

Systematic Review of Probabilistic Inference in Bayesian Networks Using Boolean Satisfaction Algorithms and Model Counting

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ABSTRACT

Probabilistic inference in Bayesian networks remains one of the most challenging problems in artificial intelligence due to its #P-complete nature. This systematic review analyzes the evolution and current state of Boolean Satisfiability (SAT) and model counting (#SAT) based approaches for exact and approximate inference. Following the PRISMA 2020 guidelines, both classical and recent literature are examined to synthesize encoding strategies, knowledge compilation techniques, weighted model counting, and approximation methods with probabilistic guarantees. The findings show that SAT-based inference achieves competitive performance, particularly in networks with low treewidth, and supports efficient multi-query inference after an initial compilation phase. Moreover, hashing-based approximate counting methods provide rigorous (ϵ, δ) guarantees. Despite these advantages, challenges remain regarding efficient encodings and limited applicability to hybrid or continuous domains. Overall, SAT/#SAT-based methods emerge as a robust complementary paradigm that strengthens probabilistic reasoning in artificial intelligence.

Keywords: Boolean reasoning; weighted model counting; probabilistic inference methods; knowledge compilation; SAT-based algorithms.

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INTRODUCTION

Probabilistic inference is one of the fundamental pillars of modern artificial intelligence, since it allows formal reasoning under conditions of uncertainty, integrating prior knowledge with observed evidence. In this context, Bayesian networks, introduced and systematized by Pearl (2014), have established themselves as one of the most influential tools for modeling causal dependencies and representing structured knowledge in complex domains. Its applicability extends from expert systems and medical

diagnostics to robotics, data mining, and autonomous decision-making.

However, despite its expressive power, exact inference in Bayesian networks presents significant computational challenges. Classic works such as those of Lauritzen and Spiegelhalter (1988) and Dechter (1999) demonstrated that this problem is #P-complete, implying that the computational cost grows exponentially with the size and structural complexity of the network. This intractability has led to the development of multiple alternative approaches, including approximate methods based

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on stochastic sampling, such as those described by Gilks et al. (1995) and Dagum and Luby (1993), which, while reducing computational cost, sacrifice accuracy and formal guarantees.

From an applied perspective, Oviedo-Bayas (2016) evidenced the value of Bayesian networks in real domains, particularly in educational contexts, where uncertainty is inherent to human behavior. Their results show that these models allow the integration of heterogeneous evidence and the generation of robust predictions, reinforcing the need for more scalable and accurate inference methods that expand their practical applicability.

In this scenario, Boolean Satisfaction (SAT)-based approaches emerge, which reformulate probabilistic inference as a model counting problem. This idea, initially founded by Roth (1996) and later developed by Darwiche (2003), allows Bayesian networks to be translated into Boolean formulas in the normal conjunctive form (CNF), enabling the use of modern SAT solvers. Such solvers incorporate advanced techniques such as clause learning, smart pruning, and structural breakdown, which has driven substantial improvements in efficiency.

These advances are complemented by the techniques of compiling knowledge, highlighted by Chavira and Darwiche (2008), which transform Boolean representations into structures such as d-DNNF and SDD. These representations allow multiple inference queries to be performed efficiently after an initial compilation phase, which is especially advantageous in systems that require repeated inference. The effectiveness of these approaches has been demonstrated in both theoretical domains and large-scale applications.

At the same time, approximate counting methods with probabilistic guarantees emerged, driven by universal hashing techniques. Tools such as ApproxMC and UniGen, documented by Soos and Meel (2019) and Gomes et al. (2021), demonstrated that it is possible to perform scalable counting even in extremely large combinatorial spaces, offering formal guarantees of the type (ϵ, δ) . These advances represent a turning point compared to purely stochastic methods, combining efficiency with mathematical rigor.

The relevance of these approaches also manifests itself in high-impact practical applications. Lucas et al. (2004) and Thrun (2002) highlight the use of Bayesian networks in medical diagnostics and probabilistic robotics, respectively, where the integration of logical and probabilistic reasoning is

critical. In these contexts, EWS and #SAT-based methods provide a solid basis for verifiable and reproducible decisions.

Recent developments further expand this picture. Van den Broeck et al. (2021) underline the growth of lifted inference, while Belle and De Raedt (2016) evidence the convergence between logical reasoning and probabilistic programming. These modern perspectives reinforce the idea that SAT and #SAT are not isolated approaches, but part of a broader ecosystem of advanced probabilistic reasoning.

Likewise, Darwiche and Marquis (2024) offer a comprehensive review of knowledge compilation, highlighting its central role in optimizing model counting. In parallel, Shaw and Meel (2024) show that modern solvers have reached a level of maturity that allows them to address real-world counting problems, consolidating the integration between SAT and probabilistic modeling.

Other recent work reinforces this trend. Bacchus (2022) delves into parameterized counting applied to inference, while Li et al. (2025) explore hybrid architectures that integrate SAT with probabilistic circuits. These contributions extend the applicability of SAT/#SAT to more expressive domains, including complex structures and hybrid scenarios.

Finally, approaches such as those of Fargier and Mengin (2021) on semantic weighting and those of Rudi and Ciliberto (2021) on PSDDs show that the structured representation of knowledge continues to be a key axis to improve inferential efficiency. Together, these lines of research, which are supported by foundational works such as those of Sang et al. (2005) and Burchard et al. (2015), reinforce the view that SAT-based methods not only complement but in certain scenarios outperform classical inference algorithms.

In this context, the objective of this systematic review is to articulate, analyze and synthesize the foundations, advances and limitations of probabilistic inference based on SAT and #SAT. By integrating classic and contemporary literature, this work seeks to offer a critical and up-to-date view of the state of the art, establishing a solid conceptual framework that allows us to understand the current and future role of these approaches within modern artificial intelligence.

METHODOLOGY

This research was developed as a systematic review of the literature, rigorously following the guidelines

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established in the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement, with the aim of guaranteeing transparency, reproducibility and methodological soundness. The approach adopted was qualitative, descriptive-documentary, since no manipulation of variables or direct experimentation was carried out, but rather an analysis, synthesis and critical interpretation of previously published studies.

In a first phase, the research questions were explicitly defined, aimed at identifying, classifying and analyzing the main methodological approaches of probabilistic inference in Bayesian networks based on Boolean satisfiability (SAT) and model counting (#SAT). At the same time, inclusion and exclusion criteria were established, considering as eligible peer-reviewed scientific articles, book chapters and relevant conference proceedings, published in indexed journals and publishers, with special emphasis on fundamental works and recent contributions. Duplicate papers, non-refereed literature, and studies that did not explicitly address probabilistic inference or its relationship to SAT and #SAT were excluded.

The literature search strategy was designed in a systematic and reproducible way, employing structured search equations with key terms such as *Bayesian Networks*, *probabilistic inference*, *SAT*, *#SAT*, *weighted model counting* and *knowledge compilation*. These searches were executed in high-impact scientific databases, including Scopus, Web of Science and IEEE Xplore, complemented by manual review of key references to ensure state-of-the-art coverage. The prioritized time interval included classic literature and recent works (mainly 2020–2024), in order to integrate consolidated theoretical foundations and contemporary advances.

According to PRISMA 2020, the selection process was structured in the phases of identification, screening, eligibility and inclusion. In the identification stage, all records obtained through the initial search were collected. Subsequently, duplicates were eliminated and screening by title and abstract was carried out, evaluating their thematic relevance. Potentially relevant studies were analysed in full text to verify compliance with the established criteria. The entire process was documented through a PRISMA flow chart, accompanied by the corresponding checklist, ensuring traceability and methodological clarity.

Table 1. Summary of the PRISMA 2020 methodology applied in the systematic review.

PRISMA Phase	Actions and Criteria Applied in the Study
Research Questions	Identify, classify, and analyze the main methodological approaches to probabilistic inference in Bayesian networks based on SAT and #SAT. Inclusion: Peer-reviewed scientific articles, book chapters, and indexed conference proceedings, with emphasis on fundamental work and recent contributions.
Eligibility Criteria	Exclusion: Duplicate documents, non-refereed literature, unrelated studies.
Sources of information	Databases: Scopus, Web of Science, IEEE Xplore. Manual search for key references.
Search strategy	Ecuaciones con términos clave: <i>Bayesian Networks</i> , <i>probabilistic inference</i> , <i>SAT</i> , <i>#SAT</i> , <i>weighted model counting</i> , <i>knowledge compilation</i> .
Search period	Classic and contemporary literature, with priority in the 2020–2024 interval.
Selection process	1. Identification of records. 2. Screening by title and abstract. 3. Full-text evaluation. 4. Inclusion in the final corpus.
Data extraction	Systematic extraction of: theoretical descriptions, algorithmic methodologies, results and references. Thematic categorization and qualitative synthesis.
Data Synthesis	Comparative analysis to detect convergences, discrepancies, emerging trends, and research gaps. Organization of results under IMRyD structure.
Methodological guarantees	Reference checking, incorporation of additional sources for relevance and topicality, filtering and standardization of tables, and internal coherence in the writing.

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The final corpus was made up of articles and academic documents whose information was analyzed respecting its conceptual integrity. The theoretical sections, algorithmic descriptions, proposed methodologies, comparative tables and bibliographic references were examined in detail. To this end, a systematic process of information extraction, thematic categorization and qualitative synthesis was applied, allowing the contents to be organized under a formal academic structure such as IMRyD (Introduction, Methodology, Results and Discussion).

Likewise, comparative analysis methods were used to contrast the approaches identified in the base documents with the recent scientific literature. This procedure allowed detecting conceptual convergences, methodological discrepancies, emerging trends, and research gaps, ensuring that the reconstruction of the article reflected both the original evidence and the most current advances in inference based on SAT and #SAT.

In order to strengthen the validity and reliability of the study, all original references were verified and additional sources selected through criteria of relevance, timeliness, and scientific rigor were incorporated. Additionally, the tables were cleaned and standardized, reorganizing headings, categories, and descriptors to improve interpretative clarity and conceptual consistency, without altering the data or the meaning of the reported results.

Finally, a process of interpretative analysis and academic writing was developed, aimed at guaranteeing internal coherence between all sections of the manuscript. This process made it possible to strengthen the scientific rigor of the document, integrate the updated theoretical framework and present the findings in a clear, structured and aligned manner with editorial standards. Overall, the methodology applied allowed to reconstruct, systematize and consolidate the existing knowledge on probabilistic inference based on SAT and #SAT, offering a critical and updated synthesis of the state of the art.

RESULTS

The results of this systematic review are derived from the structured and comparative analysis of the final corpus of studies selected according to the PRISMA 2020 methodology. First, the process of obtaining and organizing the information was systematized, extracting from the documents including methodological descriptions, algorithmic

comparisons, BN-to-SAT transformation approaches and reported results. This information was filtered to eliminate redundancies and presented under homogeneous academic criteria, in order to facilitate its interpretation and comparison. Table 1 summarizes the main methodologies identified for the transformation of Bayesian networks into formulations based on SAT and #SAT. It shows that approaches vary from direct CNF encoding to more advanced techniques for compiling knowledge and counting weighted models. This classification allowed the identification of common patterns and key differences in terms of scalability, inferential accuracy, and computational requirements.

Table 2. Mapping of BN-to-SAT transformation methodologies

Method	Description	Key features
CNF Encoding	Translation of the Bayesian network to CNF clauses	Preserves logical structure; depends on the quality of the mapping
Knowledge Compilation	Transformation to d-DNNF or SDD	Facilitates multiple quick queries after a single build
SAT-Based Sampling	Use SAT resolvers to generate distribution-compatible samples	High precision; useful when accurate counting is not feasible
XOR-Based Hashing	Introduces XOR constraints to partition model space	ApproxMC and UniGen Base; offers guarantees (ϵ, δ)
Hybrid SAT-Probabilistic Methods	Integrate SAT with advanced probabilistic models	Improve scalability and enable inference in hybrid domains, based on recent trends
Model Counting Solvers	Solvers optimized for #SAT	They employ advanced CDCL, intelligent

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Method	Description	Key features
		partitioning, and structural caching

The analysis of the methods summarized in Table 1 shows a clear trend towards hybrid approaches, in which Boolean satisfiability, model counting, and knowledge compilation are combined to optimize probabilistic inference. In particular, methods based on weighted counting and universal hashing techniques stand out for offering a solid balance between theoretical rigor and computational efficiency.

Likewise, the results show that SAT-based inference achieves competitive, and even higher, performance in Bayesian networks with low tree width, especially when a previous compilation phase is available. In these cases, the studies reviewed report that it is possible to answer multiple inference queries efficiently, amortizing the initial computational cost.

Comparison with contemporary literature reveals a strong coherence between classical approaches and recent developments. The results are consistent with fundamental work that demonstrated the feasibility of model counting for exact inference, and align with recent research highlighting the maturity of modern SAT solvers and their ability to handle large-scale combinatorial spaces. This convergence confirms that SAT and #SAT-based methods are a natural evolution of traditional probabilistic inference algorithms.

Finally, the results reveal some persistent limitations, mainly the dependence on efficient encodings and the reduced applicability to hybrid or continuous domains. However, the evidence reviewed suggests that hybrid architectures and advances in structured compilation are progressively mitigating these constraints.

Overall, the results obtained confirm that the integration of SAT, #SAT and knowledge compilation techniques represents a robust and expanding methodological axis within the field of probabilistic inference, consolidating itself as a viable and scalable alternative to classical methods.

GENERAL DISCUSSION

The results of this systematic review confirm that approaches based on Boolean satisfactory and model counting constitute a coherent and methodologically sound extension of classical

probabilistic inference in Bayesian networks. As Pearl (2014) argued, the strength of Bayesian networks lies in their ability to represent causal dependencies and reason under uncertainty; however, the findings synthesized here show that this capacity requires more computationally efficient mechanisms to scale to complex problems, a need already anticipated by Lauritzen and Spiegelhalter (1988) and Dechter (1999).

In this sense, the results are in direct dialogue with the computational limits indicated by Dechter (1999) and Dagum and Luby (1993), who demonstrated the intractability of exact inference in general Bayesian networks. Faced with these restrictions, methods based on SAT and #SAT, based on the model count proposed by Roth (1996) and formalized by Darwiche (2003), emerge as a robust alternative that transfers the inferential problem to the domain of logical reasoning, allowing decades of advances in SAT solvers to be exploited.

The findings also reinforce what was stated by Sang et al. (2005) and Chavira and Darwiche (2008), who demonstrated that probabilistic inference can be solved accurately by counting weighted models. The reviewed evidence confirms that these techniques are not only theoretically correct, but that, with the incorporation of knowledge compilation in structures such as d-DNNF and SDD, they allow multiple queries to be answered efficiently, as anticipated by Chavira and Darwiche (2008).

Likewise, the results are aligned with the advances described by Gilks et al. (1995) and Dagum and Luby (1993) in sampling methods, but show that EWS-based approaches offer additional advantages in terms of formal guarantees. In particular, approximate counting methods based on universal hashing, such as ApproxMC and UniGen, support the claims of Soos and Meel (2019) and Gomes et al. (2021) about the possibility of obtaining approximations with probabilistic guarantees (ϵ , δ), overcoming some limitations of purely stochastic approaches.

From a more recent perspective, the results confirm the observations of Van den Broeck et al. (2021) and Belle and De Raedt (2016) on the convergence between logical reasoning and probabilistic programming. The growing adoption of hybrid approaches, which integrate SAT, #SAT and lifted inference, evidences a natural evolution towards more expressive and scalable models, capable of

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handling complex structures without sacrificing inferential accuracy.

The findings are also consistent with the reviews of Darwiche and Marquis (2024), who highlight the central role of knowledge compilation as a bridge between computational efficiency and logical accuracy. Similarly, the results dialogue with Shaw and Meel (2024) and Bacchus (2022), who underscore the maturity of modern solvers and the potential of scalable and parameterized counting to address large domains.

However, the discussion also highlights the limitations pointed out by various authors. As Fargier and Mengin (2021) and Rudi and Ciliberto (2021) warn, the efficiency of these methods depends to a large extent on the quality of the encodings and structured representations used. Likewise, applicability to hybrid or continuous domains remains an open challenge, although recent work such as that of Li et al. (2025) suggests that hybrid architectures can progressively mitigate these constraints.

Overall, the general discussion allows us to affirm that methods based on SAT and #SAT do not replace the classical approaches of probabilistic inference, but complement and strengthen them. As evidenced by the reviewed authors, its integration with knowledge compilation and scalable counting techniques offers a consistent methodological framework, aligned with the current demands of artificial intelligence, where efficiency, verifiability, and scalability are fundamental requirements.

CONCLUSIONS

The present systematic review allows us to conclude that approaches based on Boolean satisfactory (SAT) and model counting (#SAT) constitute a solid, mature and constantly evolving methodological framework for probabilistic inference in Bayesian networks. The evidence analyzed confirms that these methods are not only theoretically consistent with the classical foundations of probabilistic inference, but also offer significant computational advantages over traditional algorithms, especially in scenarios with high structural complexity.

The results show that the reformulation of Bayesian inference as a model counting problem allows to effectively take advantage of advances in modern SAT solvers, including clause learning, structural decomposition, and caching. In particular, weighted counting and knowledge compilation techniques

stand out for their ability to respond to multiple inference queries efficiently after an initial processing phase, which makes them particularly suitable for networks with low tree width.

Likewise, it is concluded that approximate methods based on universal hashing, such as ApproxMC and UniGen, represent a relevant contribution by offering formal probabilistic guarantees (ϵ , δ), overcoming limitations of purely stochastic approaches. However, the review also shows that important challenges remain, such as the dependence on efficient encodings and the limited applicability to hybrid or continuous domains.

Taken together, this study confirms that the integration of SAT, #SAT, and knowledge compilation techniques strengthens probabilistic inference, providing a balance between accuracy, scalability, and verifiability. These approaches are consolidated, as well as key complementary tools for the development of artificial intelligence systems that are more robust, efficient and aligned with the current and future demands of reasoning under uncertainty.

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