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REVIEW PAPERS

A review on the applications of Bayesian network in web service

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Abstract Web services (WS) are the preferred approach in realizing the service-oriented computing paradigm. However, this comes with challenges such as complexity and uncertainty that hinder their practical application. Bayesian networks (BNs) are one of the techniques used to address these challenges. The objective of this mapping study was to determine what is known about the use of Bayesian networks in web services research. To do this, we identified and selected rigorously 69 articles (out of the 532 identified) published on the subject in 2001–2021. We then classified and analyzed these articles by **Web service themes** (Service Composition, Service Management, Service Engineering), **Objectives** (Description, Prediction, Prescription), **Types of BN** (Basic, Combined, Extended), and **Evaluation methods** (Proof of concept, Experiment, No evaluation). In doing so, we hope to provide a clear understanding of the subject. We also identify and suggest avenues for future research. Thus, the review results can help researchers and practitioners interested by the application of BNs in WS research.

Keywords Web service · Bayesian network · Service computing · Mapping study

1 Introduction

Web services (WS) have revolutionized software development practices. Defined as "software components that were self-described, loosely coupled, and easily integrated with one another" (Driss et al. 2022), WS are present in practically all fields (Bouguettaya et al. 2017; Zhao et al. 2022). This success is fueled, among other things, by the possibilities offered by WS in terms of cost reduction, ease of reuse and operational efficiency (Papazoglou et al. 2008; Zhao et al. 2022). However, the dynamic and unpredictable nature of WS (Papazoglou et al. 2008) leads to various problems, including complexity and uncertainty (Alférez and Pelechano 2013; Gabarró and Stewart 2021). All things that make their implementation difficult in practice. Structurally, a WS is a complex system based on various technologies (Tokmak et al. 2024) including Extended Markup Language (XML); Simple Object Access Protocol (SOAP); Universal Description, Discovery, and Integration (UDDI); Web Services Description Language (WSDL), to name just a few. So, developing a WS comes down to assembling the “right” technologies that meet the requirements of a situation. And the lack of clear information about these technologies and how to integrate them can cause uncertainty. This complexity and the uncertainty it induces are even more exacerbated when it comes to composing WS. Indeed, several factors must be considered: (i) the composition process itself, which is not something pre-determined, but depends on the characteristics (thus on the uncertainty) of the problem context; (ii) the choice from a multitude and diverse WS which offer more or less the same functionality (Razian et al. 2022 ; Zeyneb Yasmina et al. 2022); (iii) the targeted deployment environment which is dynamic and uncertain because of the fluctuation of network and server performances (Papazoglou et al. 2008). In other words, the composition of WS can be seen as a multi objective optimization problem (Azouz and Boughaci 2023; Ju et al. 2023).

One of the ways to address these issues is the use of machine learning (ML) techniques (e.g., Purohit and Kumar 2021; Razian et al. 2022; Song 2021). According

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to Guerra-Montenegro et al. (2021), ML techniques have two functions: modeling and optimization. "ML modeling refers to the discovery of relationships between data inputs and outputs. In the other hand, ML optimization is focused on finding which inputs are maximizing or minimizing the output of a ML model." (Guerra-Montenegro et al. 2021, p. 3). In the case of ML optimization, we can cite the nature inspired techniques (e.g., Abualigah et al. 2023; Agushaka et al. 2022, 2023; Ezugwu et al. 2022; Hu et al. 2023; Zare et al. 2023). This paper focuses on Bayesian Networks (BNs), a ML modeling technique, specifically adapted to complex and uncertain situations (Rohmer 2020).

Since their introduction in the 1980s (Pearl 1986), BNs have become very popular as evidenced by the large number of fields where they are used (e.g., Bielza and Larrañaga 2014; Chen et al. 2021; Hosseini and Ivanov 2020; Kyrimi et al. 2021; Rosário et al. 2022; Xu et al. 2022, 2023). This success is maintained despite the decades and the emergence of equally popular techniques such as the Artificial Neural Network (ANN), Support Vector Machine (SVM) or Deep Learning (DL). Indeed, compared to these techniques, BNs have certain advantages that make them unique (Correa et al. 2009; Hosseini and Ivanov 2020; Kazem et al. 2015; Malekmohamadi et al. 2011; Müller et al. 2020; Weber et al. 2012). For example, with BNs, incomplete data or data of various kinds from WS, especially during their composition, can be integrated into the same model (Kaya et al. 2023; Larrañaga and Moral 2011; Weber et al. 2012; Rohmer 2020; Xu et al. 2023). In addition, the structure of this model allows to clearly distinguish the links between its elements (Larrañaga and Moral 2011). Finally, the use of the model gives explainable results (Lacave and Diez 2002; Müller et al. 2020), responding at the same time to the requirement of a predictable and responsible Artificial Intelligence (Kitson et al. 2023; Mauro et al. 2023). These properties make BNs a natural choice in fields such as WS (Hwang et al. 2007).

Furthermore, several literature reviews on the use of ML techniques in WS research are published (e.g., Batra and Bawa 2010; Ekie et al. 2021; Purohit and Kumar 2021; Rodríguez et al. 2016; She et al. 2019). But, to our knowledge, none of these reviews is devoted to BNs. In other words, we have little information on the contexts, motivations, execution, and effects of application of BNs in WS. This lack of information prevents interested researchers and practitioners from fully exploiting the capabilities of BNs. It is therefore crucial to systematically examine the literature on the subject. The intention is to improve the understanding of how BNs are actually applied to address the previously mentioned problems of WS complexity and uncertainty.

The purpose of this research is to contribute to this understanding. Accordingly, we carried out a mapping study of 69 articles published during the period 2001–2021 in order to:

- Describe the general profile of this literature (years, types, and countries of publication);
- Determine the conditions of application of BNs based on a classification framework with four dimensions: (i) WS themes, (ii) objectives, (iii) types of BN, and (iv) evaluation methods;
- Identify and propose avenues for future research based on this analysis.

The rest of this paper is organized as follows. The basic concepts are briefly defined in Sect. 2. Section 3 describes the methods of the review, the results of which are presented discussed in Sects. 4–9. Section 10 concludes the paper.

2 Background

2.1 Web service

Before defining web service, we clarify fundamental notions such as *Service-oriented computing* (Service computing), *Service Oriented Architecture*, and *Service*.

Service computing or service-oriented computing (SOC) is a paradigm that "seeks to transform physical, hardware and software assets into a paradigm in which users and assets establish on-demand interactions, binding resources and operations, providing an abstraction layer that shifts the focus from infrastructure and operations to services." (Bouguettaya et al. 2017, pp. 64–65). In simpler terms, SOC is "… the computing paradigm that utilizes services as fundamental elements for developing applications." (Papazoglou and Georgakopoulos 2003, p. 24). To concretely translate SOC principles, one can use a Service Oriented Architecture.

Service Oriented Architecture (SOA) is "a means of structuring and reorganizing distributed software applications into a set of composed and interactive pre-existing services." (Driss et al. 2022). In this architecture, services reuse and service composition are used as software design methods (Wu et al. 2015). As we can see, the notion of service is at the heart of this paradigm.

Service is "… self-describing, open components that support rapid, low-cost composition of distributed applications." (Papazoglou and Georgakopoulos 2003, p. 26).

Finally, based on these precisions, we can define a **Web service (WS)** as an application developed and deployed on the Web according to the principles of SOC.

In addition to these high-level technologies, there are several essential concepts around WS. These notions are clearly summarized as follows: "… three key features of services are crucial: functionality, behavior, and quality. **Functionality** is specified by the operations offered by a service; **Behavior** reflects how the service operations can be invoked and

is decided by the dependency constraints between service operations; **Quality** determines the non-functional properties of a service." (Bouguettaya et al. 2017, p. 70). In particular, non-functional properties are defined in the form of parameters (Hwang et al. 2007; She et al. 2019) which can be grouped into three categories (Driss et al. 2022): Quality of Service (QoS), Quality of Experience (QoE), and Quality of Business (QoBiz). **QoS** is "a set of parameters describing the behavior of Web services in terms of performance parameters." (Driss et al. 2022). Among these parameters, we can cite accessibility, availability, reliability, response time, robustness, scalability (Driss et al. 2022; She et al. 2019; Yu et al. 2008). **QoE** is "a measure of the end-to-end performance of a whole system as both resulting and taken from the user's point of view." (Driss et al. 2022). These parameters can be friendliness, success rate, and reputation. Finally, **QoBiz** aims to "describe the financial aspects of service provisioning, such as the price of service, the costs of service provisioning, the service provisioning revenue, and the revenue per transaction (comprised of cost per transaction) parameters." (Driss et al. 2022).

2.2 Bayesian network

Formally, a BN = (***G***, ***P***) is composed of two parts (Kaya and Yet 2019; Rohmer 2020; Xu et al. 2022): a qualitative part or Structure (***G***) and a quantitative part or Parameters (***P***).

The qualitative part (***G***) is a directed acyclic graph (DAG) made up of a set of nodes X_1, X_2, …, X_n (i.e., the states of the random variables of the studied problem) and arcs between these nodes (i.e., the probabilistic dependency/causal relationship between these nodes). For example, a directed arc from X node to Y node means that Y is a *descendant* of X, and X is the *parent* of Y. Each node has a state represented in values (discrete or continuous) that come either from data (real or synthetic) or from expert knowledge or from the combination of both.

As for the quantitative part (***P***), it is composed by the cause-effect relations of nodes that are represented in tables called Conditional Probability Tables (CPTs) in the case of a BN with discrete nodes. Specifically, the uncertainty of the cause-effect relations is determined by the conditional probability distributions $P(x_i|Pa(x_i))$ associated with each node x_i, where $Pa(x_i)$ is the parent set of x_i. Then, under a conditional independence assumption (i.e., each variable is conditionally independent of its non-descendants given its parents), the elements of the CPT of $X = (x_1 \ldots, x_n)$ can be determined by:

$$P(x_1 \ldots, x_n) = \prod_{1}^{n} P(x_i|Pa(x_i))$$

In summary, building a BN therefore comes down to determining its qualitative and quantitative parts (Kaya and Yet 2019). Moreover, it is important to mention that the more complex the structure of the BN is (e.g., a large number of nodes), the more difficult is the determination of the elements of the CPTs. Several solutions to alleviate these problems are suggested in the literature (e.g., Rohmer 2020).

Finally, once developed, BN can be used to perform two types of inference (Hosseini and Ivanov 2020): (i) forward inference (cause to effect propagation), i.e., determine the effects of a phenomenon by considering its causes, and (ii) backward inference (effect to cause propagation), i.e., explain the causes of a phenomenon by analyzing its results.

3 Methods

Due to the exploratory nature of this research, we chose to use the mapping study method (Petersen et al. 2015). A mapping study allows to identify, classify thematically, and describe the articles devoted to a given subject. Its purpose is to provide an overview of this subject by determining its nature, evolution, and limits (Petersen et al. 2015). The remainder of this section is organized into the following phases based on (Petersen et al. 2015): (i) Questions definition, (ii) Article identification, (iii) Article selection, and (iv) Article classification.

3.1 Questions definition

Our objective is to provide a snapshot of the published research work on the application of BNs in WS. To do this, we organized the review around the following research questions:

- **RQ1**. What web service themes are addressed by the application of bayesian network?
- **RQ2**. What objectives are pursued when applying bayesian network in web services?
- **RQ3**. What types of bayesian network are frequently applied in web services?
- **RQ4**. What methods are used to evaluate the proposed bayesian network models?

The intent of question RQ1 is to determine which aspects of WS are explored through the use of BNs. With question RQ2, the goal is to identify the reasons that motivate the use of BNs to respond to the problems identified in RQ1. Question RQ3 aims to specify which types of BNs are actually implemented to answer question RQ2. Finally, question RQ4 characterizes how the performance of the BN models used is measured.

3.2 Article identification

For searches, we used ACM Digital Library (http://dl.acm.org), Google Scholar (https://scholar.google.com/), and IEEE Xplore (http://ieeexplore.ieee.org). These tools index the main publications on the subject at hand and have been used in similar reviews (e.g., Di Francesco et al. 2019; Rodríguez et al. 2016; She et al. 2019). In particular, we combined two groups of search expressions. The first group refers to terms related to the "web service" and the second to the "bayesian network" (see Table 1).

The searches (done on September 27, 2022) produced 523 articles which were saved in EndNote X.9 (Thomson Reuters, Philadelphia, USA). After removing duplicates, the remaining 384 articles were submitted for selection.

3.3 Article selection

In addition to the constraints introduced in the search, each article had to meet the following criteria to be **selected**:

i. Published in English;
ii. Published in refereed journals, international conferences (congresses), or workshops;
iii. Published after 1999. This choice allows us to cover the most recent articles;
iv. Focused on BNs application in WS.

This implies that are **excluded**:

i. No peer reviewed publications (e.g., Research reports, dissertations or theses, books and book chapters, preprints, working papers), editorials, opinion pieces, commentaries, reviews, etc.;
ii. Articles not available in full text;
iii. Conference papers subsequently published in a journal.

These criteria were used to select articles in two stages. First, the examination of the title and the abstract of the articles allows to select 156 articles. Then, the full text of these 156 articles was read to determine their relevance. At the end of this process, 69 articles were selected and classified.

3.4 Article classification

3.4.1 Defining the classification scheme

To structure and facilitate the classification of the papers, we developed a scheme (Fig. 1) based on the questions of the review. The details of this scheme are presented in the rest of this sub-section.

Web service themes. Based on (Li et al. 2021; Papazoglou et al. 2008) and by iteratively analysing main focus of the selected papers, we identified three broad WS themes, namely Service composition, Service engineering, and Service management.

i. **Service composition.** It "consists of collecting and assembling autonomous Web services to achieve new functionalities by creating complex, value-added service-based applications." (Driss et al. 2022);
ii. **Service engineering.** Also named Service design and development (Papazoglou et al. 2008), it consists to "Managing the entire services lifecycle—including identifying, designing, developing, deploying, finding, applying, evolving, and maintaining services." (Papazoglou and Van den Heuvel 2006);
iii. **Service management**. "Web service management refers to the control and monitoring of Web service qualities and usage." (Yu et al. 2008, p. 545). These control and monitoring are made during the execution of the WS (Papazoglou et al. 2008).

Research objectives. Based on (Mishra et al. 2023) and the objective of the selected papers, we categorize the

Table 1 Article identification (2022-09-27)

Source	Description	Results
ACM Digital Library	("web based service" OR "web based services" OR "web-based service" OR "web-based services" OR "web service" OR "web services") AND (("bayes net*" OR "bayes network*" OR "bayesian net*" OR "bayesian network*" OR "bayesian probabilistic model*" OR "belief net*" OR "belief network*" OR "causal net*" OR "causal network*" OR "probabilistic net*" OR "probabilistic network*") AND NOT ("deep belief" OR "deep learning" OR "meta-analysis" OR "naive bayes*"))	159
Google Scholar	intitle:["web service|services" "bayes|bayesian|belief|causal|probabilistic net|nets|network|networks"] -deep -"meta analysis" -naive	299
IEEE Xplore	("web based service" OR "web based services" OR "web-based service" OR "web-based services" OR "web service" OR "web services") AND (("bayes net*" OR "bayesian net*" OR "bayesian probabilistic model" OR "belief net*" OR "causal net*" OR "probabilistic net*") AND NOT ("deep belief" OR "deep learning" OR "meta-analysis" OR "naive bayes*"))	74
Total		532

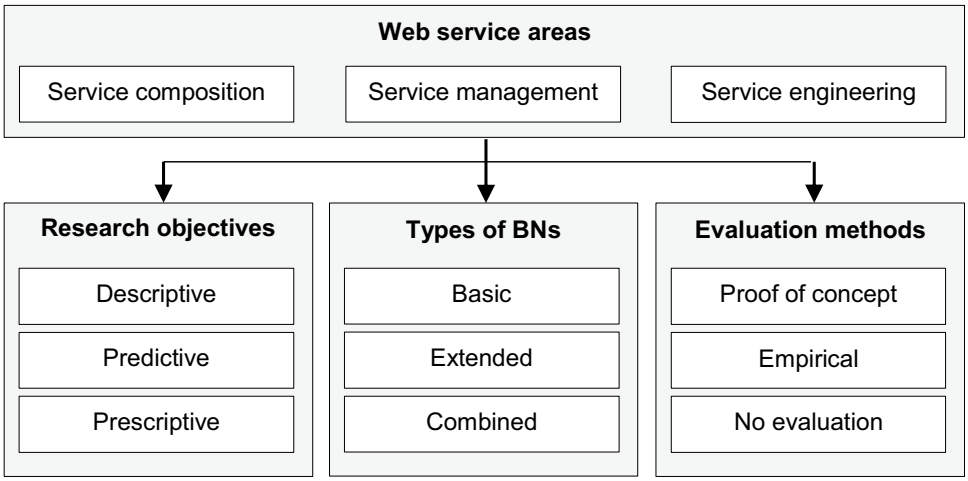

Fig. 1 Classification scheme

reasons for using BNs in WS as descriptive (exploratory), predictive, or prescriptive.

i. **Descriptive objective.** Characterize (classify, explain, model, represent, or understand) WS or its elements by using BNs;
ii. **Predictive objective.** Appraise (assess, calculate, estimate, evaluate, forecast, measure, predict, prognosis, sizing) state of WS or its elements by using BNs;
iii. **Prescriptive objective.** Using the results of the description and the prediction to define or propose a normative approach (framework, method, platform, or procedure) that favorize the use of WS.

Types of BN. In this review, we distinguished the following types of BNs (e.g., Larrañaga and Moral 2011; Marcot and Penman 2019; Weber et al. 2012):

i. **Basic.** Concerns the standard form of BNs in which data contains only discrete variables;
ii. **Extended.** More elaborated forms of BNs such as dynamic BNs, hierarchical BNs, object-oriented BNs, relational BNs, etc. This type of BN also concerns those that contain (i) both continuous and discrete variables (Hybrid BN), (ii) only continuous variables (Continuous BN); and
iii. **Combined.** Joint use of BNs with other techniques such as AHP, Fuzzy logic, Neural network, simulation, etc.

Evaluation methods. This aspect concerns methods used to evaluate the performance of the BN models. In this review, we consider the following groups of methods:

i. **Proof of concept.** Concerns papers that evaluate the performance of their BN model by example/demonstration/illustration/proof of concept;
ii. **Empirical.** Groups papers that use empirical methods (e.g., experiments, simulation, survey) to evaluate their BN model; and
iii. **No evaluation.** Refers to papers that do not evaluate their BN model.

Note that the different categories are not all mutually exclusive.

3.4.2 Classification process

We manually classified the selected articles based on the defined classification scheme. The entire process was organized according to the following rules:

i. During the classification, we reviewed the entire text of each article to ensure that the assigned categories reflected its content;
ii. In general, an article was classified into a single category, i.e., the one that most corresponds to the intention of its authors;
iii. When in doubt, we sought the opinion of another researcher.

Once all the articles were classified, we produced summary tables and figures to answer the review questions (Sects. 4–9). But, before getting there, the limitations of the review are presented.

3.5 Limitations

Like any research, our review has limitations. These relate in particular to the identification, selection, and classification

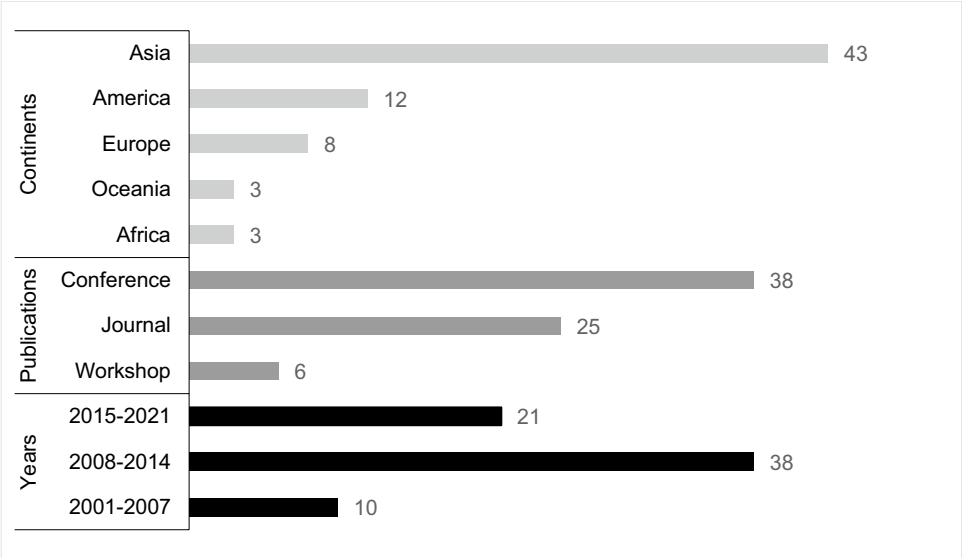

Fig. 2 Distribution of papers by years, publication types, and continents

Table 2 Top publication venues (minimum 2 papers)

Venue name	Type	Number
International Conference on Web Services	Conference	6
International Conference on Services Computing	Conference	3
Expert Systems with Applications	Journal	2
International Conference on e-Business Engineering	Conference	2
International Congress on Advanced Applied Informatics	Conference	2

of articles. With regard to the identification of articles, it may be that, despite all the rigor we have put into developing them, our search expressions are limited. And, as a result, some relevant articles were not found. However, the number and diversity of the articles finally included in the review ensure that the subject is well represented. As for the selection of articles, we probably eliminated a few by mistake. To reduce this problem, we defined, a priori, eligibility criteria that we applied as rigorously as possible. Finally, when it comes to the classification of articles, another researcher may not obtain exactly the same results as us. Nevertheless, we have defined and used a classification framework whose categories come from both the literature on the subject and the selected articles. We hope that these categories are sufficiently clear and high level to facilitate the reproduction of the classification.

4 Overview of the selected papers

The profile and evolution of the selected literature was determined by examining its (i) years of publication, (ii) types of publication, and (iii) geographical distribution (see Table 8 in Appendix for details). Figure 2 presents the results of this analysis, the details of which are described in the following subsections.

4.1 Results

Publication years. As shown in Fig. 2, the 69 selected papers are published between 2001 and 2021. By grouping them into 3 periods of 7 years (2001–2007, 2008–2014, and 2015–2021), we see a double fluctuation in their number. First of all, it should be noted that only 10 papers were published over the period 2001–2007. Then, between 2001–2007 and 2008–2014, we observe a drastic increase in the number of papers which goes from 10 to 38, i.e., nearly 4 times the starting number. However, the following period (2015–2021) is characterized by a decrease in the number of papers, which goes from 38 to 21.

Publication types and venues. In terms of publication types, Fig. 2 shows that 55% of the papers come from conferences, 36% from journals, and 9% from workshops. According to Table 2, one journal and four conferences published more than one paper. Most publications (78%) are limited to one paper each. Note that the journal Expert Systems with WS, the International Conference on Web Services and the International Conference on Services Computing are among the best in their respective fields.

Table 3 Papers on Web service themes and sub-themes ($N=69$)

Theme	Papers
Service composition (31 papers)	
Service selection	[P04, P09, P17, P55, P56, P57, P58, P59, P60, P61, P62, P63, P64, P65, P66, P67, P68]
Service discovery	[P01, P02, P03, P05, P06, P07, P08, P10, P69]
Service recommendation	[P50, P51, P52, P53, P54]
Service management (23 papers)	
Service control	[P23, P28, P29, P31, P32, P34, P36, P38, P39, P40, P43, P44]
Service monitoring	[P30, P33, P35, P37, P41, P42, P45, P46, P47, P48, P49]
Service engineering (15 papers)	
Service development	[P11, P12, P14, P16, P18, P19, P24, P25, P27]
Service application	[P13, P15, P20, P21, P22, P26]

Geographical distribution. Geographically (i.e., the country of affiliation of the main author of each paper), Fig. 2 shows that Asia, with 62% of papers, largely dominates the list of continents that publish on the subject. The Americas and Europe follow by far with 17 and 13% of papers respectively. Finally, Africa and Oceania bring up the rear with 4% of papers each. When examining the papers in detail, we identify that the 69 papers originate from 19 countries. China (28 papers), followed by India (8 papers) and the USA (8 papers) are the three countries that contribute the most to the subject.

4.2 Summary

From a bibliographic point of view, the results reveal that the 69 included papers (i) are published mainly in conferences; (ii) increased sharply in number between 2001–2007 and 2008–2014; and (iii) have authors predominantly from Asia (particularly China).

5 Web service themes (RQ1)

The thematic classification of the 69 papers (Table 3) shows that *Service composition* comes first (45% of papers), followed by *Service management* (33%), and *Service engineering* (22%).

5.1 Results

In this section, the different sub-themes are defined as well as a description of the papers they group together.

5.1.1 Service composition

Table 3 shows the distribution of the 31 papers of this theme according to the three sub-themes. The majority of papers (55%) concerns the *Service selection* sub-theme. Next comes the Service discovery sub-theme (29%), which represents just over half of the papers included in the *Service selection*. Finally, the *Service recommendation* sub-theme (16%), accounts for less than a third of the papers included in the *Service selection*. Detailed information on these sub-themes is available in the appendix (Table 9).

Service selection consists of "Choosing the most adequate service among discovered candidates, according to functional or non-functional properties" (Huf and Siqueira 2019). According to our results, the 17 papers of this sub-theme propose BN models based on non-functional requirements such as **QoS** (12 papers) and **QoE** (5 papers). For QoS, 8 papers explore QoS in general (P04, P09, P17, P55, P58, P63, P64, P68). The other 4 relate to specific QoS parameters such as *Service organization* (P67), *Data quality* (P59), *Response time* (P65) or Performance (P66). Regarding QoE, the papers explore *Trust* (P57, P60, P61, P62) and *Trust and reputation* (P56).

Service discovery aims to “Locating relevant services that offer some desired data or functionality” (Huf and Siqueira 2019). In general, three approaches are used for Service discovery: *Syntactic-aware*, *Semantic-aware*, and *Context-aware* (Huang and Zhao 2022; Rodríguez et al. 2016). According to the results, 7 of the 9 papers of this sub-theme use BN models based on the *Semantic-aware* approach (P01, P02, P03, P06, P07, P10, P69). The other 2 papers deal with BN models based on the *Context-aware* approach (P05, P08). In particular, in the paper (P07), the authors used the *Semantic-aware* mode to explore QoS ("Quality as functionality"). No paper used the *Syntactic-aware* approach.

Service recommendation refers to “… the process of automatically identifying the usefulness of services and proactively recommending services to end users.” (Yao et al. 2015, p. 453). In particular, this can facilitate the service composition (Wu et al. 2015). Examination of the papers of this sub-theme suggests that, in general, the Service recommendation is a support task. Thus, the five papers included

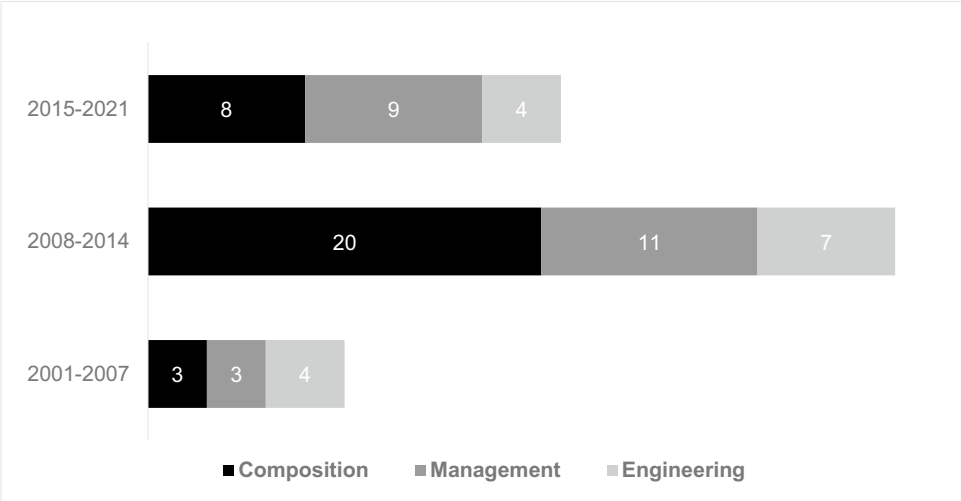

Fig. 3 Papers on Web service themes by years

in this sub-theme use the recommendation to support *Service discovery* (P50, P51) and *Service selection* (P52, P53, P54). Note that all papers are based on the "QoS-aware recommendation method" (Li et al. 2021).

5.1.2 Service management

According to the Table 3, the 23 papers of this theme are subdivided almost equally in two sub-themes: *Service control* (52%), and *Service monitoring* (48%). Detailed information on these sub-themes is available in the appendix (Table 10).

Service control aims to "… improve the service quality through a set of control mechanisms (e.g., transaction, change management, and optimization)." (Yu et al. 2008, p. 538). The results indicate that 9 of the 12 papers in this sub-theme are dedicated to *exception detection tasks* (P36, P38), *diagnosis of faults* (P23, P28, P32, P34, P44) or the *root cause of problems* (P29, P31). The other 3 papers focus on optimizing the *performance* (P40), *reliability* (P43) and *workflow* (P39) of WS.

Service monitoring consists of "… calculating the QoWS (*Quality of WS*) parameter values or assessing a Web service claim in terms of promised QoWS" (Yu et al. 2008, p. 538). Among the 11 papers included in this sub-theme, 6 relate to the *evaluation* of reliability (P35, P41, P45, P47, P48) and QoS (P46). Four other papers concern *monitoring* of the change (P37) and the performance (P30, P33, P42). Finally, a paper concerns the *process* of the WS (P49).

5.1.3 Service engineering

Table 3 shows that of the 15 papers of this theme, 60% are devoted to *Service development*, and 40% to *Service application*. Detailed information on these sub-themes is available in the appendix (Table 11).

Service development concerns the design and development of WS. The papers of this sub-theme relate to a prototype of WS to support the daily life (P25) or tourism services (P11). Others focus on web-based online data (dependency) analysis tool (P12), diagnosis service (P18), an ontology-based WS (P19) or WS API which computes learners' competence and capability assessment (P24). Finally, others explore the field of the supply chain (P14, P16) and an intelligent WS (P27).

Service application refers to the use of BNs to examine existing WS integrated in frameworks, prototypes, tools, etc. In a prototype called "whereabouts diary", a white-pages WS are used to extract information about places visited by users and BNs to classify places (P13). In (P15), an intelligent system based on spatial WS (GIS functions) to provide personalized recommendations for tourist attractions is proposed. In the (P20), a geospatial WS is integrated into Enterprise Business System. Furthermore, a diagnostic functionality is exposed through a web API in (P21), and in (P22), an interactive recommender system based on a WS, is used to manage patient information. Finally, in (P26), the authors used BNs to analyze the sensitivity of a prototype of WS.

5.2 Summary

In response to question **RQ1** ("What web service themes are addressed by the application of Bayesian network?"), the review reveals the predominance of the Service composition (Fig. 3). This is hardly surprising considering that service composition is the "raison d'être" of the SOC paradigm (Papazoglou et al. 2008). Recent studies clearly reflect this trend (e.g., Agarwal et al. 2022; Huf and Siqueira 2019; Razian et al. 2022; Zhao et al. 2022). Moreover, the review indicates that, of the three elements (Functionality, Behavior, and Quality) considered fundamental for WS (Bouguettaya et al. 2017), it is the Quality which is mainly studied with the BNs. Among the 69 analyzed papers, 33 (48%) deal with one aspect or another of Quality

Table 4 Papers on Research objectives by web service themes ($N=69$)

Theme	Research objective		
	Descriptive	Predictive	Prescriptive
Service composition (31 papers)			
Service selection	[P04, P60, P62, P64, P67]	[P09, P17, P55, P56, P58, P59, P61, P63, P65, P66, P68]	[P57]
Service discovery	[P03, P06, P07, P10, P69]	[P08]	[P01, P02, P05]
Service recommendation	–	[P50, P51, P52, P53]	[P54]
Service management (23 papers)			
Service control	[P23, P28]	[P39, P40, P43]	[P29, P31, P32, P34, P38, P36, P44]
Service monitoring	–	[P33, P35, P42, P45, P46, P48, P49]	[P30, P37, P41, P47]
Service engineering (15 papers)			
Service development	[P11, P14, P18, P25]	[P12, P16, P24, P27]	[P19]
Service application	[P13, P21, P22]	[P15, P26]	[P20]

(22 papers on Service composition, and 11 on Service management). Based on these observations, we suggest that researchers pay more attention to the Functionality and Behavior of WS when they plan to study BNs. Finally, regarding the sub-theme *Service recommendtion*, the results show that no paper mentions the type of recommendation approach used. Therefore, it would be important to explore how recommendation approaches (e.g., collaborative filtering, content-based and hybrid) may be used in concert with BNs in a WS context.

6 Research objectives (RQ2)

This section is devoted to the results of the classification of the selected papers according to the Research objectives organized by WS theme.

6.1 Results

Service composition. According to Table 4, 52% (16/31) of papers of this theme have a Predictive objective (P08, P09, P17, P50, P51, P52, P53, P55, P56, P58, P59, P61, P63, P65, P66, P68), 32% (10/31) a Descriptive objective (P03, P04, P06, P07, P10, P60, P62, P64, P67, P69) and 16% (5/31) a Prescriptive objective (P01, P02, P57, P05, P54). In these last cases, the prescription takes the form of *Approach* (P01, P02, P57), *Framework* (P05) and *Method* (P54). More specifically, the Descriptive objective mainly concerns the Service selection and Service discovery sub-themes. The Predictive objective is mainly used in Service selection. Finally, the Prescriptive objective is found mainly in the Service discovery papers.

Service management. Results reveal that among the papers of this theme, 48% (11/23) have a Prescriptive objective (P29, P30, P31, P32, P34, P38, P36, P37, P41, P44, P47), 43% a Predictive objective (P33, P35, P39, P40, P42, P43, P45, P46, P48, P49), and 9% a Descriptive objective (P23, P28). For the papers with prescriptive objective, the prescription takes the form of *Approach* (P29, P32, P38, P41, P44, P47), *Framework* (P31, P37) and *Method* (P30, P34, P36). Note that the Descriptive objective was used only in the papers of the Service control sub-theme. More specifically, the Descriptive and Prescriptive objectives mainly concern the papers of the Service control sub-theme. As for the Predictive objective, it mainly concerns Service monitoring papers.

Service engineering. Table 4 shows that in this theme, 47% (7/15) of papers have a Descriptive objective (P11, P13, P14, P18, P21, P22, P25), 40% a Predictive objective (P12, P15, P16, P24, P26, P27), and 13% a Prescriptive objective (P19, P20). In these last papers, the prescription takes the form of *Framework* (P20) and *Method* (P19). Table 6 also shows the almost equal distribution of the different types of objective between the two sub-themes.

6.2 Summary

Concerning the question "What objectives are pursued when applying Bayesian network in web services?" (**RQ2**), Fig. 4 suggests that the main reason for using BN is for prediction with a focus on the composition and management of services. These results are quite logical since these two themes contain activities aimed at predicting or evaluating WS according to predefined criteria. Furthermore, the results highlight the lack of popularity of the Prescriptive objective, particularly in Services Engineering (only 2 papers are concerned—see Table 4). This aligns perfectly with (Bouguettaya et al. 2017, p. 68) who remarked that "Service systems have so far been built

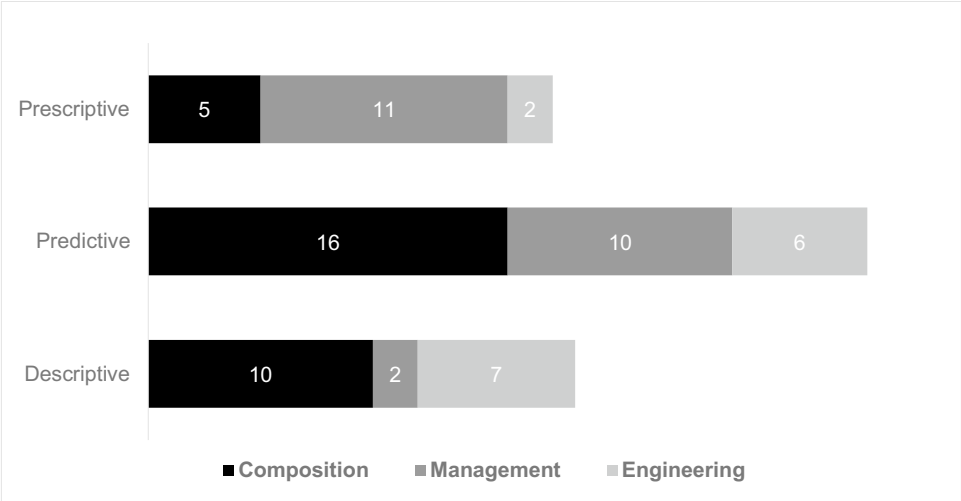

Fig. 4 Papers on Research objectives by Web service themes

Table 5 Papers on Types of bayesian network by web service themes ($N=69$)

Theme	Type of Bayesian network		
	Basic	Extended	Combined
Service composition (31 papers)			
Service selection	[P04, P17, P56, P57, P58, P59, P60, P61, P62, P63, P64, P66, P67]	–	[P09, P55, P65, P68]
Service discovery	[P01, P02, P03, P06, P07, P10, P69]	[P05, P08]	–
Service recommendation	[P50, P51, P52, P54]	–	[P53]
Service management (23 papers)			
Service control	[P23, P28, P29, P31, P32, P34, P38, P40, P43, P44]	[P39]	[P36]
Service monitoring	[P30, P33, P37, P42, P46, P49]	[P41, P45, P47, P48]	[P35]
Service engineering (15 papers)			
Service development	[P11, P12, P14, P16, P18, P24, P25]	–	[P19, P27]
Service application	[P13, P20, P21, P22, P26]	–	[P15]

without an adequate rigorous basis from which to reason about them". However, the activities of the Service engineering must be carried out according to precise prescriptions in order to design and develop applications based on the WS. Thus, we suggest that future research should pay more attention to how BNs are used for prescriptive purposes in service engineering. For this, we can rely on models such as those proposed in (Kurniawan et al. 2020; Reyes-Delgado et al. 2022).

7 Types of Bayesian network (RQ3)

This section presents the results of the classification of the selected papers according to the Types of Bayesian network organized by WS theme.

7.1 Results

Service composition. Table 5 suggests that 77% of papers the 31 papers in this theme used Basic BN (P01, P02, P03, P04, P06, P07, P10, P17, P50, P51, P52, P54, P56, P57, P58, P59, P60, P61, P62, P63, P64, P66, P67, P69), 13% used Combined BN (P09, P55, P65, P68) and 10% used Extended BN (P05, P08, P53). In particular, for Extended BN, the extension comes in the form of Dynamic BN (DBN). Finally, in the case of papers that used the combined type, BN is combined with *stochastic local search* (P09), *fuzzy logic* (P55), *Hidden Markov Model* (P65) and *cuckoo search algorithm handset* (P68). A closer examination shows that Basic BN and Combined BN are mostly used in Service selection. As for the Extended BNs, they are only used in the Service discovery.

Service management. According to Table 5, 70% of the 23 papers in this theme used Basic BN (P23, P28, P29, P30, P31, P32, P33, P34, P37, P38, P40, P42, P43, P44, P46, P49), 21% used the Extended BN (P39, P41, P45, P47, P48),

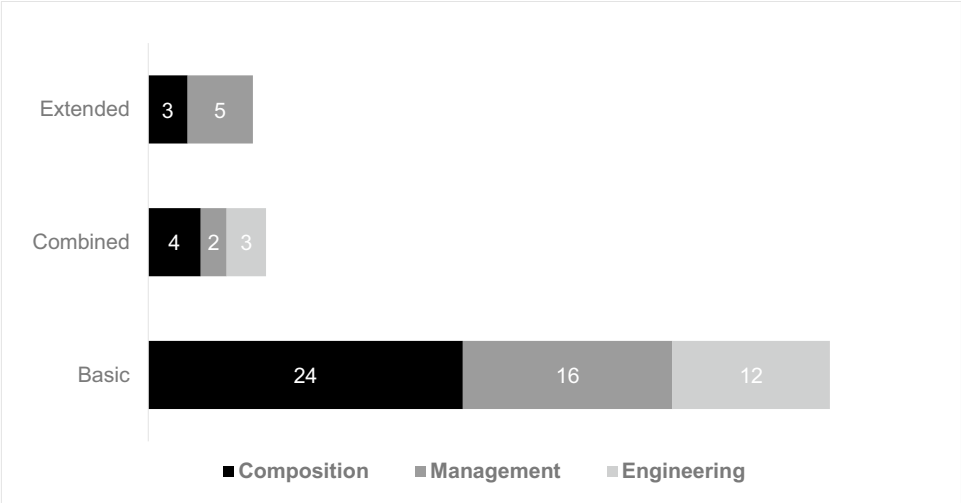

Fig. 5 Papers on types of BN by Web service themes

and 9% used the Combined BN (P35, P36). In the papers that used the combined type, the BN is associated with an *Agent* (P36) and *Ontology* (P35). For the *Extended* type, all the BN types were *Dynamic* BNs. We also note that the Basic BN is generally used in the Service control sub-theme, while the Combined BN mainly concerns Service monitoring. Finally, the Extended BN is used equally in both sub-themes.

Service engineering. In term of the types of BN, Table 5 reveals that, among the 15 papers of this theme, the Basic BN was used in 80% of papers (P11, P12, P13, P14, P16, P18, P20, P21, P22, P24, P25, P26), and the Combined BN in 20% of papers (P15, P19, P27). Regarding the combined type, the BN was combined with *Neural networ*k and *Ontology* (P19), *Multi-entity* (P27) and *Analytic hierarchy process* (P15). It is important to note the total absence of use of the Extend BN type in the concerned sub-themes. Moreover, the Basic BN and Combined BN were mainly used in the Service development sub-theme.

7.2 Summary

Regarding question **RQ3:** "What types of Bayesian network are frequently applied in web services?", the answer is that the Basic BNs are the most used, and this, mainly in Service composition (Fig. 5). These results can be explained by (i) the relative ease of use of this type of BN and (ii) their ability to visually represent the dependencies between the different elements of a WS. Which is a facilitating element (Zhao et al. 2022) in the particular case of Service composition. But, at the same time, for complex and dynamic phenomena such as WS (Papazoglou 2008), "description" alone is not enough. We need slightly more adapted techniques like DBN to better understand these phenomena. Our results suggest that, if this form of BN is actually used, it remains marginal (8 papers). This could be explained by the complexity of DBNs (Bielza and Larrañaga 2014); which can notably increase their computation time (Hosseini and Ivanov 2020). The same goes for the Combined BN which, like the Extended BN, concerns only 9 papers. However, as "BNs are limited by the modeling aspects that they can deal with" (Weber et al. 2008), it is necessary to combine them with other techniques in order to correctly model the phenomenon under study. Therefore, these constraints must be taken into account when considering using Combined and Extended BNs in a WS context.

8 Evaluation methods (RQ4)

This section describes the results of the classification of the selected papers according to the Evaluation methods organized by WS theme.

8.1 Results

Service composition. Table 6 suggests that among the 31 papers of this theme, 52% are based on empirical methods (P03, P08, P10, P50, P51, P52, P53, P54, P55, P57, P60, P63, P64, P67, P68, P69), 45% on the Proof of concept (P01, P02, P04, P06, P07, P09, P17, P56, P58, P59, P61, P62, P65, P66) and 3% do not have an evaluation (P05). In the empirical papers, 13 used *Experiment* (P03, P08, P10, P50, P51, P53, P54, P55, P63, P64, P67, P68, P69) and 3 *Simulation* (P52, P57, P60).

Service management. Among the 23 papers of this theme, 48% are based on the Proof of concept (P23, P28, P33, P34, P35, P36, P38, P39, P40, P42, P49), 43% on empirical methods (P29, P30, P32, P41, P43, P44, P45, P46, P47, P48), and 9% do not have an evaluation (P31, P37). In the empirical papers, 9 used *Experiment* (P29, P32, P41, P43, P44, P45, P46, P47, P48) and 1 *Simulation* (P30).

Service engineering. Of the 15 papers of this theme, 80% are based on the Proof of concept (P11, P14, P15, P16, P18, P19, P20, P21, P22, P24, P25, P26), 13% on empirical methods (P13, P27), and 7% do not have an evaluation (P12). The 2 empirical papers used the *Experiment* (P13, P27).

Table 6 Papers on Evaluation methods by web service themes ($N=69$)

Theme	Evaluation method		
	Proof of concept	Empirical	No evaluation
Service composition (31 papers)			
Service selection	[P04, P09, P17, P56, P58, P59, P61, P62, P65, P66]	[P55, P57, P60, P63, P64, P67, P68]	–
Service discovery	[P01, P02, P06, P07]	[P03, P08, P10, P69]	[P05]
Service recommendation	–	[P50, P51, P52, P53, P54]	–
Service management (23 papers)			
Service control	[P23, P28, P34, P36, P38, P39, P40]	[P29, P32, P43, P44]	[P31]
Service monitoring	[P33, P35, P42, P49]	[P30, P41, P45, P46, P47, P48]	[P37]
Service engineering (15 papers)			
Service development	[P11, P14, P16, P18, P19, P24, P25]	[P27]	[P12]
Service application	[P15, P20, P21, P22, P26]	[P13]	–

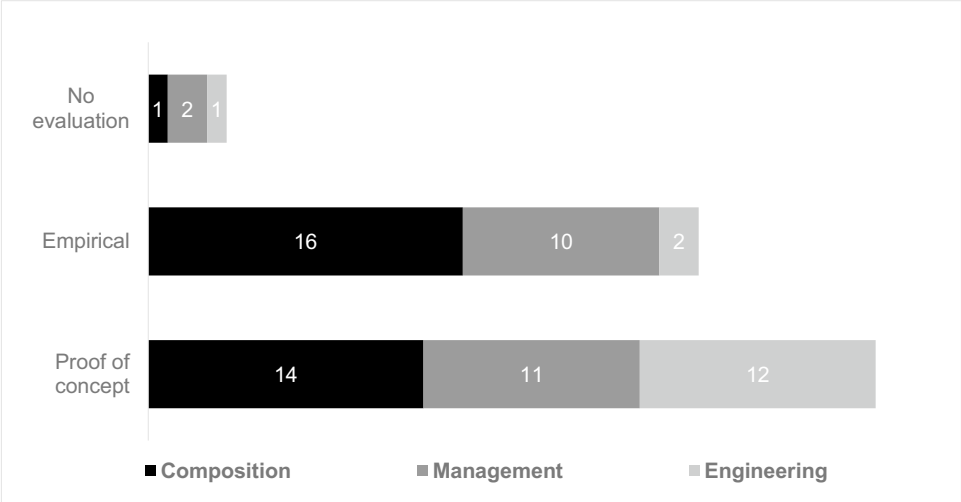

Fig. 6 Papers on evaluation methods by Web service themes

8.2 Summary

According to Fig. 6, the majority (94%) of papers present some form of assessment. More specifically, and in response to the answer to question **RQ4** ("What methods are used to evaluate the proposed Bayesian network models?"), the evaluation methods used are Proof of concept (57%), Experiment (37%), and Simulation (6%).

The predominance of proof of concept suggests the poor quality of the studies proposed. Indeed, "…these studies are only demonstrations that a technology works…" (Sjøberg et al. 2007). Moreover, the results reveal that the empirical methods used (Experimentation and Simulation) are, for the most part, based on small samples. In other words, the BN models in the reviewed papers are not robustly and convincingly evaluated. This means that these evaluations do not constitute a solid basis for making informed decisions. Therefore, a possible avenue for future research is to improve the quality of BN model evaluations by carefully selecting the methods used.

9 Pros and cons of the application of BNs in WS

To facilitate the comparative analysis of the pros and cons of the use of BNs in WS, we considered the following three aspects of BNs: (i) *Technological*, (ii) *Informational*, and (iii) *Performance*.

The **Technological** aspect refers to factors related to the BN technique itself (e.g., its construction, training, verification, etc.). The **Informational** aspect corresponds to the characteristics of the data used in BN models. Finally, the **Performance** aspect lists the evaluations (accuracy, precision, etc.) of the resulting model.

Table 7 summarizes the comparative analysis of each of these aspects in relation to the themes identified in the review.

Table 7 Summary of pros and cons of the application of BNs in WS

Focus	Theme	Pros	Cons
Technological	SC	BNs is a simple and a graphical representation tool with substantial foundations of mathematics (P02, P06) BN is an effective and flexible tool to model the causal relationships for elementary services (P01, P10, P57)	Fails to estimate the (unconditional) trustworthiness of the constituent services (P57)
	SM	The BN can learn from training data with different structural information (P44)	The integration of new data requires retraining the model, which consumes time (P45) When the prediction object changes, the model becomes unusable (P46) The BN structure has an influence on the performance of the resulted model (P28, P49)
	SE	Automatic missing data handling and discretization (P12)	Information lost when de the continuous variables are discretized (P12) The BN approach remains conceptual and does not propose a specific implementation (P16) The BN approach may not find the best structure due to heuristic methods (P19)
Informational	SC	Dealing with incomplete data (P57) BN combines different types of data (P56)	Synthetic or fictional data (P04, P52, P54, P69)
	SM	BN can deal with both real and synthetic data (P32)	Synthetic data (P42, 43)
	SE	BN combines different types of data (P18)	Lack of information caused by missing data (P12)
Performance	SC	Model Accuracy (P02, P52, P67, P68) and Efficiency (P02, P04, P08, P50, P51, P53, P55) The BN model is Quick (P67) and has high Quality (P50), high Recall and Precision (P03), high Performance (P60), and good Robustness (P50, P51)	The performance of the composite service is determined by the number of component services (P03, P61) The model has low Accuracy (P51)
	SM	The model is Simple and Flexible and has a good Accuracy and Efficiently (P23) The model increases performance (P44)	The model doesn't work properly in certain scenarios (P45) Model Accuracy prediction decreases as dataset size increases (P48)
	SE	The BN model has the ability to anticipate disruptive event (P16) BN model is efficient and stable (P20)	The BN model may be relatively slow (P19)

SC Service composition, *SM* Service management, *SE* Service engineering

10 Conclusion

This review, the first devoted specifically to the application of BNs in WS, offers important contributions. First, by organizing its results by a framework, the review provides interested researchers and practitioners with (i) an accessible and structured source of references on the subject; and (ii) a clear indications of the Where (WS themes), Why (Research objectives), and How (Types of BN, Evaluation methods) BNs can be used in WS. A summary of the pros and cons of the use of BNs in WS was also proposed. These results are therefore likely to help them in the planning of their research or the implementation of BNs in a WS context. Second, the review reveals that, despite the advent of other forms of services such as cloud, fog, grid, micro, mobile services, "traditional" web services remain a very active field of research (e.g., Mezni 2023; Razian et al. 2022). Finally, this review demonstrates once again the relevance of BNs as a decision support tool in dynamic and uncertain situations (Kaya et al. 2023; Nyberg et al. 2022; Xu et al. 2023).

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Research involving Human Participants and/or Animals This is a review study. No ethical approval is required.

Informed consent N/A.

Appendix

See Tables8,9,10, and11.

Table 8 List of selected papers

No	Author(s)	Year	Title	Venue
P01	Yue et al	2007	Towards web services composition based on the mining and reasoning of their causal relationships	Asia–Pacific web and 8th international conference on web-age information management conference on Advances in data and web management (APWeb/WAIM'07)
P02	Yang et al	2008	Study on uncertainty of Geospatial Semantic Web Services composition based on broker approach and Bayesian Networks	Geoinformatics 2008 and Joint Conference on GIS and Built Environment: Geo-Simulation and Virtual GIS Environments
P03	Yue et al	2009	Discovering semantic associations among Web services based on the qualitative probabilistic network	Expert Systems with Applications
P04	Mohanty et al	2012	Classification of Web Services Using Bayesian Network	Journal of Software Engineering and Applications
P05	Wei and Jin	2012	Service discovery for internet of things: a context-awareness perspective	Asia–Pacific Symposium on Internetware (Internetware '12)
P06	Rajesh et al	2013	Web Service Discovery Using Semantically Annotated Belief Network	International Journal of Research in Engineering & Advanced Technology
P07	Gnanasekar and Suresh	2014	Web Service Discovery with Quality of Service (QoS) Parameters using Bayesian Belief Network	Research Journal of Applied Sciences, Engineering and Technology
P08	Chandrasekaran et al	2018	Towards an Effective QoS Prediction of Web Services using Context-Aware Dynamic Bayesian Network Model	Technical Gazette
P09	Laachemi and Boughaci	2020	Improved machine learning classifiers combined with a stochastic local search for Web services classification	Intelligent Decision Technologies
P10	Li et al	2020	bi-HPTM: An Effective Semantic Matchmaking Model for Web Service Discovery	International Conference on Web Services (ICWS)
P11	Ghosh et al	2001	Knowledge representation for Web based services in a multi-cultural environment	International Workshop on Web Site Evolution (WSE 2001)
P12	Myllymaki et al	2001	B-Course: a Web service for Bayesian data analysis	International Conference on Tools with Artificial Intelligence (ICTAI 2001)
P13	Castelli et al	2007	The Whereabouts Diary	International Symposium on Location- and Context-Awareness (LoCA 2007)
P14	Koyuncu et al	2007	DDDAS-Based multi-fidelity simulation for online preventive maintenance scheduling in semiconductor supply chain	Winter Simulation Conference
P15	Huang and Bian	2009	A Bayesian network and analytic hierarchy process based personalized recommendations for tourist attractions over the Internet	Expert Systems with Applications
P16	Fernández et al	2010	Compound Web Service for Supply Processes Monitoring to Anticipate Disruptive Event	Conference on e-Business, e-Services, and e-Society (I3E)
P17	Ge et al	2010	Service-oriented personalized potal platform with QoS guarantee	International Conference on Advanced Computer Theory and Engineering(ICACTE)
P18	Gilabert and Garcia	2010	Bayesian Networks for Diagnosis Automation in an e-Maintenance architecture	IFAC Proceedings Volumes
P19	Wang and Xu	2010	Building Semantic Web Services Automatically Based on PART	International Conference on Management and Service Science
P20	Yang et al	2011	Integrating Geospatial Web Services Into Enterprise Business System based on Service Intelligent Agents and Bayesian Network	Intelligent Automation and Soft Computing
P21	Zagoreckia et al	2013	A System for Automated General Medical Diagnosis using Bayesian Networks	World Congress on Medical and Health Informatics (MEDINFO 2013)
P22	Liu et al	2014	Pathway-Finder—An Interactive Recommender System for Supporting Personalized Care Pathways	International Conference on Data Mining Workshop

Table 8 (continued)

No	Author(s)	Year	Title	Venue
P23	Li et al	2016	Design of integrated architecture of Web Service-Based diagnosis system for TBM	International Conference on Mechatronic and Embedded Systems and Applications (MESA)
P24	Badea et al	2018	A service-oriented architecture for student modeling in peer assessment environments	International Symposium on Emerging Technologies for Education (SETE 2018)
P25	Matsumoto and Ohigashi	2019	Analyzing Young People's Awareness for Mutual Assistance Support System with Bayesian Network	International Congress on Advanced Applied Informatics (IIAI-AAI)
P26	Matsumoto and Ohigashi	2020	Analyzing Youth Attitudes towards Mutual Assistance Support System based on Sensitivity Analysis of Bayesian Networks	International Congress on Advanced Applied Informatics (IIAI-AAI)
P27	Sekkal et al	2020	Proactive and reactive context reasoning architecture for smart web services	International Journal of Data Mining, Modelling and Management
P28	Wang et al	2006	Modeling Bayesian Networks for Autonomous Diagnosis of Web Services	International Florida Artificial Intelligence Research Society Conference
P29	Zhang et al	2006	Accountability in Service-Oriented Architecture—Computing with Reasoning and Reputation	International Conference on e-Business Engineering
P30	Zhang et al	2007	Efficient Statistical Performance Modeling for Autonomic, Service-Oriented Systems	International Parallel and Distributed Processing Symposium
P31	Lin	2008	The design of an accountability framework for service engineering	Hawaii International Conference on System Sciences
P32	Han et al	2010	Similarity-Based Bayesian Learning from Semi-structured Log Files for Fault Diagnosis of Web Services	International Conference on Web Intelligence and Intelligent Agent Technology
P33	Yang et al	2010	A multiple system performance monitoring model for web services	International Workshop on Agents and Data Mining Interaction
P34	Zhu and Dou	2010	QoS-Based Probabilistic Fault-Diagnosis Method for Exception Handling	International Conference on Web-Based Learning
P35	Wang et al	2011	Ontology-Based Reliability Evaluation for Web Service	Annual Computer Software and Applications Conference
P36	Chen et al	2012	Bayesian network-based exception handling for web service composition	International Conference on Computer Science and Network Technology
P37	Huang et al	2012	Managing Web Service Dynamic Changes at Run-Time Based on Bayesian Network	International Conference on Services Computing
P38	Chen et al	2013	Exception Detection for Web Service Composition Using Improved Bayesian Network	Journal of Digital Information Management
P39	Clarke	2013	Towards a dynamic declarative service workflow reference model	International Conference on Service-Oriented Computing
P40	Thakore and Kadu	2013	Enriching Batched Stream processing using Bayesian Networks for Web services	International Journal of Emerging Technology and Advanced Engineering
P41	Wang et al	2014	A Novel Online Reliability Prediction Approach for Service-Oriented Systems	International Conference on Web Services
P42	Almulla et al	2015	Inferring relevance and presence of evidence in service-oriented and SaaS architectures	International Workshop on Security and Forensics in Communication Systems
P43	Delac et al	2015	A Reliability Improvement Method for SOA-Based Applications	IEEE Transactions on dependable and secure computing
P44	Han et al	2016	Exploiting structural similarity of log files in fault diagnosis for Web service composition	CAAI Transactions on Intelligence Technology
P45	Wang et al	2017	Online Reliability Prediction via Motifs-Based Dynamic Bayesian Networks for Service-Oriented Systems	IEEE Transactions on software engineering

Table 8 (continued)

No	Author(s)	Year	Title	Venue
P46	Li et al	2018	A Novel QoS Prediction Approach for Cloud Services Using Bayesian Network Model	IEEE Access
P47	Wang et al	2018	A proactive approach based on online reliability prediction for adaptation of service-oriented systems	Journal of Parallel and Distributed Computing
P48	Wang et al	2019	Learning the Evolution Regularities for BigService-Oriented Online Reliability Prediction	IEEE Transactions on services computing
P49	Awad et al	2021	Composing WoT services with uncertain and correlated data	Computing
P50	Wu et al	2009	Bayesian network based services recommendation	Asia–Pacific Services Computing Conference (APSCC)
P51	Wu et al	2012	Composite Service Recommendation Based on Bayes Theorem	International Journal of Web Services Research
P52	Mehdi et al	2014	Probabilistic approach for QoS-aware recommender system for trustworthy web service selection	Applied Intelligence
P53	Chu et al	2015	Web Service Recommendations Based on Time-Aware Bayesian Networks	International Congress on Big Data
P54	Liu et al	2018	Research of Web Service Recommendation Using Bayesian Network Reasoning	International Conference on Services Computing (SCC 2018)
P55	Wu et al	2007	A Bayesian network based Qos assessment model for web services	International Conference on Services Computing (SCC 2007)
P56	Nguyen et al	2010	A trust and reputation model based on bayesian network for web services	International Conference on Web Services (ICWS)
P57	Hang and Singh	2011	Trustworthy Service Selection and Composition	ACM Transactions on Autonomous and Adaptive Systems
P58	Guofeng	2012	Using Bayesian networks to measure Web service QoS	International Conference on Communication, Electronics and Automation Engineering
P59	Hwang et al	2012	Data Providing Web Service Selection Using Bayesian Network	International Conference on e-Business Engineering
P60	Mehdi et al	2012	Trustworthy Web Service Selection Using Probabilistic Models	International Conference on Web Services
P61	Motallebi et al	2012a	Component Trust for Web Service Compositions	AAAI Spring Symposium
P62	Motallebi et al	2012b	Trust Computation in Web Service Compositions Using Bayesian Networks	International Conference on Web Services
P63	Xu	2012	Web service QoS measure approach based on Bayesian networks	International Conference on Uncertainty Reasoning and Knowledge Engineering
P64	Mehdi et al	2013	A QoS-based Trust Approach For Service Selection and Composition via Bayesian Networks	International Conference on Web Services
P65	Atluri and Mohanty	2014	Web Service Response Time Prediction Using HMM and Bayesian Network	International Conference on Intelligent Computing, Communication and Devices (ICCD 2014)
P66	Homayounvala	2015	A Bayesian Approach to Service Selection for Secondary Users in Cognitive Radio Networks	International Journal of Advanced Computer Science and Applications
P67	Liu and Xia	2017	An Approach of Web Service Organization Using Bayesian Network Learning	Journal of Web Engineering
P68	Chandrasekaran et al	2018	Bayesian Network with CSA to optimize the selection of QoS- aware Web service	International Journal on Computer Science and Engineering
P69	Heß and Kushmerick	2003	Automatically attaching semantic metadata to Web services	Workshop on Information Integration on the Web (IIWeb 2003)

Table 9 Papers on service composition ($N=31$)

Sub-theme	Paper	Objective	Type of BN	Evaluation method
Service selection (17 papers)	P04	Descriptive	Basic	Proof of concept
	P09	Predictive	Combined (SLS)	Proof of concept
	P17	Predictive	Basic	Proof of concept
	P55	Predictive	Combined (Fuzzy logic)	Empirical-experiment
	P56	Predictive	Basic	Proof of concept
	P57	Prescriptive (Approach)	Basic	Empirical-simulation
	P58	Predictive	Basic	Proof of concept
	P59	Predictive	Basic	Proof of concept
	P60	Descriptive	Basic	Empirical-simulation
	P61	Predictive	Basic	Proof of concept
	P62	Descriptive	Basic	Proof of concept
	P63	Predictive	Basic	Empirical-experiment
	P64	Descriptive	Basic	Empirical-experiment
	P65	Predictive	Combined (HMM)	Proof of concept
	P66	Predictive	Basic	Proof of concept
	P67	Descriptive	Basic	Empirical-experiment
	P68	Predictive	Combined (CSA)	Empirical-experiment
Service discovery (9 papers)	P01	Prescriptive (Approach)	Basic	Proof of concept
	P02	Prescriptive (Approach)	Basic	Proof of concept
	P03	Descriptive	Basic	Empirical-experiment
	P05	Prescriptive (Framework)	Extended (DBN)	Not evaluated
	P06	Descriptive	Basic	Proof of concept
	P07	Descriptive	Basic	Proof of concept
	P08	Predictive	Extended (DBN)	Empirical-experiment
	P10	Descriptive	Basic	Empirical-experiment
	P69	Descriptive	Basic	Empirical-experiment
Service recommendation (5 papers)	P50	Predictive	Basic	Empirical-experiment
	P51	Predictive	Basic	Empirical-experiment
	P52	Predictive	Basic	Empirical-simulation
	P53	Predictive	Extended (DBN)	Empirical-experiment
	P54	Prescriptive (Method)	Basic	Empirical-experiment

Table 10 Papers on service management ($N=23$)

Sub-theme	Paper	Objective	Type of BN	Evaluation method
Service control (12 papers)	P23	Descriptive	Basic	Proof of concept
	P28	Descriptive	Basic	Proof of concept
	P29	Prescriptive (Approach)	Basic	Empirical-experiment
	P31	Prescriptive (Framework)	Basic	Not evaluated
	P32	Prescriptive (Approach)	Basic	Empirical-experiment
	P34	Prescriptive (Method)	Basic	Proof of concept
	P36	Prescriptive (Method)	Combined (Agent)	Proof of concept
	P38	Prescriptive (Approach)	Basic	Proof of concept
	P39	Predictive	Extended (DBN)	Proof of concept
	P40	Predictive	Basic	Proof of concept
	P43	Predictive	Basic	Empirical-experiment
	P44	Prescriptive (Approach)	Basic	Empirical-experiment
Service monitoring (11 papers)	P30	Prescriptive (Method)	Basic	Empirical-simulation
	P33	Predictive	Basic	Proof of concept
	P35	Predictive	Combined (Ontology)	Proof of concept
	P37	Prescriptive (Framework)	Basic	Not evaluated
	P41	Prescriptive (Approach)	Extended (DBN)	Empirical-experiment
	P42	Predictive	Basic	Proof of concept
	P45	Predictive	Extended (DBN)	Empirical-experiment
	P46	Predictive	Basic	Empirical-experiment
	P47	Prescriptive (Approach)	Extended (DBN)	Empirical-experiment
	P48	Predictive	Extended (DBN)	Empirical-experiment
	P49	Predictive	Basic	Proof of concept

Table 11 Papers on Service engineering ($N=15$)

Sub-theme	Paper	Objective	Type of BN	Evaluation method
Service development (9 papers)	P11	Descriptive	Basic	Proof of concept
	P12	Predictive	Basic	Not evaluated
	P14	Descriptive	Basic	Proof of concept
	P16	Predictive	Basic	Proof of concept
	P18	Descriptive	Basic	Proof of concept
	P19	Prescriptive (Method)	Combined (NN-Ontology)	Proof of concept
	P24	Predictive	Basic	Proof of concept
	P25	Descriptive	Basic	Proof of concept
	P27	Predictive	Combined (MEBN)	Empirical-experiment
Service application (6 papers)	P13	Descriptive	Basic	Empirical-experiment
	P15	Predictive	Combined (AHP)	Proof of concept
	P20	Prescriptive (Framework)	Basic	Proof of concept
	P21	Descriptive	Basic	Proof of concept
	P22	Descriptive	Basic	Proof of concept
	P26	Predictive	Basic	Proof of concept

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