execution. Because of this, the dependencies are implicit and do not provide details in the analysis after execution. Different articles discuss the importance of explicit representation of attributes in business process models, for instance [1, 7, 14, 30]. For example, in Petri nets, the presence of all involved elements is abstractly represented by a token (dot). Similarly, the rules and other assumptions are not explicitly represented in models. The representation of involved elements (business objects) is important for a business analyst who wants to analyze the participation role played by these elements in business process execution. In [23], authors found that activities extended with attributes provide a better capability for process analysis.

Incomplete representation of elements in process models is discussed in [38] where authors see it as main hindrance for specification of rules. For example, representation of kinds of objects like gold/silver customer is still missing in the process models. Based on characteristics of cases, different process structures/paths are followed.

5.3 Representation of Successful and Failure Paths

The perspective of business processes and involved elements is not fully represented in business process models. For example, how weak structures in process models can be identified and represented. The weak structure means that the path on which often process executions leads to failure or most of the time is consumed without significant

contribution, e.g., iterations. What are the alternative paths to avoid from such structures for improvement and optimization? The best practices of carrying out business operations are also needed to be represented in business process models.

5.4 Structural Challenges of Business Process Models

Restrictions of most modeling languages are not compliant with business processes that occur in reality. For example, few modeling languages apply the structural restrictions on process models like workflow nets [45] where more than one input place are not allowed because of the complexity in its formalism, validation, and verification. Similarly, explicit representation of other involved elements is also often avoided. Due to this, business process models do not represent the details of reality. In a real business process more than one starting place can occur and it requires all business elements to be represented explicitly. This question requires further investigation that how the reality should be represented in business process models.

5.5 Simulation, Reality, and Representation

In case of loops, certain paths are highly unlikely to be executed in real life. Consider the example presented in Sect. 1.2, in this case activity B will not be repeated in case of failure by activity C. Because process models represent details at an abstract level, therefore the model represented in Fig. 1 show that activity B will also be repeated. Simulation logs of this model will also generate activity B as repeated activity which is not repeated in reality as discussed in Sect.1.2. Apart from the problem of granularity level in process model of 1, various conditions and objects are involved in business process execution due to which simulation of business process does not represent the reality. Representation of business processes in reality requires the extension of current modeling languages.

5.6 History Construct

Business process models lack in representing the history of process instances [38], like through which particular process structure the instance has been executed. Different annotations and lists are used to represent such information with models. For example, in a loan mortgage application, the profile of a client (his past behavior with the company and transactions) is important to take decisions. Currently, such information is not explicitly presented in models. In [38], Recker et al. found it as a main hindrance for

integration and specification of rules in business process models. The specification of history construct in a model will help the stakeholders to better understand the dependencies between activities and rules. It would also help the stakeholders to understand which processes lead to success and which not.

5.7 Priority of Activities

In business processes, some activities are executed independently from one another i.e., in parallel. In most cases, users want to prioritize their executions for efficiency and use annotations for communication in models. Like longer activities should be started earlier (or later depends on the situation of resources and importance), therefore, other activities would not have to wait for the completion of a previous activity. The modeling languages do not provide any constructs, therefore, separate lists or annotations are currently used for this purpose. This priority of activities has to be represented in models for better understanding and planning for efficient utilization of resources.

If the priority of activities is followed strictly, then process discovery algorithms [54] would consider such activities as a sequential in structure. Therefore in the analysis, the independence of activities with one another would not be represented in models. Therefore, casual independence and priority of activities should also be represented in a business process model for ease in communication.

5.8 Importance and Representation in Models

The importance of earlier mentioned challenges and their existing representation are summarized in Table 3. Three ranking levels are defined with symbols like "+", "O", and "–" which represent high, medium, and low respectively. Two major phases of BPM are used for this evaluation; one is before execution and on the other hand is after execution. This ranking is carried out after studying the several surveys and comparison in business process modeling literature discussed earlier. The *x/y* notation is used, where x represent the importance of attribute, and y represent the level of modeling support by existing modeling language i.e., importance/representation. Therefore, the notation +/– means that challenge is important in phase, but it is not represented using models. The notation O/O means that challenge is at a medium level of importance, and partially represented by models. Some modeling languages address the limitations which we mentioned earlier like extended notations of BPMN to represent the different messages and involved elements. However, the other limitations are not addressed at all or if addressed then different other models are used. This makes business process modeling as an expansive job as models developed for one purpose are not reusable for another.

Table 3: Challenges, their importance, and representation

Challenges	Importance & Representation	
	IT Sys. Dev.	Post Exec.
5.1 Environment of BPs	+/O	+/–
5.2 Attributes representation	O/O	+/–
5.3 Successful & Failure Paths	O/–	+/–
5.4 Structural Limitations	O/O	+/–
5.5 Simulation & Reality	+/O	+/O
5.6 History	+/O	+/–
5.7 Priority representation	O/–	O/–

6 Characteristics for Analytical Modeling Language

Efficiency and performance of business processes are measured using key performance indicators (KPIs). Similarly, when the structure followed by business processes executions has to be analyzed, then business process models are used. However, what is the case when both are required for analysis? Then, we need key performance indicators (KPIs) and models simultaneously. For this reason, investigations should be made for analytical modeling language that will provide statistics within the models. Similarly, the limitations of modeling languages discussed earlier also need to be addressed in analytical modeling language. In the following, we discuss some of the characteristics which should be included in an analytical modeling language. These characteristics will help to overcome the limitations of modeling language for analysis. We assume that the detailed data about business process executions and its involved elements are already available from information systems. Data collection about involved business objects and formalism of proposed characteristics in an analytical modeling language is out of scope of this report.

6.1 Granularity of Detail

Business process models are viewed by different stakeholders and so at different levels of granularity (abstract or in detail). Executives are interested in an overall picture of business processes, thus they require a suitable abstraction of BP models whereas operational managers look for specific details of processes and their activities of their responsibility. The same situation holds in analytical data perspective. Therefore, an analytical modeling language should provide constructs to represent processes and quan-

titative analysis at a different granularity of details.

In case of structural limitations as discussed earlier in Sect. 5.4, analytical modeling language may apply limitations at an abstract level. However, at an operational level, these restrictions must be relaxed to provide further details through models.

6.2 Context Based Representation

Different stakeholders are involved in business processes and each wants to view the processes in his own perspective like monitoring, control, and organizational analysis. Context adaptive views or models are required to be built based on user demands rather than models built earlier. Such views/models can be further extended to provide better insights into processes. Model adaptation based on its usage by stakeholders can also be considered to provide maximum flexibility to end users. For example, the profile of and end-user can be maintained which stores his personal preferences (likeness, expectations) and based on these models are represented (like providing specific details and extension of attributes).

6.3 Integration of Analytical Data and Elements with Models

Attributes and involved elements should be part of the models for analysis because of the reasons discussed in Sect. 5.2. Explicit representation of elements with attributes values will help to understand the structural deficiencies and reasons of failure. For example, in case of product manufacturing discussed in Sect. 1.2, the iterative structure with attributes and values explains the reasons that why a certain part of the process has to be repeated again and which activity should be carried out again. Similarly, involved conditions and rules should also be explicitly specified in models. These explicit representations will provide the rationale for the decisions made in business process executions. Such extended models can also be used to provide training to new users. In this way, the new user can analyze the past executions and understand the decisions made by experienced users.

6.4 Formalism of Analytical Modeling Language

An Analytical modeling language should define business processes precisely and provides the semantics to be followed. Important representational elements should be provided, even though the formalism becomes complex or hard to define. Because enrich

representation of models will make their formalism complex, as representation of models and its formalism discussed in [37]. With the formalism, the analytical data can be automatically integrated with the business process models.

6.5 Generic Representation of Business Processes

Different models are used during business process lifecycle phases, which involves different constructs and details. These models have different focus like data models and other models. During analysis, when different models consulted back and forth then ambiguities (confusion) may arise because models are at different levels of abstraction. Post execution phase of business process analysis requires an integrated view of business processes and its elements. Therefore, the analytical modeling language should be integrated and generic in representation, so that organizational elements would have one consistent view of business processes. This also enables to understand the dependencies among processes. The generic representation of business processes will enable to extend the models with different attributes to provide different views, like extending the model with time attributes will help in performance analysis.

6.6 Characteristics and Challenges

The characteristics of analytical modeling language mentioned in the earlier sections will help to address the challenges discussed in Sect. 5. The expected contribution of characteristics and challenges is summarized in Table 4. The contribution of characteristics is defined in three levels where symbol "+" means supported at a high level, "O" at a medium level, and "–" means at a negligible level.

Table 4: Characteristics and challenges addressed

Challenges / Characteristics	Environ.	Attr.	Path	Struct.	Simul.	Hist.	Priority
6.1 Granularity	O	O	–	+	O	–	–
6.2 Context based rep.	+	+	O	–	–	–	+
6.3 Data integration	–	+	O	–	O	+	+
6.4 Formalism	O	O	–	+	+	O	–
6.5 Generic representation	O	O	–	+	+	O	O

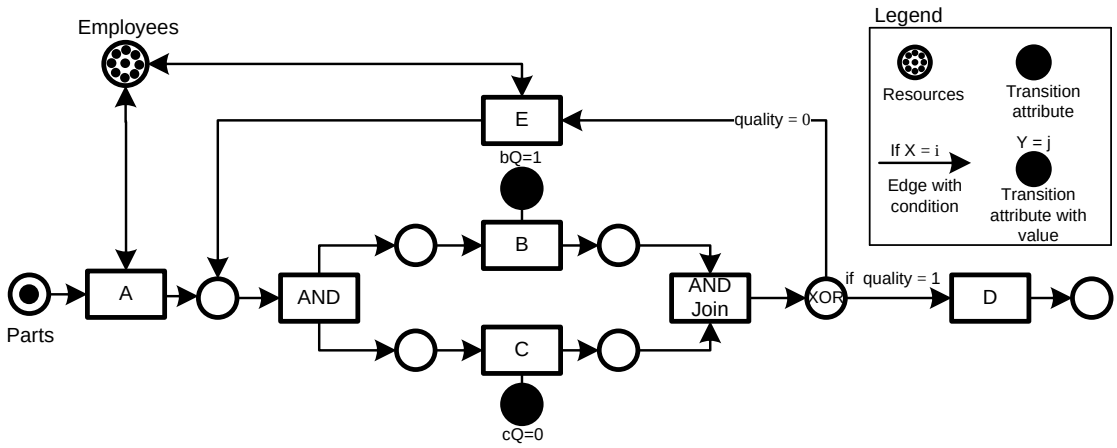

Figure 7: Extended model of product manufacturing example

7 Case Study

The anticipated characteristics discussed earlier are further explained with a case study. For the case study, we use the same example introduced in Sect. 1.2. The model represented in the Fig. 1, can be extended by different elements to provide further details about the execution. We extend the model with an imaginary Petri net which includes the features of other high level Petri nets cf. [27]. The model of Fig. 1 is extended with a pool of resources (like employees and parts), attributes of involved elements (quality of activity), and involved conditions. An example of the extended model is given in the Fig. 7. In the model, Petri nets are graphically extended to represent the involved elements, resource pool (circle with many tokens), conditions (on the edges), attributes (filled circle), and their values.

The bi-directional arrow to resource place *Employees* indicate that employees can be assigned to certain tasks, and after completion they can become available for other tasks again. At a choice (XOR) place, a decision is made that if the quality is at desired level (value 1), then product moves for packing, otherwise it has to be disassembled. The choice (XOR) can be further decomposed to represent the evaluation process and assignment of values to certain attributes of elements. The filled circle connected with activity B and activity C represent the attributes related to the activity. The attributes of activities are set (get values) after the quality evaluation, and in case of iterations the stakeholder (employees, process owners) knows which activity will be repeated again (in presented case activity C).

This model can be extended with more involved elements, attributes, and business rules to provide further information. Activity E, can be further represented to show the

decision rules for disassembling a specific part (e.g., only part from activity C) instead all parts. The case study shows that the characteristics we introduced in Sect. 6 will enhance the understanding about business processes and involved decisions. Extended models are useful for process owners, who will find out deficiencies and carry-out process improvements.

The modeling language represented in the Fig. 7 is not a natural extension of Petri nets for proposed characteristics. There are also other possibilities for extensions of modeling language. However, these other extension should consider the analytical requirements and characteristics of post execution phases. In our future work, we will try to formalise the presented imaginary Petri nets and also try to evaluate other modeling languages for post execution analysis and improvement.

8 Application of Extended Model

An evaluation of business processes after execution provides means to understand the implicit dependencies, and problems faced by employees during execution. Graphical representation of business processes and involved elements provides intuitive understanding. Extended representations are more useful for process managers and process owners because these details are important for them. Extended models and attached statistical data would provide details on processes, entities, and their participation (role in execution). Thus, it would help a lot to improve the structure (design) and execution of business processes in the future. In this section, we explain the benefits and application areas of extended models.

8.1 Analytical Queries

The following analytical queries can be answered using extended models. Although these queries can be answered by other techniques, they do not represent elements explicitly in models, and thus do not provide an intuitive understanding. Here, these queries are discussed in post execution context and therefore has a different focus compared to pre-execution phases. Extended process models will help more effectively in business process improvement.

- What are the dependencies between elements and processes?
- Which decisions are made in business processes, what are the rationale for these decisions? What are the characteristics of cases that affect the decisions?

- Whether a specific execution leads to success from process models or not?
- Which parts of a process affect the efficiency?
- Which resources are assigned to the business process, but are rarely used?
- What are reasons for their rare usage and for which cases (and kinds)?
- Which objects are involved in task execution?
- What are the information requirements (attributes) for executions?

Some of the above questions do not require a query language. Those questions can be answered by simple analysis of extended business process models like involved resources. However, a query language and other techniques are needed to answer some other questions. In [26], Graph mining based techniques are investigated to answer the questions related with business processes.

8.2 Benefits

A very critical and important question will always be raised whenever a new modeling method or approach is introduced: what are the benefits that can be achieved? The analytical modeling language focuses more on business domain and process structure rather than technological or other aspects. Therefore, deficiencies with respect to a business domain are addressed here. In the following, we discuss the anticipated benefits of analytical modeling language.

8.2.1 Intuitive Understanding

In case of iterations, it is not always clear from the business process model why an instance has to be repeated several times. Extension of attributes in the model would help to understand such situations intuitively about the reasons of failure. Similarly, the extension of attributes will increase an intuitive understanding about business processes.

8.2.2 Rationale for Decisions

For better analysis and understanding, implicit assumptions must be represented explicitly. Using Petri nets, required conditions, and elements are represented very abstractly like presence of token at places. Explicit representations of involved elements, their

attributes, and rules will improve the understanding of business process executions. Extended business process models will help to understand the dependencies between elements of business processes, like which elements are required for the execution of business processes. The analytical business process modeling will provide the rationale for the decisions made in business process executions.

8.2.3 Training of Users

Extended business process models, can also be used for knowledge management. New users can be trained on business process operations and informed about the situations handled by experienced employees in the past. Detailed descriptions will help to model the reality with attributes and values of instances executed.

8.2.4 Models/Directions for Improvement

The detailed description of business processes in models will help to identify the deficiencies in execution. The specific areas can be further investigated for improvement or reengineering. Better understanding of problems will also give directions to take steps to rectify the causes of problems.

8.2.5 Just-in-Time Analysis

A history construct in business process models provides the capability to state the elements of business processes at a particular stage of operation. This is important, because at later stages the efficiency of elements can be affected by other elements or processes. For example in case of comparison between two instances, at a particular stage the cost of one instance is very low because of efficient processing and the path it took during execution, but at later stages other elements/processes may affect the efficiency of instance and so overall cost of two instances remain the same. In this case, the reasons of efficient execution will not be noticed. The improvement in one part of phase is overcome by other parts of the process.

8.2.6 Understanding the Context

Representation of environment elements in business processes models will allow the analysis of the environment in which business processes are executed and thus improve the understanding about business processes.

Besides the environment of a business process, representation of involved elements is also important for analysis and understanding of business processes. Explicit representation of elements with attributes will help to understand the structural deficiencies. For example, in case of delivery of goods, the loop structure with attributes explains the reasons of failure in delivery and why it has to be repeated again. Once we are able to represent the executions of business processes (and its environment) completely in a business process model, then we can use extended models to understand the structural deficiencies of business processes. Because in abstract representation, the structural deficiencies are not clear and understandable so cannot be easily found.

9 Related Work

Most of the research in business process modeling domain is related to information system, like information system development [4], workflow management [45], simulation of business processes [25], alignment of IT services with business processes [48], or for the configuration of information systems [15]. The focus of research on business process modeling after execution is limited. The approaches which analyze business processes after execution use the same models which are conceptualized for information system development, like process mining [51], use Petri nets [45].

Several approaches attempt to integrate different modeling approaches for analysis phase of system development like [9,32]. However, integration of modeling approaches poses new challenges as discussed in [14]. In [6,7,14], authors discuss the importance of an integrated framework for modeling and enrichment of models but only in perspective of information system development phases or for project management.

A survey on business process analysis for optimization and improvement is provided in [56]. In that survey, authors categorize different approaches into notational, formal and semi formal categorizes. Their survey indicates the lack of business process modeling languages for post executional phases. However, they do not mention any limitations or challenges of modeling languages which we have provided in this report.

Context and environment of business processes are discussed in many papers with respect to adaptation of changes in information systems [34, 40]. Such approaches should be further extended to build business process models for analysis. Environment and context elements should be explicitly represented in detailed process models.

The concept of excluding activities at the abstract level and including them at the detailed level is also discussed in [5, 15] whereas in [6], it is discussed at the attribute level. BPMN also provides concept for activities (containing sub-activities) [5], however, they do not discuss the attributes to be attached with model as explicitly. Currently,

most of the modeling languages provide facilities in one perspective but do not support other perspectives. For example, some modeling languages allow the representation of involved elements but do not provide a formalism for simulation or other analysis. In analytical modeling language, we will attempt to provide both functionalities.

Business processes are also analyzed at a simulation level to understand the environment and involved elements like Income [25], but in simulation based approaches often the assumptions/conditions are implicit and do not provide the intuitive understanding through models and users have to use other sources, e.g., lists to get more details.

Different views of models are generated based on the environment (role) of execution as discussed in [10], but they only discuss them in software process perspective. The concept is needed to be applied in a business process domain.

Most of the surveys and comparisons in business process modeling discuss the limitations with the focus on development of information systems. In this report, we have provided the limitations of business process modeling in post execution analysis perspective.

10 Summary and Outlook

This report provides the motivation for intuitive analytical modeling language in post execution analysis. In this report, we identified the challenges and open issues involved in modeling business processes in post execution phase. We show that the languages conceived for information system development are not sufficient to represent reality and do not fulfill the requirements of post execution analysis phases. Several limitations of modeling languages are identified and discussed in detail with the examples. We also proposed characteristics of analytical modeling language and discussed them with a case study. Characteristics of business processes are also discussed to understand the context for business process analysis and improvement. A classification of elements and attributes is provided to help in deciding which elements and attributes are important for representation in a model for evaluation and improvement. The anticipated benefits of the proposed characteristics of modeling languages are also discussed.

Different characteristics of business process models should also be further discovered which will provide help in business process improvement. Based on the limitations and characteristics discussed in this report, different modeling languages will be further evaluated. Collaboration with different corporations will be made for collection of post execution analysis data and its representation in the model. The characteristics of new modeling language discussed in this report will be formalized with new constructs, and structures for better representation in the analysis. A framework for business process

improvement including the data collection from information systems, its representation, and guidelines will be proposed in the future.

Acknowledgment

Azeem Lodhi is supported by a grant from the federal state of Saxony-Anhalt in Germany. Veit Köppen is supported by the German Ministry of Education and Science (BMBF), within the VierforES project No. 01IM08003C.

References

[1] R. S. Aguilar-Savén. Business process modelling: Review and framework. *International Journal of Production Economics*, 90(2):129–149, July 2004.

[2] M. D. Backer and M. Snoeck. Business process verification: A Petri net approach. *SSRN eLibrary*, 2007.

[3] M. J. Blechar. Magic quadrant for business process analysis tools. Technical Report 2H07-1H08, Gartner, 2007.

[4] G. Booch, J. Rumbaugh, and I. Jacobson. *Unified Modeling Language User Guide*. Addison-Wesley Professional, 2 edition, May 2005.

[5] BPMI.org and OMG. Business Process Modeling Notation Specification, Final Adopted Specification, Feburary 2008. http://www.omg.org/bpmn/Documents/BPMN

[6] T. R. Browning. The many views of a process: Toward a process architecture framework for product development processes. *Syst. Eng.*, 12(1):69–90, 2009.

[7] T. R. Browning, E. Fricke, and H. Negele. Key concepts in modeling product development processes. *Syst. Eng.*, 9(2):104–128, 2006.

[8] J. F. Chang. *Business Process Management Systems: Strategy and Implementation*. Auerbach Publications, 1 edition, September 2005.

[9] C. Climent, J. Mula, and J. E. Hernandez. Improving the business processes of a bank. *Business Process Management Journal*, 15(2):201 – 224, 2009.

[10] D. Correal and R. Casallas. Using domain specific languages for software process modeling. In *ACM OOPSLA, Workshop on Domain-Specific Modeling*, 2007.

[11] M. Cumberlidge. *Business Process Management with JBoss jBPM: A Practical Guide for Business Analysts*. Packt Publishing, 2007.

[12] B. Curtis, M. I. Kellner, and J. Over. Process modeling. *Commun. ACM*, 35(9):75–90, 1992.

[13] N. Damij. Business process modelling using diagrammatic and tabular techniques. *Business Process Management Journal*, 13(1):70 – 90, 2007.

[14] D. Delen, N. P. Dalal, and P. C. Benjamin. Integrated modeling: the key to holistic understanding of the enterprise. *Commun. ACM*, 48(4):107–112, 2005.

[15] A. Dreiling, M. Rosemann, W. van der Aalst, and W. Sadiq. From conceptual process models to running systems: A holistic approach for the configuration of enterprise system processes. *Decision Support Systems*, 45(2):189–207, 2008.

[16] P. Eeles and O. Sims. *Building business objects*. Wiley & Sons, New York, NY, USA, 1998.

[17] R. A. Etoundi, M. F. Ndjodo, M. A. Monessa, and E. P. Zobo. Feature oriented workflow modelling based on enterprise human resource planning. *Business Process Management Journal*, 12(5):608 – 621, 2006.

[18] C. Gernert and V. Köppen. *Handbuch-IT in der Verwaltung*, chapter Geschäftsprozesse optimal gestalten, pages 195–224. Springer, 2006.

[19] M. Hammer and J. Champy. *Reengineering the Corporation: A Manifesto for Business Revolution*. Harper Collins, London, 1993.

[20] IBM. Flowcharting techniques. Technical report, IBM Data Processing Techniques, Yorktown Heights, NY, 1969.

[21] M. Imai. *Kaizen: The Key To Japan's Competitive Success*. McGraw-Hill, 1986.

[22] M. Indulska, J. Recker, M. Rosemann, and P. Green. Business process modeling: Current issues and future challenges. In P. van Eck, J. Gordijn, and R. Wieringa, editors, *Advanced Information Systems Engineering, 21st International Conference, CAiSE 2009, Amsterdam, The Netherlands, June 8-12, 2009. Proceedings*, volume 5565 of *Lecture Notes in Computer Science*, pages 501–514. Springer, 2009.

[23] Z. Irani, V. Hlupic, and G. Giaglis. Editorial: Business process reengineering: A modeling perspective. *International Journal of Flexible Manufacturing Systems*, 13(2):99–104, Apr. 2001.

[24] M. Juhrisch, G. Dietz, and W. Esswein. Perspectives on semantic business process modeling a generic approach. In *Pacific Asia Conference on Information Systems PACIS*, 2009.

[25] S. Klink, Y. Li, and A. Oberweis. INCOME2010 - a toolset for developing process-oriented information systems based on petri nets. In *Simutools '08: Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*, pages 1–8, Belgium, 2008. ICST.

[26] A. Lodhi, G. Kassem, V. Köppen, and G. Saake. Investigation of graph mining for business processes. In *Proceedings of The International Conference on Intelligence and Information Technology ICIIT*, Lahore, Pakistan, Oct. 2010. IEEE Computer Society.

[27] A. Lodhi, G. Kassem, and C. Rautenstrauch. Modeling and analysis of business processes using business objects. In *Proceedings of The 2nd IEEE International Conference on Computer, Control and Communication*, Karachi, Pakistan, Feb. 2009. IEEE Computer Society.

[28] R. Lu and S. Sadiq. A survey of comparative business process modeling approaches. In W. Abramowicz, editor, *Business Information Systems, 10th International Conference, BIS 2007, Poznan, Poland, April 25-27, 2007, Proceedings*, volume 4439 of *Lecture Notes in Computer Science*, pages 82–94. Springer, 2007.

[29] W. Luo and Y. A. Tung. A framework for selecting business process modeling methods. *Industrial Management & Data Systems*, 99(7):312–319, 1999.

[30] A. Macintosh. The need for enriched knowledge representation for enterprise-modelling. *AI (Artificial Intelligence) in Enterprise Modelling, IEE Colloquium on*, (Digest No.078):3/1 – 3/3, Apr 1993.

[31] J. Mendling, H. Verbeek, B. van Dongen, W. van der Aalst, and G. Neumann. Detection and prediction of errors in EPCs of the SAP reference model. *Data & Knowledge Engineering*, 64(1):312–329, 2008.

[32] G. N. Mentzas. Coupling object-oriented and workflow modelling in business and information process reengineering. *Information Knowledge Systems Management*, 1(1):63–87, 1999.

[33] J. Nicola. Business object modeling with collaboration patterns. White Paper, Streamlined Modeling., 2002.

[34] S. Nurcan and M.-H. Edme. Intention-driven modeling for flexible workflow applications. *Software Process: Improvement and Practice*, 10(4):363–377, 2005.

[35] K. Phalp and M. Shepperd. Quantitative analysis of static models of processes. *Journal of Systems and Software*, 52(2-3):105–112, June 2000.

[36] K. T. Phalp. The CAP framework for business process modelling. *Information and Software Technology*, 40(13):731–744, Nov. 1998.

[37] J. Recker and J. Mendling. Adequacy in process modeling: A review of measures and a proposed research agenda. In B. Pernici and J. A. Gull, editors, *CAiSE 2007 Workshop Proceedings*, volume 1 of *Eighth Workshop on Business Process Modeling, Development, and Support (BPMDS 2007)*, pages 235–244., Trondheim, Norway, June 2007.

[38] J. Recker, M. Rosemann, M. Indulska, and P. Green. Business process modeling: A comparative analysis. *Journal of the Association for Information Systems*, 10(4):333–363, 2009.

[39] J. Rumbaugh, I. Jacobson, and G. Booch. *The Unified Modeling Language – Reference Manual*. Addison-Wesley, 1998.

[40] O. Saidani and S. Nurcan. Towards context aware business process modelling. In *In proceedings of Workshop on Business Process Modelling, Development, and Support (BPMDS'07)*, Trondheim, Norway, 2007.

[41] A.-W. Scheer. *ARIS–Business Process Modeling*. Springer-Verlag New York, Inc., Secaucus, NJ, USA, 1998.

[42] D. R. Shaw, C. P. Holland, P. Kawalek, B. Snowdon, and B. Warboys. Elements of a business process management system: theory and practice. *Business Process Management Journal*, 13(1):91–107, 2007.

[43] D. J. Sutherland. The object technology architecture: Business objects for corporate information systems. In O. E. en P. Scheuermann, editor, *Business Object Design and Implementation*. Springer, 1997.

[44] W. van der Aalst. Three good reasons for using a Petri net based workflow management system. In S. Navathe and T. Wakayama, editors, *Proceedings of the International Working Conference on Information and Process Integration in Enterprises IPIC'96*, pages 179–201, Camebridge, Massachusetts, 1996.

[45] W. van der Aalst. The application of Petri nets to workflow management. *The Journal of Circuits, Systems and Computers*, 8:21–66, 1998.

[46] W. van der Aalst. Challenges in business process management: Verification of business processes using petri nets. *Bulletin of the European Association for Theoretical Computer Science*, 80:174–198, 2003.

[47] W. van der Aalst. Business alignment: Using process mining as a tool for delta analysis. *Proceedings of the 5th Workshop on Business Process Modeling, Development and Support (BPMDS'04), Caise'04 Workshops*, 2:138–145, 2004.

[48] W. van der Aalst. Business alignment: using process mining as a tool for delta analysis and conformance testing. *Requir. Eng.*, 10(3):198–211, 2005.

[49] W. van der Aalst. Tomtom for business process management (TomTom4BPM). In P. van Eck, J. Gordijn, and R. Wieringa, editors, *Proceedings of the 21st International Conference on Advanced Information Systems Engineering (CAiSE 2009)*, volume 5565 of *Lecture Notes in Computer Science*, pages 2–5. Springer, 2009.

[50] W. van der Aalst, H. A. Reijers, and M. Song. Discovering social networks from event logs. *Computer Supported Cooperative Work*, 14(6):549–593, 2005.

[51] W. van der Aalst, H. A. Reijers, A. J. M. M. Weijters, B. F. van Dongen, A. Medeiros, M. Song, and H. M. W. Verbeek. Business process mining: An industrial application. *Inf. Syst.*, 32(5):713–732, 2007.

[52] W. van der Aalst, A. ter Hofstede, and M. Weske. Business process management: A survey. In W. van der Aalst, A. ter Hofstede, and M. Weske, editors, *Business Process Management*, volume 2678 of *Lecture Notes in Computer Science*, pages 1–12. Springer, 2003.

[53] W. van der Aalst, B. F. van Dongen, C. Günther, A. Rozinat, H. M. W. Verbeek, and A. J. M. M. Weijters. Prom: The process mining toolkit. In A. K. A. de Medeiros and B. Weber, editors, *Proceedings of the BPM 2009 Demonstration Track*, volume 489 of *CEUR Workshop Proceedings*, pages 1–4. CEUR-WS.org, September 2009.

[54] W. van der Aalst, A. J. M. M. Weijters, and L. Maruster. Workflow mining: Discovering process models from event logs. *IEEE Transactions on Knowledge and Data Engineering*, 16(9):1128 – 1142, 2004.

[55] B. F. van Dongen, M. H. Jansen-Vullers, H. M. W. Verbeek, and W. van der Aalst. Verification of the SAP reference models using EPC reduction, state-space analysis, and invariants. *Comput. Ind.*, 58(6):578–601, 2007.

[56] K. Vergidis, A. Tiwari, and B. Majeed. Business process analysis and optimization: Beyond reengineering. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 38(1):69–82, 2008.

[57] J. Wortmann, D. Hammer, J. Goossenaerts, and A. Aerts. On the relation between Business, Business Model, Software, and ICT Platform Architectures. In

H. de Bruin, editor, *Proceedings of ICT-Architecture'99: ICT Architecture in the BeNeLux 1999*, Amsterdam, The Netherlands, November 1999.