

SURVEY

A Systematic Literature Review of the Analysis of Costs and Other Dimensions in Process Mining and Related Disciplines

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ABSTRACT Process mining allows the discovery, monitoring, and improvement of processes through records of their executions. When used for discovery, models depicting the process behavior can be obtained and then analyzed through a performance perspective, focusing on performance indicators for the dimension of interest. In process mining, there has been scarce research on the analysis of some dimensions, such as the cost dimension. A systematic literature review has been conducted to identify the methods used for analyzing the cost dimension in process mining and other process-oriented disciplines, the dimensions considered jointly with costs, and how such a joint analysis is carried out. The review identified 68 publications. The results indicate ample research within distinct disciplines, like business process management and cost management, regarding the costs of performing processes, their reporting and forecasting. However, there is a need to further enrich their visualization and analysis, and to provide cost-aware operational support. Moreover, the utility of further researching cost analysis jointly with other dimensions, like time, flexibility, and quality, is also observed. These results provide a structured focal point of research that can be considered when analyzing costs from a process perspective and the identification of research gaps within this domain.

INDEX TERMS Business process management, cost dimension, performance analysis, process mining, systematic literature review.

I. INTRODUCTION

Process mining is a research discipline that allows the discovery, monitoring, and improvement of real processes by extracting knowledge from event logs [1]. These event logs contain records produced by the actual executions of a process [2]. When used for discovery, the goal of process mining is to create a process model based on the behavior observed in the event log [2]. Two mainstream approaches are then followed to analyze these models: verification and performance analysis [1]. Verification is concerned with the correctness of the process, whereas performance analysis focuses on the analysis of distinct key performance indicators based on the dimension of interest [1]. Three

main dimensions can be identified: time, cost, and quality. While the time dimension has been broadly considered when analyzing event logs, there has been scarce research on the other two [3]. Specifically, for the cost dimension, the focus has been on obtaining and annotating costs information in event logs [4], as well as visualizing them through process models, in a similar fashion to the time dimension [3], [5], [6].

Several open research questions can be observed when addressing the cost dimension in process mining. Namely, there is a need to identify the existing methods utilized for performing various process mining tasks, such as visualization, analysis and optimization, for the cost dimension, as well as observing possible gaps and limitations in these methods that could leverage further research on the topic. Moreover, most of the observed research has

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focused on a particular dimension. However, insights that could not be observable by analyzing the cost dimension individually could emerge when analyzing it jointly with other dimensions, such as time and resources. For example, resources could be allocated while considering the costs associated to these allocations [7], [8], or trade-offs between costs and time when executing processes could be identified.

Based on the above, this work aims to address the open research questions by surveying relevant literature regarding the analysis of the cost dimension through a process perspective. To achieve this, a systematic literature review (SLR) has been undertaken, which focuses on the process dimensions that have been considered jointly with the cost dimension, as well as the specific characteristics of the methods that have been used for the analysis of this dimension. Due to the scarce research on the cost dimension within the process mining discipline [3], the scope of this SLR extends from process mining to other related disciplines and industries that possess a process perspective as well. Insights from these disciplines and industries are of interest as they could also be applicable to process mining.

This work is part of a research project aimed at enhancing the state-of-the-art regarding the analysis of the cost dimension within process mining. The results of the SLR will be used as the knowledge base required for the analysis methods to be proposed.

The remainder of this work is structured as follows: the second section synthesizes existing research on costs through process mining that has been previously identified through a scoping review. This scoping review allowed the identification of the open research questions and review objectives of the SLR. In the third section, the review questions, as well the search and review protocols of the SLR are formalized. The strategy defined for classifying the selected literature is also presented. The fourth section shows the results of the SLR, whereas the fifth section provides a discussion of these results. Finally, the conclusions of this research are provided in the sixth section.

II. COSTS IN PROCESS MINING

Before the realization of the SLR presented in this work, publications related to the cost dimension in process mining were scoped. This was done to ascertain and define the need for the review covered in this work. The cost dimension is briefly described as part of performance analysis in process mining since the first edition of the process mining reference book [9]. The book mentions that distinct cost models can be used for defining performance indicators related to this dimension, and that activity costs can be described either as a fixed amount or one that depends on variables such as the type of resource or the activity duration.

The earliest identified process mining discipline publication that focuses on the cost dimension is [4]. This publication, in the context of management accounting, proposes the creation and utilization of cost models to annotate the activities in event logs based on their associated cost drivers.

Cost drivers refer to anything that causes a change in the costs of an activity due to resource consumption [10], [11].

Later research on the topic has maintained the idea of annotating costs in event logs through cost models. In [3], a framework to include information regarding the cost and quality dimensions in event logs from the manufacturing industry is proposed. The author proposes a visualization of either aggregated or remaining costs in a process model, showing metrics, such as the sum, average, min and max costs, per activity.

Through a series of conference publications, such as [6], [12], and [13], the association of costs to a business process as an instance of a costs-extended metamodel is proposed. These costs are obtained from costs-annotated event logs. The business model can then be used to visualize costs at both the process and activity levels. Moreover, the utilization of machine learning classification algorithms to improve the definition of cost drivers is also proposed.

More recent publications make use of process mining to leverage information for the calculation of costs using time-driven activity-based costing (TD-ABC) [14], [15]. TD-ABC is a costing strategy that calculates costs by estimating the cost of every resource and their utilization time during each activity of a process [16].

To summarize, most works have focused on obtaining and annotating the information regarding costs in event logs. The main strategy for this has been the use of cost models. There has also been some research on the visualization of costs from the information in cost annotated event logs. This has followed a similar approach as the visualization of the time dimension. However, there are several open research questions that should be addressed. Namely, the identified process mining literature mainly focuses on the annotation of costs data and partial visualization of this data, but not on the task of analyzing the annotated costs. Moreover, the publications have focused on the cost dimension independently from other dimensions, but research opportunities can be observed by analyzing several dimensions jointly. For example, it is possible to identify trade-offs when analyzing costs, time, and resources jointly [17].

Based on the above, a more in-depth review of publications concerning the cost dimension is of interest. Such a review should focus on identifying the methods that have been utilized for process-related tasks, such as visualization, analysis, or optimization, while considering the cost dimension. Moreover, the dimensions that have been considered jointly with the cost dimension, as well as the application contexts of the publications, are of interest. The realization of this review would allow the identification of current research gaps and opportunities for further enhancing the analysis of the cost dimension through process mining.

Due to the results from the scoping review, the number of existing process mining publications regarding the cost dimension was expected to be low. To address the above and given the multidisciplinary nature of process mining, the scope of this SLR has been extended to other disciplines

where a process perspective is relevant. In this work, analysis through a process perspective is defined as the analysis of processes by recognizing that they can be divided in a sequence of activities that utilize organizational resources. Methods used in other disciplines that possess a process perspective are of interest as these could be applicable to the process mining discipline.

III. METHODOLOGY

This section outlines the methodology followed for conducting the SLR. Specifically, this review followed the guidelines in [18] for conducting systematic reviews, which consists of three main stages: (i) planning the review, where the review questions and objectives are defined, while also detailing the protocols that will be used during the search and review process; (ii) conducting the review, where publications are searched and reviewed by following the previously defined planning; and (iii) reporting the review, where the results of the review are presented and discussed. Throughout this section, the first two stages of this SLR are described, whereas the next two sections report the results of the SLR and discuss over them, respectively.

The structure of this section is as follows: The first subsection presents the reviewing questions that are addressed. The second subsection defines the strategies for classifying the information extracted from the selected publications. Finally, the third subsection indicates the strategy used to search and review publications.

A. REVIEW QUESTIONS

The main objective of this SLR was to research the utilization of the cost dimension for process analysis within the process mining discipline. In addition, it was also of interest to identify other process dimensions that have been analyzed jointly with the cost dimension, as well as the methods utilized for doing such analysis. While the focus is firstly on process mining, the review of related disciplines and industries where a process perspective is relevant was also considered, as the methods used in them could be applicable to the process mining discipline.

Based on the above, the following research questions have been formulated:

- How has the cost dimension been analyzed through a process perspective in the literature?
- What process dimensions have been considered in the literature, for their joint analysis with the cost dimension, through a process perspective?
- How has the analysis of the cost dimension jointly with other process dimensions been carried out, through a process perspective, in the literature?

B. CLASSIFICATION STRATEGY

Several classification strategies have been defined to facilitate the extraction and synthesis of information from the reviewed publications. These classifications are described through this subsection.

1) GENERAL INFORMATION

General descriptors of the publication, such as its publication year and type of publication have been extracted. Specifically, the following types of publication were considered: journal articles, conference papers, theses, books, and book sections.

Additionally, the affiliations of the authors were obtained to identify the regions where cost-aware process research has been carried out the most.

2) PUBLICATION CONTEXT

Information that contextualizes the publication has been identified. First, the publications have been categorized based on their research discipline: process mining, business process management, operations research, cost management, service management, project management and quality management.

Second, the target industry of the methods proposed in the publications was also used for their categorization. Examples of industries are manufacturing, healthcare, and finances. A 'general' category was also considered for publications whose proposed methods did not address a specific industry.

3) PROCESS PERSPECTIVE

From a process perspective, the main interest was to identify the process dimensions that were considered by the publications. Moreover, the granularity of the methods proposed in the publications was observed. Two possible categories were considered:

- **Process:** the proposed method allows the analysis of process dimensions at process level. An example for this category would be a method that defines performance indicators to observe the current situation of the process based on its executions.
- **Activity:** the proposed method allows the analysis of process dimensions at activity level. An example for this category would be a method that defines performance indicators that are observable for every single activity of the process.

4) METHOD APPLICATION

Regarding the application of the surveyed publications, the methods were classified in four possible categories:

- **Applied to a real case study:** the method is applied to real-life scenarios using existing data.
- **Use fictional data:** the method is validated through its use on already existing fictional data.
- **Simulate data for application:** data is specifically simulated for testing the proposed method.
- **No application (theoretical research):** the proposed method is not validated through its application, but rather through theoretical approaches or surveys.

The expected results from applying the methods were also categorized. The following categories were considered:

- **Analysis:** the proposed method provides guidelines for the analysis of the considered performance indicators.
- **Cost estimation:** the proposed method is concerned with the estimation of costs associated to the process.

- **Monitoring and/or operational support:** the proposed method focuses on the analysis of real-time performance indicators for monitoring and/or operational support.
- **Optimization and/or redesign:** the proposed method generates information that facilitates the optimization and/or redesign of processes.
- **Visualization:** the proposed method allows the generation of diagrams, process maps or other graphics that allow the visualization of the considered performance indicators.

5) METHOD CLASSIFICATION

In addition to the above classifications, the methods proposed in every publication have been reviewed in-depth. This has allowed the identification of particularities for every method and similarities between them. These specifics are presented and discussed through the fourth and fifth sections.

C. SEARCH STRATEGY

The search and review protocols for the realization of the SLR are described in this subsection. The search protocol refers to the strategies utilized to define the search string and sources. The review protocol refers to the strategies utilized to review every identified publication. Fig. 1 shows the general outline of the steps taken during the review.

1) SEARCH PROTOCOL

Based on the outcomes presented in [19], three eligible search sources were selected as the primary sources for this SLR:

- ACM Digital Library (<https://dl.acm.org>).
- Science Direct (<https://www.sciencedirect.com>).
- Web of Science (<https://www.webofscience.com>).

Using a preliminary search string, an initial set of results from the above sources was obtained, which were screened by two reviewers. Through this, it was possible to align the selection criteria for the review, as well as refine the search string for the acquisition of useful search results. Thus, the final search string is:

(*“cost dimension” OR “cost perspective”*)
AND

(*“process mining” OR “business process management” OR
“operations research” OR “supply chain management” OR
“manufacturing” OR “service management”*)
AND

(*“process improvement” OR “process analysis” OR
“performance analysis” OR “process redesign”*)

This string is composed of three sections joined by AND operators. Every section possesses various terms combined with OR operators. The first section provides the main search context of the review, which is the cost dimension. The second section contains process-oriented contexts where it was expected to find methods that considered this dimension. Most of these contexts were identified and included in the refined search string after the preliminary results. Finally, the

third section describes the application outcomes that were expected from incorporating costs.

Using the refined search string, a set of 225 publications to be reviewed was obtained from the primary sources. To increase the scope of the review, Google Scholar (<https://scholar.google.com>) was used to complement the results from the primary sources, through the utilization of the same search string, which yielded 1,453 publications.

A total of 1,678 results were obtained. After removal of duplicates, a final set of 1,584 publications to be reviewed was obtained.

2) REVIEW PROTOCOL

A two-stage process was followed for the selection of publications that were useful for this SLR. The first stage consisted of the screening of potentially useful publications based on their titles and abstracts. Only in specific cases where a decision could not be made from the title and abstract alone, the remainder of the publication was read in the following order until a decision could be made: introduction, conclusions, figures and tables, and body.

To minimize bias during the review, the references of the publications were incorporated in a spreadsheet in order of appearance and numbered. One reviewer was assigned the reviewing of odd-numbered publications, whereas the other was assigned the even-numbered ones.

For the selection of potentially useful publications, two inclusion criteria were defined:

- The publication must propose a method applicable for tasks related to process dimensions through a process perspective.
- The method proposed in the publication must consider the cost dimension.

The following exclusion criteria were also defined:

- Publications that consider the cost dimension, but do not have a process perspective.
- Publications that possess a process perspective, but do not consider the cost dimension.
- Gray literature. Specifically, publications that are not journal articles, conference papers, theses, books, or book chapters.

The above process resulted in the selection of 98 potentially useful publications.

The second stage consisted of an in-depth review of the potentially useful publications. To achieve the above and to minimize bias, the two reviewers performed a cross-review of the publications. That is, each reviewer performed the in-depth review of the publications selected by the other reviewer. During this stage, the publications were categorized based on the classifications defined in the previous subsection.

Two additional exclusion criteria were included at this stage:

- Publications that are unavailable.

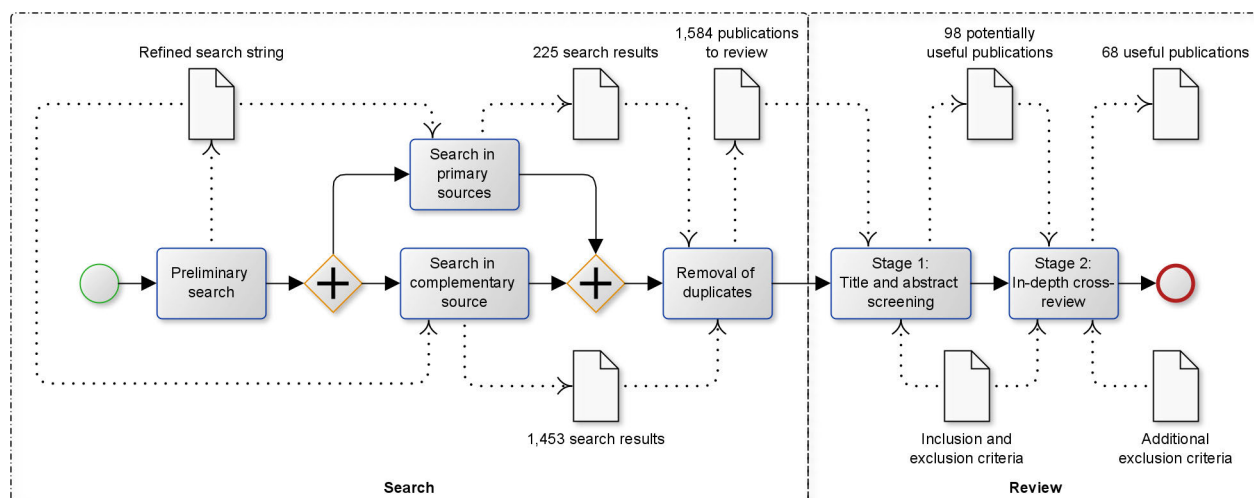


FIGURE 1. Outline of the steps taken during the SLR.

- Publications that are preliminary versions of other selected publications, e.g., conference papers that were later published as journal articles.

During this stage, if a reviewer considered that one of their assigned publications met any of the exclusion criteria, this publication was marked and later discussed with the other reviewer. If there was a disagreement, the publication was presented to a third reviewer, who was in charge of supervising the realization of the SLR, for the final decision.

As a result of this stage, a final set of 68 useful publications for this SLR was obtained.

IV. RESULTS

This section shows the results for the 68 selected publications according to the above-mentioned review protocol. Results are categorized by their relationship with the research questions (RQ) presented in the methodology section. In particular, the first subsection shows general results that cannot be assigned to a specific RQ, the second subsection explores how cost dimension has been researched in the literature, the third subsection covers the use of costs jointly with other dimensions through a process perspective, and the fourth subsection discusses how this simultaneous analysis of costs and other dimensions has been carried out.

A. GENERAL RESULTS

The selected publications most frequently correspond to journal articles or theses, each with 24 publications (35.3%). The remaining correspond to conference papers (10, 14.7%), books (8, 11.8%), and book sections (2, 2.9%).

The time range of publications analyzed is between 1988 and 2022. As Fig. 2 shows, there has been a growing interest in cost analysis with a process perspective since 2000. It can also be observed that the greatest number of publications in a single year was in 2016 (9 publications), followed by the years 2015 and 2019 with 6 and 5 publications, respectively. Only 2 publications are prior to 2000 [20], [21].

In addition to the frequency of publications per year, the origin of the publications corresponding to the period described above was analyzed. Fig. 3 shows the number of publications by continent, where a high predominance of the European continent can be seen (29 publications; 43%). This analysis includes collaborations between different continents (multi-continent), where the most recurrent collaboration in the selected publications was between Europe and North America.

A continent-level analysis may be too general to detect trends. Therefore, Fig. 4 analyzes the origin of publications in greater detail, this time at country level. There are 3 countries that predominate in the number of publications: the United States (10 publications; 15.7%), Netherlands (8 publications; 11.8%) and Germany (8 publications). However, it can be seen that the largest number of publications was obtained from collaborations between two or more countries (12 publications; 17.6%), with the United States and Norway collaborating most frequently (3 publications; 4.4%).

In addition to the above, an interesting finding is observed when considering both publication year and continent of origin. Table 1 shows the number of publications that have had the participation of European researchers and those that have not, before and since 2018. Before this year, most publications had participation from European researchers (60%). However, since then, research has been mostly conducted by non-European researchers (55.6%). This shows that the international interest in cost analysis with a process perspective is growing.

TABLE 1. Number of publications, before and since 2018, with participation of European and non-European researchers.

Participation of European researchers	Before 2018	Since 2018
Yes	30 (60%)	8 (44.4%)
No	20 (40%)	10 (55.6%)

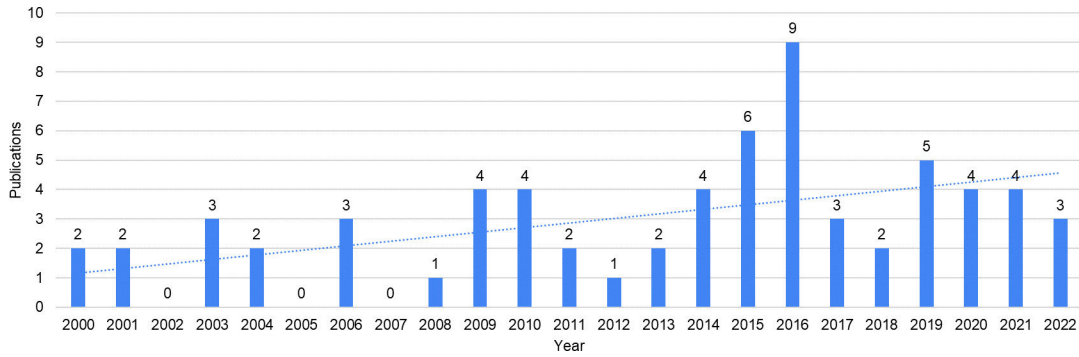


FIGURE 2. Number of publications per year from 2000 to 2022.

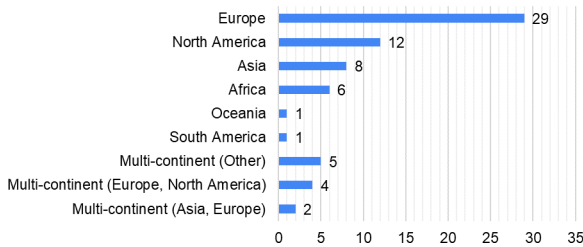


FIGURE 3. Number of publications per continent.

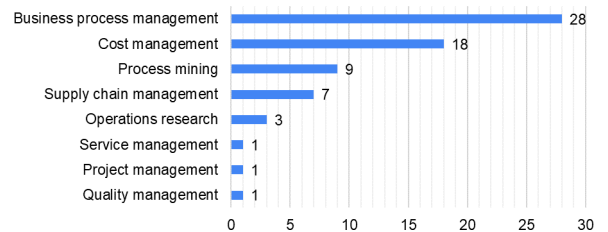


FIGURE 5. Number of publications per discipline.

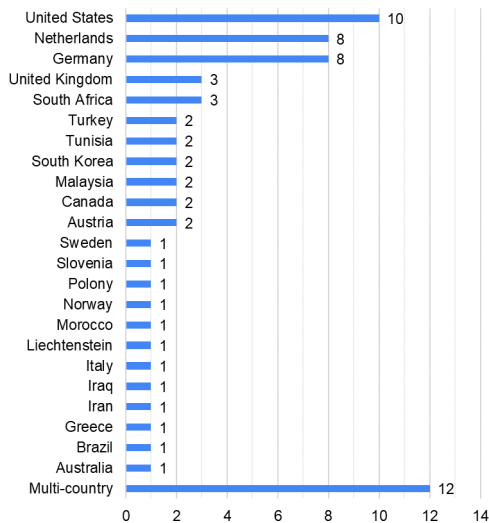


FIGURE 4. Number of publications per country.

B. COST DIMENSION ANALYSIS IN THE LITERATURE

The exploration of the cost dimension in the literature has been extensive, so the approach used to cover all publications was to group them into categories according to their characteristics. Namely, the research discipline and the target industry of the publication, the granularity of the proposed method, its application, and the results that were expected from it.

The selected publications were grouped into 8 disciplines. Fig. 5 shows these disciplines and their publication count, where over half (37 publications; 54,4%) of the publications

belong to the business process management and process mining disciplines. It can also be seen that about a quarter (18 publications; 26,5%) belong to cost management. Cost management is concerned with systems that provide information for costing out elements of interest for management, their planning, control and decision-making [22].

The analysis by industry provides great value to know where there is more experience in cost analysis with a process perspective. Fig. 6 shows the results for the industries identified in terms of number of publications. Most publications (45; 66,2%) focus either on manufacturing or no specific industry, while healthcare and banking, commerce and finances account for 17.6% of the results (12).

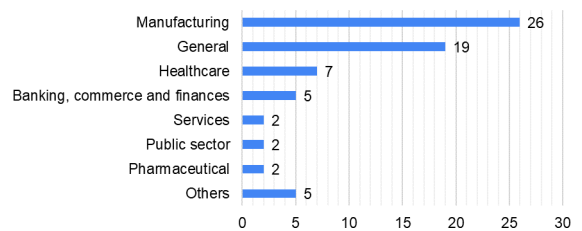


FIGURE 6. Number of publications per industry.

Regarding how frequent the analyses at the process or activity level are (see the classification strategy in the methodology section), Fig. 7 shows that most publications have adopted an activity level granularity (43 publications; 63%), while less frequently process level granularity was adopted (25 publications, 37%).

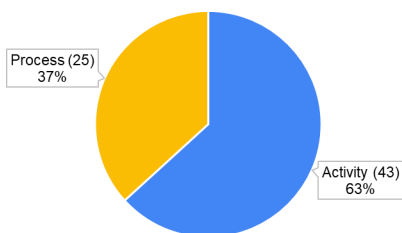


FIGURE 7. Number of publications per granularity.

Also, it is important to consider how the cost dimension analysis is applied in the context of the publications and where the data used comes from. The application cases are classified according to the classification strategy presented in the methodology section. Fig. 8 shows that nearly half (32) of the publications are applied in real case studies, nearly a third (21) utilize fictional data, and over a sixth (12) involve theoretical-only research. 3 publications simulate the data required for their proposal.

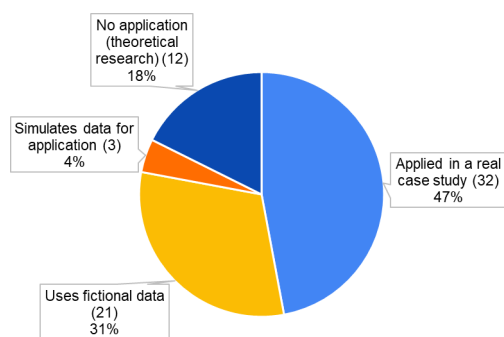


FIGURE 8. Number of publications per application.

Finally, the last category explored was the expected results from applying cost dimension in each publication. Fig. 9 summarizes the target results identified with their frequency of appearance in the publications. This provides relevant indicators to understand the application from a theoretical perspective, since more than half (46 publications) used the cost dimension to perform an analysis of an activity/process.

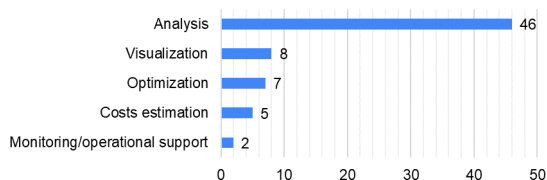


FIGURE 9. Number of publications per target results.

C. OTHER DIMENSIONS ANALYZED IN THE LITERATURE

In accordance with the review protocol outlined in the methodology section, publications with simultaneous analysis of the cost dimension with another dimension were of interest. The dimensions identified were: costs, time,

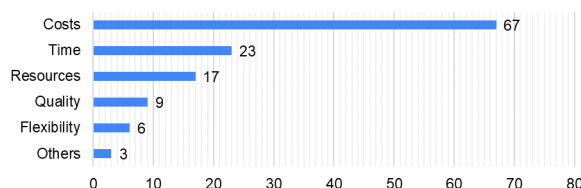


FIGURE 10. Number of publications per dimension.

resources, quality, flexibility, efficiency and productivity. Fig. 10 summarizes the frequency of occurrence of each dimension in the 68 publications included. It is important to note that there are four main dimensions analyzed together with costs: time (23), resources (16), quality (10) and flexibility (7).

Fig. 10 reports the dimensions independently from each other. However, the actual combinations that have been considered by the reviewed publications are also of interest. Table 2 presents the number of publications belonging to every combination of dimensions that has been observed. In line with the results shown in Fig. 10, most publications combine the cost dimension with the time dimension, but some publications also consider the resources dimension, or the quality and flexibility dimensions.

TABLE 2. Number of publications per combination of dimensions.

Dimensions	References	Publications
Only costs	[5], [6], [12], [13], [21], [23]–[45]	28
Costs & time	[20], [46]–[55]	11
Costs & resources	[56]–[66]	11
Costs & quality	[3], [67], [68]	3
Costs & flexibility	[69]	1
Costs & time & resources	[17], [70]–[74]	6
Costs & time & resources & quality & flexibility	[75]–[79]	5
Others	[80]–[82]	3

Both Fig. 10 and Table 2 group a number of dimensions under the label “others“. These correspond to 2 publications that utilized, jointly with the cost dimension, uncommon process dimensions (efficiency and productivity) and 1 publication which proposed a generic method that could be applied to any dimension, including costs.

One of the uncommon dimensions is efficiency, which was utilized jointly with cost and time dimensions to propose a parallel dimension visualization framework based on business process model notation (BPMN) [80]. The second uncommon dimension included in the literature is productivity, which was used in conjunction with the cost and quality dimensions to propose a multidimensional process improvement methodology for manufacturing systems through statistical process control (SPC) and activity-based costing (ABC) techniques [81]. Finally, in [82], a framework for predicting dynamic behavior based on an event log is proposed, where a dimension can be used as a dependent or

independent variable. Due to this behavior, it can be applied to most dimensions, being categorized as general.

D. METHODOLOGIES FOR JOINT ANALYSIS OF COSTS AND OTHER DIMENSIONS IN THE LITERATURE

In addition to the above categorizations, the selected publications were also categorized based on specific recurring characteristics that were observed in each of them.

Table 3 shows that over a third (25) of the publications annotate costs using a cost model. This consists of assigning costs to each activity, so that the sum of their costs represents the total cost of the process. A prime example of the use of this strategy is the one used in [5], which is a continuation of the earliest publication regarding the cost dimension [4]. In [5], costs are annotated in event logs for their later analysis, reporting and prediction.

The second most frequent category includes publications that use some costing strategy (20 publications). The most common is activity-Based costing (ABC) with 15 publications, which is a method for assigning costs to each activity of a process [30]. The second most common is time-driven activity-based costing (TD-ABC) with 3 publications. This costing strategy consists of incorporating the time required to complete each activity of a process into ABC [73]. And the third is resource consumption accounting (RCA) with 2 publications, which is a cost strategy that incorporates a dynamic accounting approach through a system that allows tracking expenses at the activity or process level [62].

It is important to mention that, on one hand, not all publications that utilize costing strategies belong to the cost management discipline. For example, in [46], a strategy that links the dimensions of time and cost with a focus on improving supply chain performance is proposed. This publication shows the application of activity-based costing under the discipline of business process management. On the other hand, there are also publications that belong to the cost management discipline, but do not use costing strategies. An example of this is in [54], where a cost-benefit analysis strategy that uses performance indicators to find the optimal benefit is proposed. Fig. 11 illustrates the above.

Table 3 also shows that over a fourth (18) of the publications propose performance indicators. These indicators allow the performance of a process to be analyzed by comparing ideal values with empirical values [76]. As an example, in [75], performance indicators to be used as a resource in the application of process mining within an emergency room are proposed.

The consideration of the devil’s quadrangle (DQ) for defining performance indicators was often observed. The DQ depicts the process performance according to four dimensions: time, cost, quality and flexibility [76], thus allowing to evaluate the process in a bounded way understanding the relationship between the four dimensions. Nearly a tenth (6) of the publications consider the devil’s quadrangle. Additionally, 5 of these publications also belong to the Performance Indicators category. Fig. 12 illustrates this.

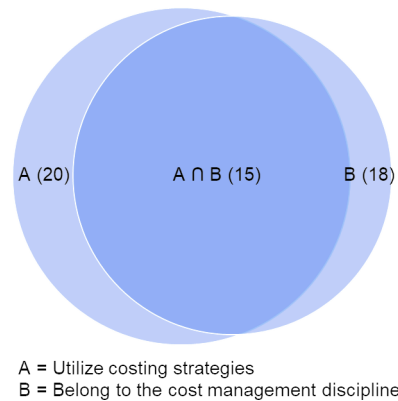


FIGURE 11. Relationship between publications that utilize costing strategies and publications that belong to the cost management discipline.

TABLE 3. Classification of publications by category.

Category	References	Publications
Annotate costs using a cost model	[3], [5], [6], [12], [13], [17], [23], [25], [27], [28], [31], [40]–[42], [46], [48], [49], [51], [53], [56], [59], [61], [63], [67], [71]	25 (37%)
Propose performance indicators	[20], [32], [34]–[36], [45], [50], [52], [54], [58], [65], [69], [72], [74]–[78]	18 (26%)
Utilize ABC	[21], [26], [29], [30], [37], [39], [43], [44], [46], [49], [57], [60], [63], [64], [66]	15 (22%)
Consider machine learning	[6], [12], [13], [17], [38], [68], [81], [82]	8 (12%)
Consider the devil’s quadrangle	[32], [75]–[79]	6 (9%)
Utilize TD-ABC	[20], [55], [73]	3 (4%)
Utilize RCA	[56], [62]	2 (3%)
Group costs by levels (high, medium, low, etc.)	[24], [80]	2 (3%)
No category	[33], [47], [70]	3 (4%)

The use of DQ is closely related to obtaining performance indicators, since it provides guidelines on which dimensions should be considered to measure the performance of a process. This can be seen in the same publication mentioned above [75], where the indicators obtained belong to the dimensions of the DQ.

However, the use of DQ in the publications analyzed is not limited only to the search for performance indicators. An example of this is in [79], where the DQ is used to perform a qualitative analysis of each of these dimensions for a given process. It can also be seen in Fig. 12 that there are 12 publications that do not consider the DQ for obtaining performance indicators. These publications consider indicators for different sets of dimensions, such as costs and resources [58], or only costs [34].

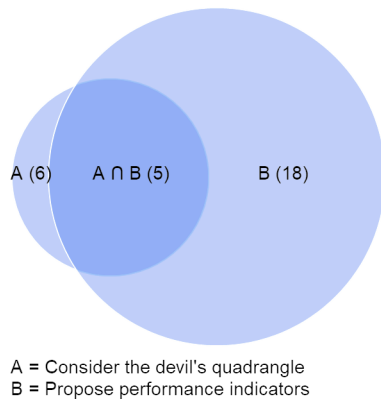


FIGURE 12. Relationship between “propose performance indicators” and “consider the devil’s quadrangle” categories.

Another category is that of publications that utilize machine learning techniques (8). These techniques have been used for tasks such as analyzing the effects of process dimensions over costs [6], [82], and cost-aware process improvement recommendations [17], [81].

An alternative category to include cost analysis with a process perspective is to group costs into several ranges. This is done by the authors of [24] and of [80]. In both publications, the followed procedure is similar, starting with a BPMN model, followed by a classification of costs (low, medium, or high). Then, the BPMN is modified according to the defined cost levels and conclusions are drawn from this. These publications mention that this analysis can be extended to other dimensions.

Lastly, Table 3 shows that there are 3 publications without a category: in [70], a methodology to find the optimal cost allocation through a colored petri net is proposed, in [47], a cost visualization strategy based on the graphical inclusion of costs in a process model is presented, and in [33], a reference process model to obtain the cost-benefit of an improvement process is built.

V. DISCUSSION

Having described the results of reviewing the 68 selected publications, it is possible to highlight several insights into the state of current research on cost-aware process analysis.

First, an increasing interest on the topic can be observed through the years, with a peak in 2015 and 2016. Although there was limited research during 2017 and 2018, the interest has resurfaced in subsequent years, with an average of 4 publications per year. Complementing the above, the fact that authors from non-European countries have started publishing more on this topic is a positive finding. This shows that the interest in analyzing costs through a process perspective in the international community has increased recently. However, only one publication from South America [69], and two from Oceania (one in collaboration with researchers from a European country) [5], [17] have been selected during this review, highlighting the need to further promote cost-aware research through a process perspective in these continents.

It is interesting to see that there has been collaborative research on several occasions between the two continents with the most selected publications, Europe and North America. Furthermore, having the United States as the leading country in terms of the number of publications is interesting, as Germany and the Netherlands are often the leading countries regarding participation in the BPM research area [83]. Conversely, although Australia is also considered within the leading countries in BPM [83], only two publications addressing costs from this country have been selected in the review [5], [17].

The high number of selected theses should also be highlighted. Their inclusion allowed the identification of 24 relevant publications that would not have been identified otherwise. Authors of theses regarding cost-aware process analysis should be encouraged to either publish their works as journal articles, or to submit them to related conferences, with the objective of increasing the awareness of the community regarding research on the topic.

The remainder of this section highlights insights regarding the three review questions. Limitations of this research are discussed subsequently.

A. CONTEXT AND APPLICATION - HOW HAS THE COST DIMENSION BEEN ANALYZED?

To address this question, findings that contextualize the application of the methods proposed by the selected publications are considered. Findings on the actual methods are addressed in the subsection addressing the third review question.

The first two insights are related to the search string defined for the review. On one hand, due to their inclusion in the search string, several publications from disciplines like operations research and service management were expected. However, only four publications from these two disciplines were selected. Particularly, further research on cost-aware operations Research should be considered, as several optimization techniques from this discipline, such as assignments, networking, and scheduling [84], could be used to model process costs jointly with other dimensions. On the other hand, although cost management was not included in the search string, a high number of publications from this discipline was selected. This is explained by the fact that most of the selected publications from this discipline make use of costing strategies that possess a process perspective, such as ABC, TD-ABC and RCA. Ideas from cost management could be leveraged to analyze costs through a process perspective. Namely, the capacity of the costing strategies to estimate future costs [22].

Regarding the industries covered by the selected publications, the prevalence of manufacturing (over 38% of publications) is highlighted. However, it is important to mention that publications from this industry were expected, as it was included in the search string, partly explaining the results. Considering that another 28% of publications did not consider a specific industry, there is a need to focus

cost-aware process research on other specific industries. Doing this could help to understand the suitability of the approaches that have been developed with a general perspective to answer the particularities of each industry, such as specific cost models or business rules.

While the aggregated trend of selected publications is to apply the proposed methods over real case studies (47%), interesting results are observed from analyzing these trends grouped by discipline. Table 4 shows the number of publications, per application type, for disciplines with more than 3 selected publications. This shows that the cost management discipline leans more often than other disciplines toward using fictional data (50%), whereas supply chain management leans more often toward theoretical research (43%). Similarly, process mining leans more often toward application over real case studies (56%). This last trend is highlighted, as applying the proposed methods over real case studies allows their applicability in real instances to be validated.

TABLE 4. Number of publications, per application type, for common disciplines.

Application	BPM	CM	PM	SCM
Applied in a real case study	12 (43%)	7 (39%)	5 (56%)	3 (43%)
Uses fictional data	8 (29%)	9 (50%)	3 (33%)	1 (14%)
Simulates data for application	2 (7%)	0 (0%)	1 (11%)	0 (0%)
No application (theoretical research)	6 (21%)	2 (11%)	0 (0%)	3 (43%)

Similarly, Table 5 shows the number of publications, per application type, for industries with more than 2 selected publications (including general - publications not related to a specific industry). When grouped this way, an interesting insight is that, when considering publications from the manufacturing, healthcare, and banking, commerce and finances industries, the trend of applying the methods over real case studies increases (62%, 71% and 60%, respectively). Conversely, the predominant use of fictional data gains among the publications not directed to specific industries (42%). The tendency for only theoretical research is also higher in this group (26%). The above results can be

TABLE 5. Number of publications, per application type, for common industries.

Application	Manufacturing	Healthcare	Banking, Commerce & Finances	General
Applied in a real case study	16 (62%)	5 (71%)	3 (60%)	5 (26%)
Uses fictional data	3 (12%)	2 (29%)	2 (40%)	8 (42%)
Simulates data for application	2 (8%)	0 (0%)	0 (0%)	1 (5%)
No application (theoretical research)	5 (19%)	0 (0%)	0 (0%)	5 (26%)

explained when considering that the application of the proposed methods in real case studies often implies a focus of the publication in a particular industry. Thus, most publications with real case studies were categorized under the case study's industry.

Finally, a concern regarding the target results of the selected publications arises, as most of the proposed methods focus on the analysis task. However, there is a need for methods concerned with tasks prior to the analysis task, such as designing visualizations to facilitating cost analysis, or defining cost estimations. Similarly, there should be further research on tasks after the analysis task, such as process optimization, monitoring, and operational support.

B. PROCESS DIMENSIONS - WHAT PROCESS DIMENSIONS HAVE BEEN CONSIDERED FOR THEIR JOINT ANALYSIS?

The answer to this question is straightforward, as the dimensions considered by the selected publications have been recorded and reported through the results section. Nevertheless, some insights can be observed.

First, due to the results of the preliminary review, publications regarding the analysis of the cost dimension, jointly with either the time and resource dimensions, were expected. However, several publications that also addressed the quality and flexibility dimensions were identified. Most of these publications highlight the utilization of the devil's quadrangle, as it involves the cost, time, quality and flexibility dimensions [85]. This, coupled with the two publications that consider the cost dimension jointly with less common process dimensions (efficiency, productivity) highlights the possibility of further researching the joint analysis of other dimensions through a cost-aware perspective.

Second, identifying a generic method that could be applied to distinct process dimensions [82] was interesting, as this indicates the potential of directing research toward the design of other generic methods that could be applied on any process dimensions of interest for the processes being analyzed.

C. METHODS - HOW HAS THE JOINT ANALYSIS BEEN CARRIED OUT?

This question concerns with insights obtained from the similarities observed on the methods proposed by the selected publications. It was possible to classify most methods based on recurrent similarities that were observed in several of them. This indicates that research has progressed in a way that connections between the methods can be observed, providing greater utility to practitioners.

In line with the above, the annotation of costs through cost models is highlighted, as it has become a best practice due to its widespread use throughout several of the selected publications, showing good results. This is due to cost models allowing to obtain the data required for analyzing costs in a straightforward and feasible way. Moreover, the use of

costing strategies for defining these cost models has also been a widespread strategy within the selected publications.

The utility of costing strategies is further illustrated when analyzed jointly with the granularity of the methods proposed by the selected publications. Specifically, 80% of the publications (16 out of 20) that utilize some costing strategy consider an activity-level granularity over a process-level granularity. This is desirable, and acquiring higher granularity data should be encouraged.

In contrast, the 6 publications that consider the DQ are concerned with a process-level granularity. This implies that the DQ is used for process analysis at higher abstractions than other methods. This is complemented with the high intersection between publications that consider the DQ and publications that propose performance indicators (see Fig. 12). This highlights the utility of the DQ for defining process-level indicators and analyses. Nevertheless, an interesting research direction would be to research the possibility of applying the DQ on higher abstraction levels.

Machine Learning is also highlighted, as techniques from this domain were utilized by some of the methods proposed by the selected publications. The utility of these techniques for identifying the reasons behind costs could become essential for analysts in the future. However, there is still room for further research in the utilization of techniques from this domain with a cost-aware process perspective. Particularly, the possibility of using machine learning techniques for cost-aware operational support is observed.

D. LIMITATIONS

The limitations of this work align with those that must be considered when performing SLR. First, regarding the search protocol, it is not possible to guarantee that all publications regarding the Cost dimension through a process perspective have been identified. However, the search protocol was defined with the objective of identifying as many of these publications as possible. Specifically, the utilization of multiple primary search sources, as well as Google Scholar as a complementary source, allowed obtaining publications that could otherwise not be identified due to their unavailability in some of the sources. Moreover, the realization of a preliminary search allowed the refinement of the utilized search string so that it would allow the identification of as many useful publications for the review as possible. Second, regarding the review protocol, it is important to consider the possibility of the existence of researcher bias [18]. To mitigate this bias, strategies such as the cross-review of selected publications and the inclusion of a third researcher who supervised the review were utilized.

VI. CONCLUSION

This paper synthesized the results of an extensive SLR on cost analysis and other dimensions in process mining and related disciplines. The purpose of this review was to find historical evidence on how the cost dimension has been investigated with a process perspective, seeking to discover what methods

have been used for its analysis and what other dimensions have been considered jointly with costs. This review was aimed at finding research opportunities to enhance the state-of-the-art of the cost dimension within process mining. This allowed observing the relevance of measuring performance through the joint analysis of costs and other dimensions.

This review sought to understand how much the cost dimension has been analyzed and how this has been done. It was identified that there is an increasing interest in this topic of study since 2018 in countries where there had not been many related publications. This allows us to deduce that there has been a growing international interest in studying cost analysis from a process perspective in recent years. Regarding how the cost dimension has been analyzed, it was identified that most methods relied on the utilization of cost annotation and costing strategies to acquire the cost data required to analyze processes. It was also observed that the utilization of performance indicators was a common strategy to support its analysis, which can be further complemented through the usage of the devil's quadrangle framework.

Initially, a predominance of publications belonging to the disciplines of operations research and service management was expected. However, they were finally surpassed in quantity by those belonging to the discipline of cost management, which is closely related to the recurrent use of costing strategies such as ABC, TD-ABC, and RCA. Therefore, the origin of the data used for each strategy is of interest, since costing strategies are characterized by the use of real data. In this context, it should be noted that for industry-specific research, mostly real data were used. This provides valuable information on which industries and disciplines present models that have been applied to real contexts.

Regarding the joint analysis of costs and other process dimensions, a high predominance of analyses limited to the dimensions of time and resources was expected. However, this contrasted positively with the actual results, as the frequent incorporation of the devil's quadrangle into the analyses showed that the quality and flexibility dimensions are often addressed as well.

Finally, the results of this SLR allow the direction that publications have taken in recent years regarding methods, disciplines, and industries that have been addressed to be identified. These results can be contrasted with the cost-aware business process management research agenda previously proposed in [86]. Based on this, some lines of future work can be proposed.

- **Associating cost with business processes:** cost annotation through the use of cost models has been the predominant strategy for associating costs with business processes. This aligns with the expectations of the authors of [86]. Several publications have made use of this strategy, which indicates a certain maturity regarding this research line. However, the particularities of industries that have not been often researched (e.g., the public sector) should be taken into consideration when conducting cost-aware process research.

- **Enriching process design with cost information:** some of the selected publications address cost visualization through process models. However, there is a need to research additional methods that align with the particularities of the cost dimension and with the needs of practitioners. Namely, there is a challenge regarding the visualization of cost decomposition (e.g., fixed and variable costs), and the facilitation of the comparison of costs in distinct process variants.
- **A cost-aware process execution environment:** the need for a cost-aware execution environment can be related to the need for analysis methods that demonstrate the utility of cost-awareness in processes. Several of the selected publications propose guidelines for the analysis of the cost dimension. However, most methods focus on individually analyzing the considered dimensions. Further researching strategies that allow a joint analysis of costs and other dimensions of interest (e.g., costs and flexibility, or costs, time, and resources simultaneously) would facilitate the adoption of cost-aware process execution environments. As an example, studying how higher granularity levels can be considered for the devil's quadrangle would be valuable, as it inherently allows the comparison of several process dimensions.
- **Cost-aware operational support:** the results of this SLR do not indicate that there has been much research regarding cost-aware operational support. However, the utilization of machine learning techniques in some of the publications shows the potential of utilizing techniques from this domain for cost-aware operational support and process monitoring. Further reviewing the literature, with a focus on the utilization of machine learning techniques for prediction and recommendation in a process context, is considered.
- **Process-driven cost reporting and forecasting:** there is maturity in this research line as up-to-date research has focused on analyzing costs through the analysis of reports. Enriching process design with cost information and a cost-aware process execution environment should be prioritized by researchers. Nevertheless, similarly to the cost-aware operational support research line, room for further research in the use of machine learning techniques for cost forecasting is observed.

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