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A methodology for constructing narrative Bayesian networks for the evaluation of forensic fibre evidence given activity level propositions

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A B S T R A C T

The evaluation of forensic fibre evidence given activity level propositions is complex, due to the circumstances and factors of consideration in each case. While Bayesian Networks (BNs) are increasingly recognised for their potential in supporting this evaluative process, their application within the fibre and microtrace specialties remains limited, often relying on complex representations. This paper presents a simplified methodology for constructing narrative BNs for the activity-level evaluation of forensic fibre findings. Through an illustrative case scenario, we develop three examples of BNs designed as an accessible starting point for practitioners to build case-specific networks. These examples emphasise the transparent incorporation of case information, facilitate the assessment of the evaluation's sensitivity to variations in data, and highlight avenues for further research. Significantly, the qualitative, narrative offers a format that is easier for both experts and the Court to understand, enhances user-friendliness and accessibility, and aligns with successful approaches in other forensic disciplines as forensic biology. This alignment has the potential to readily facilitate interdisciplinary collaboration and ultimately a more holistic approach.

1. Introduction

Textile fibres are commonly encountered in forensic investigations due to their prevalence in the environment, high degree of polymorphism and ease of transfer yet difficulty in removal by perpetrators. These attributes make them valuable microtraces – microscopic remnants of past activities such an individual's presence and actions – that can contribute to investigations as associative or exclusionary clues, reconstruct past events and for forensic intelligence purposes [1–3]. Following their detection, recognition, recovery and examination, fully realising the evidential value of textile fibres hinges on a fundamental principle underpinning forensic science as outlined in the *Sydney Declaration* – namely, the interpretation of these traces within the context of each case [4].

However, the mass production of textile fibres distinguishes them from other traces such as DNA and fingerprints. Commercial and industrial developments have seen an increasing diversity of fibre types and manufactured features, in contrast to the relatively limited range of acquired individual features. Consequently, whilst fibres can offer valuable insights into what happened, their interpretation to reveal this information has been long acknowledged as complex and challenging [5–7].

The principles of interpretation [8,9] provide a guiding structure for the evaluation of analytical results within a Bayesian logical framework. One of these four principles is addressing a pair of propositions, usually representing the prosecution and the defence [9,10], against which the forensic scientist evaluates the findings. The probability of the findings given each proposition are expressed as a likelihood ratio (LR), the magnitude of which represents the evidential value. The hierarchy of propositions broadly categorises the questions of concern into three levels[1], namely source, activity and offence [13]. The higher up the hierarchy, the more directly useful is the scientist's testimony to the Court, as more expert knowledge and case information is needed to understand the meaning of the findings.

Over the past two decades, there has been a growing call for the evaluation of findings considering activity level propositions (the "how did it get here"), in lieu of source level ("what did it come from"). While questions of activity have a long history of association with fibre traces –

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[1] Additional level 1 source sublevels have since grown in relevance, namely sub-source and sub-sub-source, concerning the source of a DNA profile or component of a mixed DNA profile, respectively [9,11,12].

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as widely recognised and emphasised in reporting guidelines [14,15] – this has become a critically important topic across forensic disciplines, particularly in forensic genetics [16]. The shift in focus on the criminalistics aspects of biological traces [2] has consequently reinvigorated discussion surrounding activity level interpretation in other forensic fields, notwithstanding the fact that such discussion had started long before. From these, a number of transversal challenges have been identified [16–20], including:

- identifying the relevant variables influencing findings,
- deficiencies in knowledge on these variables and their interdependencies,
- lack of supporting data, and
- lack of training and education in performing these complex assessments

Activity-level evaluation requires additional information and consideration of the many factors affecting transfer, persistence, prevalence and recovery (TPPR) of fibres [21,22]. As stressed in Principles 1 and 5 of [4], having an adequate knowledge of trace behaviour and TPPR issues that are relevant in the framework of circumstances is fundamental in the interpretation of all material traces (as for any traces) – whether biological, physical or chemical [1] – yet further development is still required.

Research has to date steadily contributed empirical data on fibre TPPR and influential factors in a range of realistic scenarios [23–30]. Supplemental approaches include databases such as the BDATT-TTADB (Base de Données pour une analyse à l'Activité des Traces de Transfert – Transfer Traces Activity DataBase) to enhance access to research data and literature [31,32]. A shared knowledge base as a two-way channel for expert access and contribution has also been proposed [8,17]. However, as multiple influential variables, their dependencies and inter-dependencies and numerous pieces of evidence are considered, the conceptual and mathematical complexity of evaluation rapidly escalates [33]. Consequently, reasoning can become unclear and readily misunderstood.

Complex domains in which multiple variables have an influence (subject to uncertainty) have been represented using Bayesian networks (BNs). BNs are probabilistic graphical models of these variables (represented by *nodes*), the dependence relationships amongst them (represented by *arrows* or *arcs*) and their assigned probabilities (contained in the *conditional probability table* [CPT] of each node) that use Bayes' theorem to calculate event probabilities [34]. First proposed for forensic evidence evaluation by Aitken and Gammerman [35], BNs are a valuable tool supporting experts [36–39] that can be a preferable alternative to hand derivation of likelihood ratio (LR) formulae. The simultaneous graphical representation of qualitative and quantitative information promotes improved communication and reduces misinterpretation of the likelihood ratio [40].

The conventional approach to constructing these networks has been long established [34,41–45], but presents several practical difficulties. The design and validation process can be time-consuming; and the heavy reliance on complex mathematical notation requires extensive theoretical explanation, reducing accessibility to both practitioners and non-experts. Moreover, the visual architecture remains limited in adaptability – it is not readily apparent at a glance what case information has been considered or if information changes. A clearer and more user-friendly representation that minimises technical language whilst providing straightforward guidance to experts in the process would be a valuable development.

The utility of BNs for activity level evaluation has witnessed a recent surge in interest. In 2018, Taylor et al. [46] presented a template to guide practitioners through the process of BN construction in forensic biology cases. However, the architecture is visually distinguished by narrative elements – nodes are labelled with descriptive phrases representing aspects of case information, instead of parameters representing variables. The qualitative nature of the narrative representation also enables the inclusion of nodes representing additional information that may not necessarily influence the LR. This enhances transparency regarding the information available to the expert and the evaluation process. Similar approaches to BN representation have also been developed in the law domain to support reasoning and clear communication [47–50].

Whilst other approaches use fragments of BNs (termed *idioms*) that can be combined to create larger models [51,52], the narrative-based representation has gained traction in development. An increasing body of literature explores TPPR issues in scenarios including distinguishing between primary and secondary transfer of trace DNA [53–55], combining DNA and mRNA results [56], redistribution after packaging [57] and complex situations [58–60]. A heightened interest on activity level reporting of fingermarks is also exploring the application of BNs [19,61].

These advances primarily concern *intrinsic* evidence (ie. biological traces including DNA). However, in scenarios involving *extrinsic* evidence (eg. microtraces including fibres), there is additional uncertainty about the true source of the trace, and the probability of association requires consideration. Whilst narrative BNs in forensic soil analysis have recently been presented [62], research in the fibre domain continues the conventional BN approach [63,64] and work in other microtraces remains limited.

Recently, Vink et al. extended previous work on an idiom-based approach [51] and presented a generalised template model for the interdisciplinary evaluation of a combination of forensic evidence [52]. The authors showed its application in a fictitious case example adapted from Taroni et al. [64] for the evaluation of DNA and fibre evidence given propositions when the actor and/or the activity are in dispute. They additionally addressed uncertainty surrounding the relevance of an item of interest and an activity, a prerequisite 'sub-evaluation' for activity-level evaluation.

However, to the best of our knowledge, whilst monodisciplinary narrative BN representations have been shown for intrinsic biological traces, there remains no guidance for the construction of such BNs for the evaluation of forensic fibre findings and other extrinsic traces considering activity-level propositions. There is a need to enhance application of BNs in the chemical criminalistics community, breaking the barrier of their perceived complexity. This will ultimately assist to facilitate movement towards a holistic interdisciplinary approach [65].

This study demonstrates the process of constructing narrative style Bayesian networks for the evaluation of forensic fibre findings and extrinsic traces given activity level propositions. Our goal is to promote the development and adoption of narrative BNs for activity level evaluation by forensic fibre experts, in alignment with advancements seen in other forensic specialties. Our focus is providing practical guidance with an emphasis on reasoning and qualitative structure. It is not our aim to model every aspect of a case that would be considered in practice but rather to provide a simplistic template model that can be adapted to various cases.

2. Bayesian network construction

In the present study, the steps in network construction from Taylor et al. [46] has been adapted for the evaluation of fibre findings given activity level propositions. These are namely:

- Step 1: Define the main competing propositions and construct the starting nodes (black)
- Step 2: Define the activity node/s (blue)
- Step 3: Define the findings node/s (red)
- Step 4: Define the transfer and persistence nodes (yellow)
- Step 5: Define the root node/s (grey)
- Step 6: Check for absolute support within the BN

The stepwise process will be detailed systematically for the initial scenario (Section 2.1.1) to introduce and demonstrate the approach. For the subsequent two scenarios, modifications to the architecture will be highlighted. The corresponding colour scheme has also been employed for purposes none other than consistency and facilitating comprehension of the network at a quick glance.

We provide three examples of narrative BNs for the evaluation of results of fibre analysis given questions of activity. Three fictitious case scenarios are presented to discuss the construction of networks and consideration of the variables providing information. For purposes of clarity and simplification, only one-way transfer is considered.

The software Hugin Lite (v9.4)[2] [66] was used for construction of the BNs and mathematical calculations. The probabilities used in these examples are fictional but have been chosen based on literature [24,67,68] and informed judgement to be representative for illustrative purposes. The full BNs and Hugin files shown in these scenarios are provided as Supplementary Material. Only a selection of the conditional probability tables (CPTs) are presented in the text, others may be found in the Supplementary Material and within the Hugin files. Verbal equivalents corresponding to the calculated quantitative LRs were assigned according to widely cited reporting guidelines [14,69].

2.1. Mock scenario and model assumptions

Three different BNs have been constructed, each based on a version of a fictional case example outlined below. In the first scenario, the suspect provides no counterclaim, and it is questioned if a criminal action occurred. The second scenario concerns the question of the suspect having had performed the criminal activity or a legitimate interaction took place. The final scenario addresses the question whether the criminal activity was performed by the suspect or another unrelated person.

In this paper, we focus on one-way transfer of fibres recovered from a victim's garment.

> The victim (V) attended a social function at a licensed venue. After a short time inside, he exited and was tackled and assaulted by an individual who then fled the scene. Police attended and collected tapelifts of V's yellow cotton T-shirt and denim jeans.
>
> Shortly after, a suspect (S) was taken into custody and the garments he was wearing were collected: a red cotton/polyester blend hoody and black trackpants.
>
> Laboratory examination of the fibre tapings from V's T-shirt demonstrated the presence of a large number (eg. 1000) of red fibre collectives. These are a mixture of primarily a large number of red cotton fibres (900) and a small number of red polyester fibres (100). Additionally, a moderate number of blue cotton fibres are present but found indistinguishable from V's jeans. As the presence of these fibres can be accounted for, they will be ignored for simplicity of this exercise. However, the red fibres are considered indistinguishable to those comprising the suspect's hoody (X). For the purposes of the evaluation, we will only consider the large group of red cotton fibres.

It is assumed that the red hoody belongs to S and has not been worn by anyone else, thereby establishing a direct association between the suspect and garment. Given they do not claim otherwise, such can be considered undisputed case information [70]. Evidence evaluation at the activity level where there is uncertainty about the relevance of a link between the garment and incident (whether the suspect actually wore the garment) is discussed elsewhere in the literature [71] and has been modelled using a BN in the conventional approach [64]. Implementation of these considerations in the narrative style BN is considered outside the scope of the present paper but is a current area of development [51].

[2] https://www.hugin.com/

Additional assumptions include:

- V had a new laundered T-shirt, such that the probability of encountering other fibres not attributable to him as the owner (ie. foreign fibre groups [FFGs]) is low and the origin of any background fibres is known
- all recovered fibres (Y) are indistinguishable from reference fibres (X) from S's hoody
- the questioned recovered fibres (Y) have originated from a single source

The case information, assumptions and prosecution proposition (H_p) remain constant for the three scenarios.

2.1.1. Scenario A: no counterclaim provided

The suspect (S) denies knowledge of the incident[3] and provides no explanation for the traces recovered from the victim's garment. The BN structure for Scenario A is shown in Fig. 1 and the process outlined following.

2.1.1.1. Step 1: define proposition node. The first step involves determining the pair of competing propositions, generally H_p and H_d. It is emphasised that when an individual denies involvement in an activity (or a "no comment" situation), further specification of the circumstances and assumptions are required, as this may mean the alleged activity did not occur; or that the activity occurred but involving another person. Previous work regarding DNA evidence demonstrated effects of these differing claims on the construction and final architecture of the BN [12].

The activity-level propositions reflecting the case information of the prosecution (ie. contact occurred) and defence (no contact) can be formulated as:

H_p: S tackled V

H_d: No tackle occurred

The proposition node "Hp/Hd" (1) is defined with two states corresponding to H_p and H_d of equal probability (Supplementary Data Table S2).

2.1.1.2. Step 2: define activity node(s). Given the propositions, there is only one questioned activity of a tackle. Thus, the propositional node is parent to one activity node "S tackled V" (2) with binary states of '*yes*' or '*no*' and probability values of 0 or 1.

Activities that are not disputed under both propositions but are still important to consider in overall evaluation of the findings can also be added and represented as child nodes to the main propositional node. For example, if both prosecution and defence state they were at the same venue before an alleged assault. For the purposes of simplicity, these have not been created in this example; but facilitates creation of a more populated BN that illustrates what context-specific information the expert has taken into consideration during the evaluation process.

2.1.1.3. Step 3: define findings node(s). This step involves representing the results of analyses that are directly relevant to the propositions. In this simple scenario, we only have results of 'laboratory analysis' that the fibres are indistinguishable from each other. Consequently, this is represented by creation of a single findings node "fibres matching X on V shirt" (7). This can be extended to facilitate evaluation combining results from each analytical technique (eg. chemical analyses).

2.1.1.4. Step 4: define transfer and persistence node(s). Transfer and

[3] The 'incident' is also referred to as the 'alleged activity' or 'tackling'.

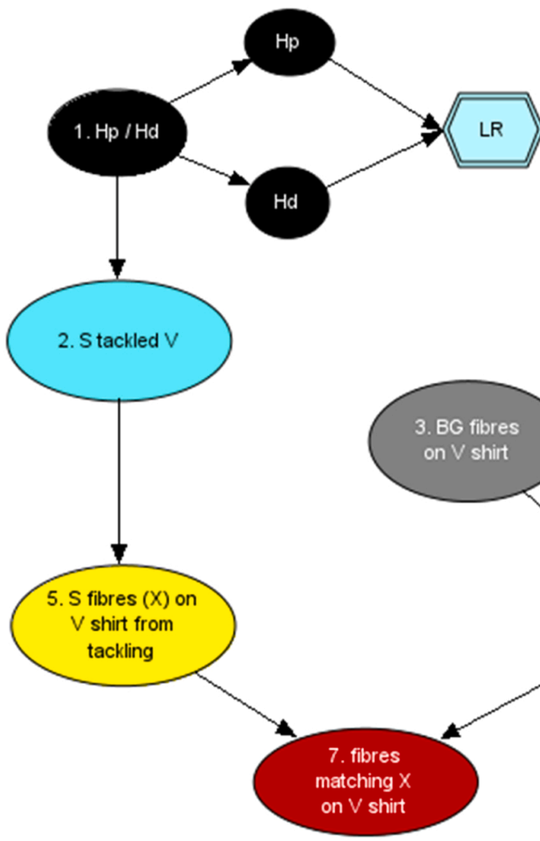

Fig. 1. Qualitative Bayesian network construction for Scenario A described in Section 2.1.1. Nodes are coloured where black represents the main propositional node, blue the activity node, yellow the transfer node, grey are root nodes and red the findings node. In this given scenario, *S* stands for suspect, *V* for victim, *X* the reference and *BG* for background. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

persistence nodes define the mechanisms linking the activity and possible findings. In this scenario, there are two[4] primary explanations for the presence and recovery of the trace fibres from V's shirt: they were either transferred from the tackle (and were not there before); or were there beforehand by chance and originated from the background environment. Thus, two transfer and persistence nodes are created respectively.

The node "S fibres (X) on V shirt from tackling"(5) is defined with three states representing the number of fibres transferring being '*none*', '*low*' and '*high*'.

For the node "BG fibres matching X on V shirt" (6), the number of fibres may likewise be none, low or high. However, the characteristics of these BG fibres additionally needs to be considered, as they may have X characteristics or U (unknown or other) characteristics. This node is thereby defined with five states representing the probability of '*no BG fibres*', '*high #X*', '*low #X*', '*high #U*' or '*low #U*'. While the model allows for the presence of background fibres matching the source, a low background is assumed overall, with higher probabilities assigned to the absence of such fibres or the presence of unmatched types.

There are numerous approaches to defining the states of both these nodes. Theoretically, every number could be a separate state (continuous approach). For our example, the categories representing a range has been chosen. Depending on case circumstances, these could be further specified with a numeric range or addition of a '*moderate*' state.

In this scenario, the transfer and persistence probabilities have been combined within each node, consistent with the assumption that the victim's garment was recovered shortly after the alleged contact event. The assignment of probabilities to the defined states is detailed in the Supplementary Material and was informed by relevant literature. This modelling approach prioritises the transfer aspect, which was of primary interest given the case circumstances, whilst keeping the BN simple to demonstrate the overall framework. More detailed modelling, such as the addition of a separate persistence node, may be appropriate in scenarios where the temporal gap between contact and recovery is more substantial, but is beyond the scope of the present example.

2.1.1.5. Step 5: define root node(s). Root nodes do not relate to the propositions nor activities under consideration but have a relevant parental relationship with transfer or findings nodes. For example, we consider the transfer of matching background fibres is influenced by the probability of background fibres being present and the probability of background fibres matching Y. These are represented as two root nodes (3 and 4, respectively) connected to the background transfer node. Both are defined by the states '*none*', '*low*' and '*high*'.

Additional root nodes that can explain some of the findings, such as contamination, can be included to indicate consideration of these factors' influence on the findings. In this scenario, the low possibility of a contamination event is anticipated to have little effect on the strength of the results i.e. calculated LR. However, in instances where this is relevant given the context, it can be accounted for.

2.1.1.6. Step 6: assign probabilities and check for absolute support. Once all the nodes have been defined and connected with relevant links, the overall structure is checked and the conditional probability tables (CPTs) of each node populated with probability values.

Node states may be either binary (yes/no, true/false) or assigned a

[4] there is also a third possibility of both occurring simultaneously, ie. background fibres being present prior to the alleged activity taking place, and fibre transfer. However, for the purposes of this example, we refrain from exploring this consideration.

value between 0 and 1. When the latter, the expert may assign a specific probability value informed by simulation experiments, casework data, published literature, previous experience and expert opinion [16]. In this scenario, values have been assigned based on informed judgement guided by literature and values previously used by Palmer [72] and Champod and Taroni [43] in examples illustrating and verifying the process.

Starting with the proposition node (1), equal prior probabilities are assigned to each of the two possible states representing H_p and H_d as shown in Table 1.

A function node (labelled "LR" in light blue)[5] has been added to automatically calculate the LR. Alternatively, this may be achieved by calculating the ratio of propositional probabilities in the results node (7) when instantiating the proposition node firstly in the H_p state, and then in the H_d state, thus providing for the posterior odds. As equal prior probabilities have been assigned to the two states of the propositional node, this represents the LR.

The activity node (2) is child to the proposition node, and probabilities are given values of 1 or 0 as shown in Table 2, reflecting whether the activity occurred or not under either proposition.

The transfer and persistence node "S fibres (X) on V shirt from tackling" (5) is assigned probability values given the state of the parent activity node. Under H_p, the three states of '*none*', '*high*' and '*low*' number have been assigned values of 0.01, 0.90 and 0.09, respectively. As shown in Table 3, under H_d, the values take either 1 or 0.

The root node "BG fibres on V shirt" (3) refers to the probability of foreign fibres being present on V's shirt, whether or not a tackle has taken place. This node has three states of '*None*', '*high*' and '*low*' being assigned values of 0.80, 0.01 and 0.19 (Table 4). The node "BG fibres match X" (4) has two states of '*yes*' or '*no*' and has values of 0.10 and 0.90 respectively (Table 5), whereby the probability of *yes* corresponds to the random match probability (γ).

The second transfer and persistence node "BG fibres matching X on V shirt" (6) has five states and two root nodes resulting in a total of six states that influence it. As shown in Table 6, values of 0 or 1 are assigned depending on the states of the root nodes.

The main findings node "fibres matching X on V shirt" (7) has three states and the two transfer and persistence nodes giving a total of fifteen states that influence it. The assigned probabilities take values of 0, 0.5 or 1 (see Table 7) whereby the accumulation of two '*low*' number of fibres has been considered to be between '*low*' and '*high*' (i.e. insufficient to be considered 'high') and probabilities of 0.5 have been assigned to each low and high to illustrate the model. This decision, however, is dependent on examiner judgement and case circumstances.

After populating all tables, the constructed BN can be run by instantiating (selecting) any of states of the findings node to perform two critical checks. Firstly, absolute support for a single proposition is to be avoided. In our example, all probabilities in the table were assigned values above zero. Instantiating each of the three states of the findings node returns posterior probability values for both propositions and thus satisfies this requirement. Secondly, all findings should be observable under either proposition. By instantiating either state of the propositions node, probabilities are distributed across the three states of the findings node (ie. no single state has probability of either 1 or 0). The constructed BN satisfies these requirements and can be run to evaluate the findings. Instantiating the findings node to a '*high*' number of matching fibres returns a LR of 901 (Fig. 2).

Table 1
CPT for main proposition node (1).

Propositions	Probability
H_p: S tackled V	0.5
H_d: no tackle occurred	0.5

Table 2
CPT for activity node (2) "S tackled V".

Propositions:	Hp: S tackled V	Hd: No tackle occurred
Yes tackle	1	0
No tackle	0	1

Table 3
CPT for transfer node (5) "fibres (X) on V shirt from tackle".

S tackled V:	Yes tackle	No tackle
No fibres	0.01	1
High #	0.90	0
Low #	0.09	0

Table 4
CPT for root node (3) "BG fibres on V shirt".

BG fibres on V shirt	Probability
None	0.80
High #	0.01
Low #	0.19

Table 5
CPT for root node (4) "BG fibres match X (reference)".

BG fibres match X	Probability
Yes BG match	0.1
No BG match	0.9

Table 6
CPT for transfer node (6) "BG fibres matching X on V shirt", where U represents fibres of unknown or other characteristics.

BG fibres on V shirt	None		High # BG fibres		Low # BG fibres	
BG fibres match X	Yes BG match	No match	Yes BG match	No match	Yes BG match	No match
None (no BG fibres)	1	1	0	0	0	0
High # X	0	0	1	0	0	0
Low # X	0	0	0	0	1	0
High # U	0	0	0	1	0	0
Low # U	0	0	0	0	0	1

Additionally, back-propagation of the BN allows the exploration of how different circumstances hypothetically influence the LR. This means that, given a certain outcome within the network, the BN can calculate and update probabilities of preceding states. Such capability also shows the network's adaptability to new information. For example, if it becomes known that matching fibres are present in the background environment (instantiating root node 4 to the '*yes*' state) the LR associated with recovery of a '*high*' number of matching fibres would be 91. Conversely, if such information about background fibres is unavailable and a *low* number of matching fibres were recovered, the LR would be 4.7 (Fig. 3). When '*none*', LR = 0.01 meaning that it is 100 times more likely to observe the findings given no tackle occurred than if S tackled V.

Beyond the evaluation of findings, the network also demonstrates its utility at the pre-assessment stage [36,73] – ie. considering expected

[5] This node is sometimes labelled "Value of Evidence" in literature. Another method of evaluating the strength of the findings is by way of a results node as outlined in [46].

Table 7
CPT for findings node (7) “fibres matching X on V shirt”.

BG fibres matching X on V shirt	None			High #X			Low #X			High #U			Low #U		
S fibres (X) on V shirt from tackle	None	High	Low	None	High	Low	None	High	Low	None	High	Low	None	High	Low
None	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0
High	0	1	0	1	1	1	0	1	0.5	0	1	0	0	1	0
Low	0	0	1	0	0	0	1	0	0.5	0	0	1	0	0	1

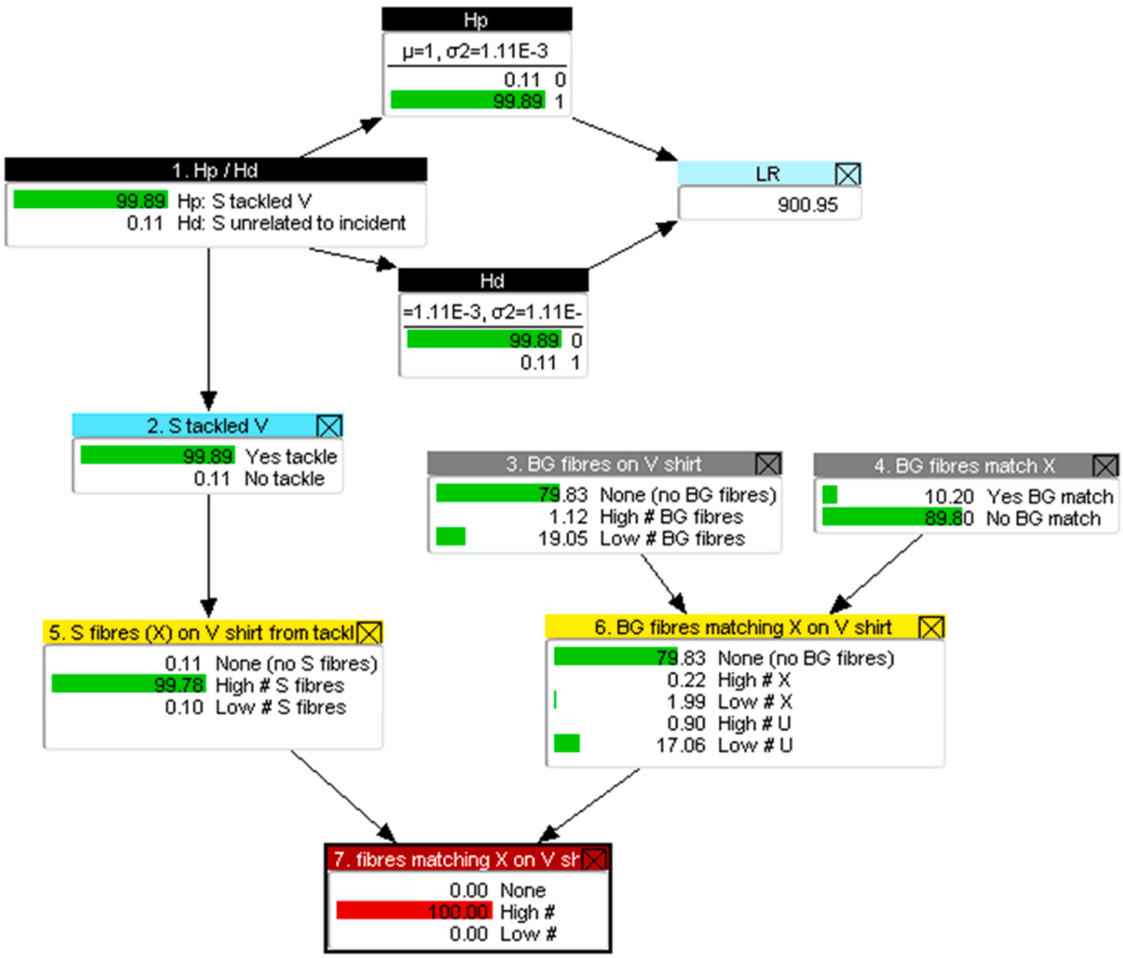

Fig. 2. Bayesian network returns LR = 901 when a high number of fibres matching X are recovered on V’s shirt.

outcomes prior to performing analyses. For example, by setting the probability of H_p in the propositional node (1) to 100 % and H_d to 0 %, the network calculates the probabilities for all possible outcomes assuming Hp is true (Fig. 4).

Thus, the narrative elements and architecture of the BN enhance transparency, clearly communicating to fact-finders and other experts what information has been taken into consideration. This highlights the BN’s broad applicability throughout the investigation process, serving as a valuable tool from the initial case pre-assessment to final evaluation of results.

2.1.2. Scenario B: nature of the activity disputed

We now consider the scenario where S denies assaulting V and claims that they accidentally bumped into them. The activity level propositions are then:

H_p: S tackled V (criminal contact)

H_d: S bumped into V (legitimate contact)

This scenario exemplifies where interpretation at the source level would be uninformative, as the source of the trace is not in question. Compared to the BN for Scenario A (Fig. 1), the BN constructed for the new set of propositions shown in Fig. 5 features additional nodes. The alternate proposition (dispute of the defence) requires us to consider the nature of the questioned activity, with legitimate presence of the trace material from bumping. This requires an additional activity node “S bumped into V” (3).

Corresponding probabilities of fibres transferring and persisting are assigned in the node “S fibres on V shirt from bumping” (7). The relative probability of none or a low number transferring from bumping is expected to be greater than tackling, whereas the probability of a high number of fibres is anticipated to be smaller. As such, the states of ‘*none*’, ‘*low*’ and ‘*high*’ have been assigned 0.10, 0.89 and 0.01, respectively.

It is visually evident from the network structure that three possible explanations for the recovery of fibres matching X on V’s shirt have been considered in the evaluation.

The main findings node (9) has three states and the accumulation of three transfer and persistence nodes giving a total of 126 states. As for scenario A, the probabilities are assigned values of 0, 0.5 or 1.

The BN can be run following validation of the network structure

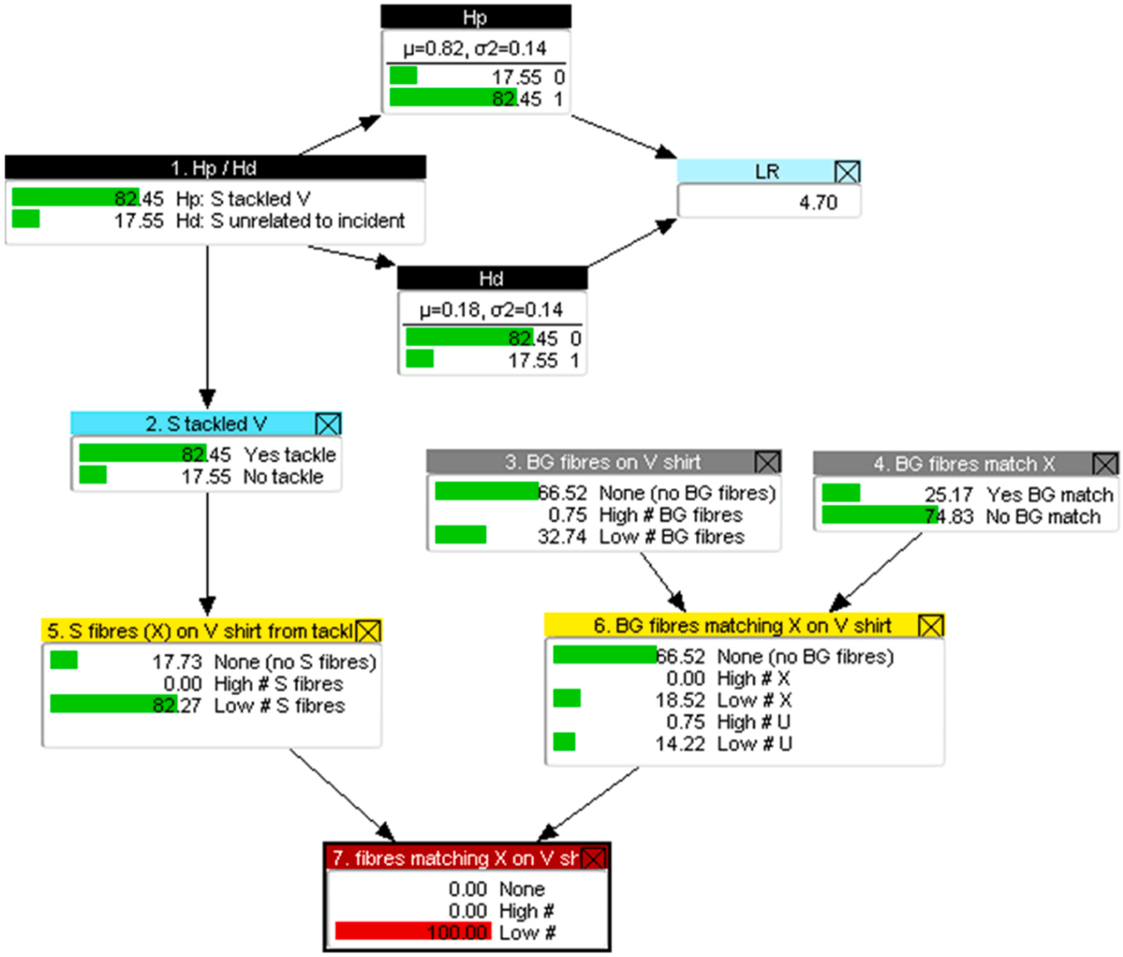

Fig. 3. Bayesian network returns LR = 4.7 when a low number of fibres matching X are recovered on V's shirt.

(Step 6 in 2.1.1.6). Setting the findings to the case result of a *high* number of matching fibres, the BN calculates a LR of 46 (Fig. 6). The network returns a LR of 0.1 for when either *low* or *none* is instantiated, meaning that such findings are 10 times more likely to be observed if H_d were true and S bumped into V. However, this result may vary upon updating the probability values in the transfer and persistence node (6). In practice, it can also be anticipated that location of recovered fibres may have a considerable influence on the evidential value and can be incorporated into the evaluation for by extending the network structure.

The root nodes (4, 5) have a similar effect on the LR as was shown for Scenario A. Given the scenario findings of a high number of matching fibres, the absence of fibres matching X in the background environment (node 5) returns a LR of 90; whereas their presence unremarkably provides a lower LR of 8.7. This is helpful as the network updates the assigned probabilities in node 8 (BG fibres matching X recovered on V shirt) (Fig. 7).

Crucially, this scenario highlights the narrative BN framework in incorporating realistic alternative propositions which are pertinent in practical casework. The network's architecture visually represents the alternative activity and its distinct pathway for potential transfer of fibres, making the considerations for both propositions transparent, user-friendly and readily explainable in the overall evaluation.

2.1.3. *Scenario C: actor performing the activity disputed*

If we suppose that S denies assaulting the victim and claims no prior contact with V, but claims that someone else assaulted the victim. In contrast to Scenario B, the occurrence of an assault is not in question; however, the dispute concerns the actor being an alternate offender (AO). This leads to the following propositions:

H_p: S tackled V (suspect-oriented contact)

H_d: Another offender (AO) tackled V (alternate offender-oriented contact)

The resultant structure for this scenario is shown in Fig. 8.

The activity node "AO tackled V" (3) accounts for considering the presence – or absence – of fibres transferred from an individual other than the suspect.

In the previous scenarios, where the activity was in question, the evaluation focused solely on fibres matching the suspect's garment (X) on V's shirt. Non-matching fibres were not considered relevant, as their presence would not directly affect the posterior probability of matching fibres transferring and resultant evaluative outcome.

However, Scenario C introduces an unknown offender and, consequently, an unknown garment with undefined extrinsic and intrinsic characteristics. Therefore, the presence of both matching and non-matching fibres must be included in the evaluation. These fibres could be recovered from the suspect's reference garment (X), the background environment, or from an unknown garment of the alternate offender. To address this, an additional findings node "fibres not matching X on V shirt" (11) is created, defined by three states of '*none*', '*high*' or a '*low*' number.

The node "AO fibres on V shirt from tackling" (5) considers mechanisms of fibre transfer and persistence associated with the activity under the defence proposition. It is defined by three states (*none*, *high* or a *low* number of AO fibres), analogous to the corresponding node for H_p ("S fibres (X) on V shirt from tackling" [8]).

Given that the properties of AO fibres are unknown, the probability

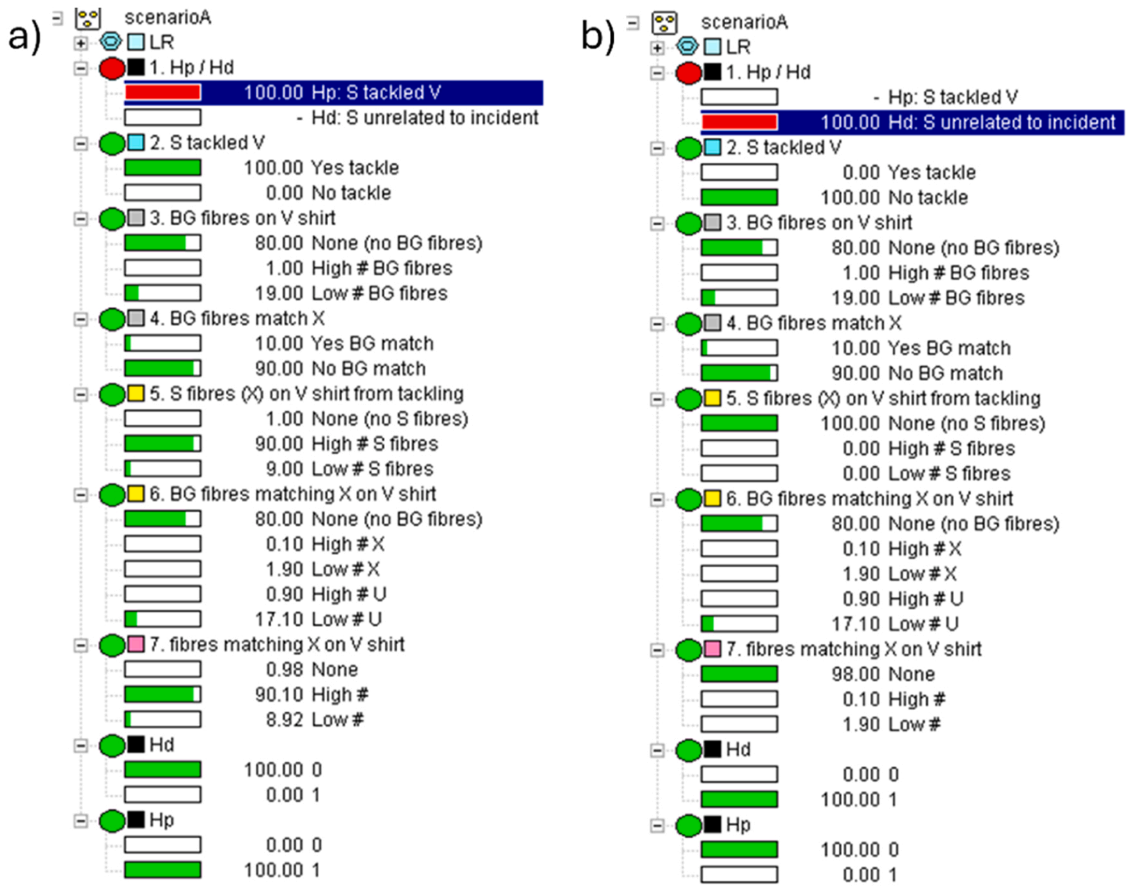

Fig. 4. Bayesian network used for pre-assessment when instantiated for a) Hp; and b) Hd.

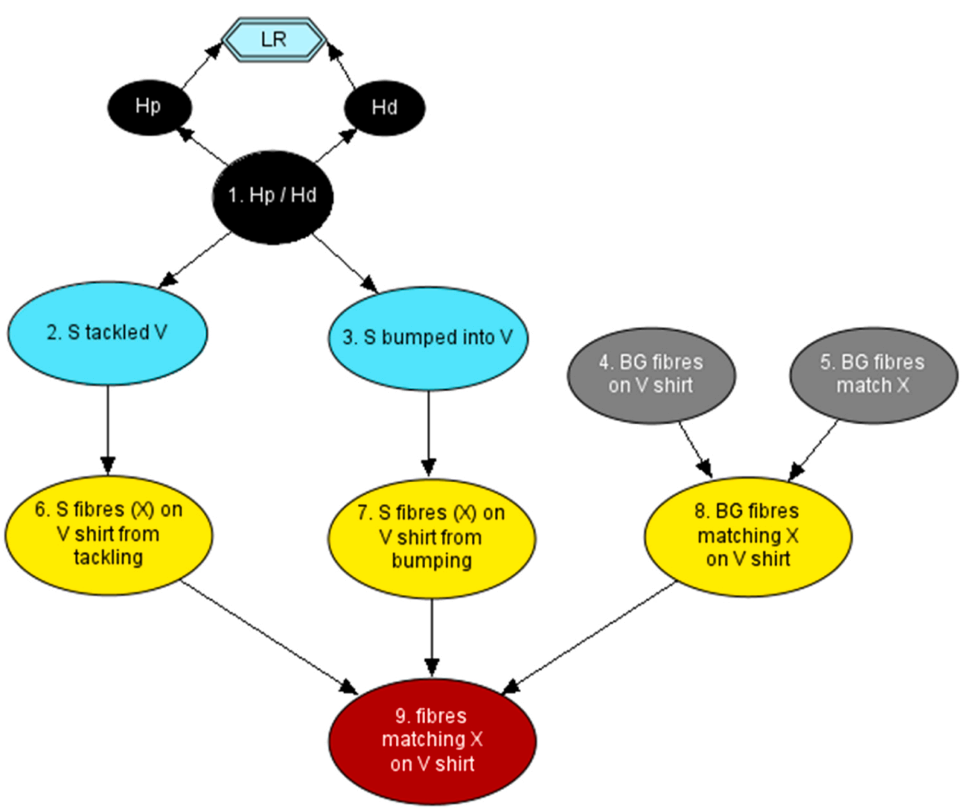

Fig. 5. Bayesian network constructed for Scenario B considering an alternate activity.

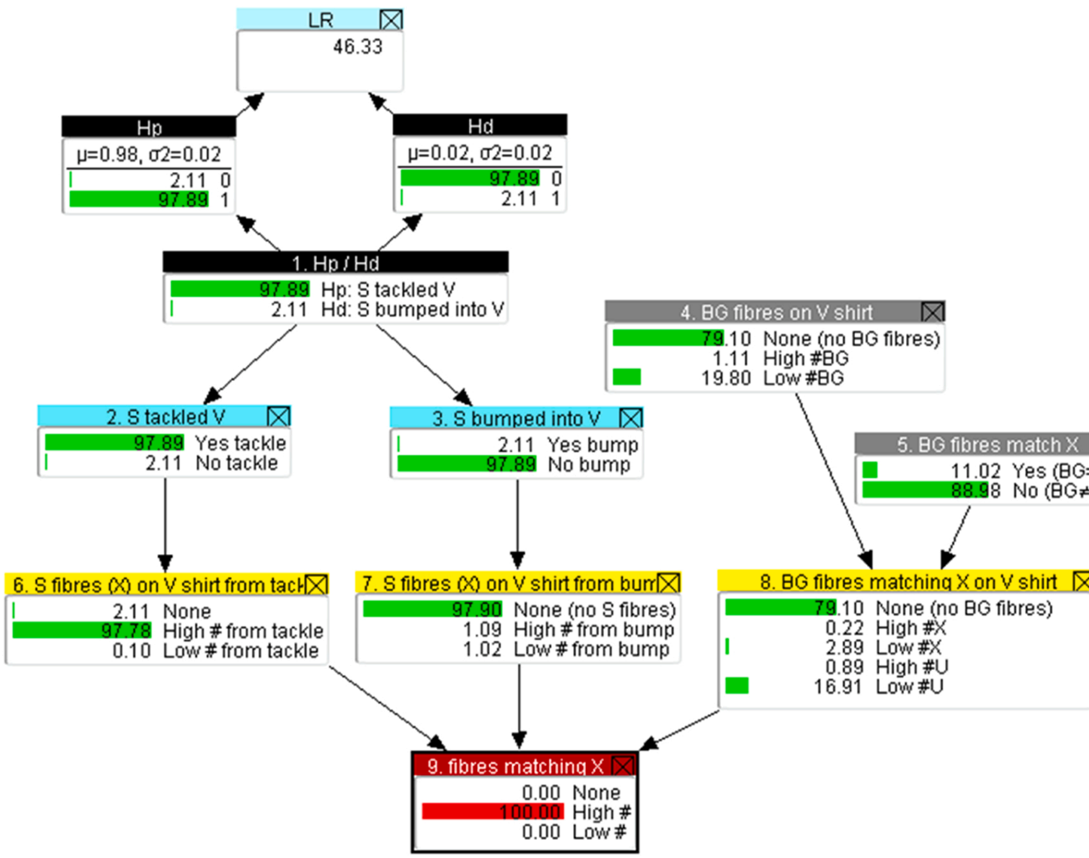

Fig. 6. BN returns LR = 46 when high number of fibres matching X recovered on V's shirt.

of transfer and persistence for both matching and non-matching fibres needs to be incorporated. This secondary step in the process is achieved by creating a child node "AO fibres on V shirt" (9) with six states of *none*, a *high* and *low number matching*, a *high* and *low number of non-matching*, and a *mixture* of matching and non-matching fibres, as summarised in Table 8. The probability of AO fibres matching X is considered in the addition of a binary root node "AO fibres match X" (4) with states '*yes*' and '*no*'. In the event these have different characteristics, this node would be in the 'false' state with a probability of (1 – match probability [γ]).

Similarly, transfer from the background environment must also account for both matching and non-matching fibres. Hence, the node "BG result on V shirt" (10) is defined with the same six states as (9) and is connected to both findings nodes.

The probability tables of the activity nodes (2, 3) and root nodes (6, 7) remain the same as in the previous two scenarios. Likewise, the assigned probabilities in the transfer and persistence nodes "S fibres (X) on V shirt from tackling"(8) and "AO fibres on V shirt from tackling"(5) remain unchanged as there is no specific information about either the suspect or the alternate offender (eg. height and build) that would suggest different transfer probabilities.

Following validation of the network structure, setting the findings node for matching fibres to the case result of a '*high*' number yields a LR of 3.4 (see Fig. 9). If it is additionally known that there are '*none*' non-matching fibres (node 11), it is logical that a slightly higher LR of 3.6 is returned.

The relatively lower LR values calculated in this scenario, compared to the previous ones, clearly illustrate the effect of introducing more variables and greater uncertainty. This holds true even if no non-matching fibres are recovered, which is expected as the characteristics of the AO garment and fibres are not known.

Until this point in the scenario, only the suspect's garment has been recovered; no garment or information related to the alternate offender is available. However, the BN can be used to explore the impact of additional information on the value of the findings. For example, if a garment from AO was recovered and the AO fibres found to not match X, instantiation of the root node (4) results in a LR of 17.9. Conversely, if they do match, the LR is 1.9. While the specific assigned probabilities within the network would require revision based on the unique circumstances of each case, with the current values being for exemplary purposes, this demonstrates the BN's utility in helping the expert establish preliminary expectations and guide decision making.

3. Discussion and concluding remarks

BNs are increasingly recognised as valuable tools for evidence evaluation, however their application in forensic fibre examination remains limited and rooted in conventional representations. These are largely viewed as complex to construct, interpret and explain, limiting the use of BNs in practice. This contrasts with the growing trend in forensic biology and other specialty areas towards a qualitative narrative style of BN. Ensuring greater transparency in communicating scientific opinion is fundamental in forensic science, along with the logic and reasoning that informed the scientist's conclusions [4,74]. The accessible and qualitative nature of narrative BNs provide a solution to assist consideration of this crucial issue. However, whilst practitioner guidance in the form of accessible template models have been developed for other traces, no exemplar specific to textile fibres has been presented to date.

Our work aimed to bridge these gaps by developing a template model for constructing narrative BNs for the evaluation of fibre transfer evidence given activity level propositions including disputes about the actor and/or the activity. We believe that such models will promote the adoption of both activity-level evaluation and narrative BNs for fibre evidence, in alignment with advancements in other forensic disciplines.

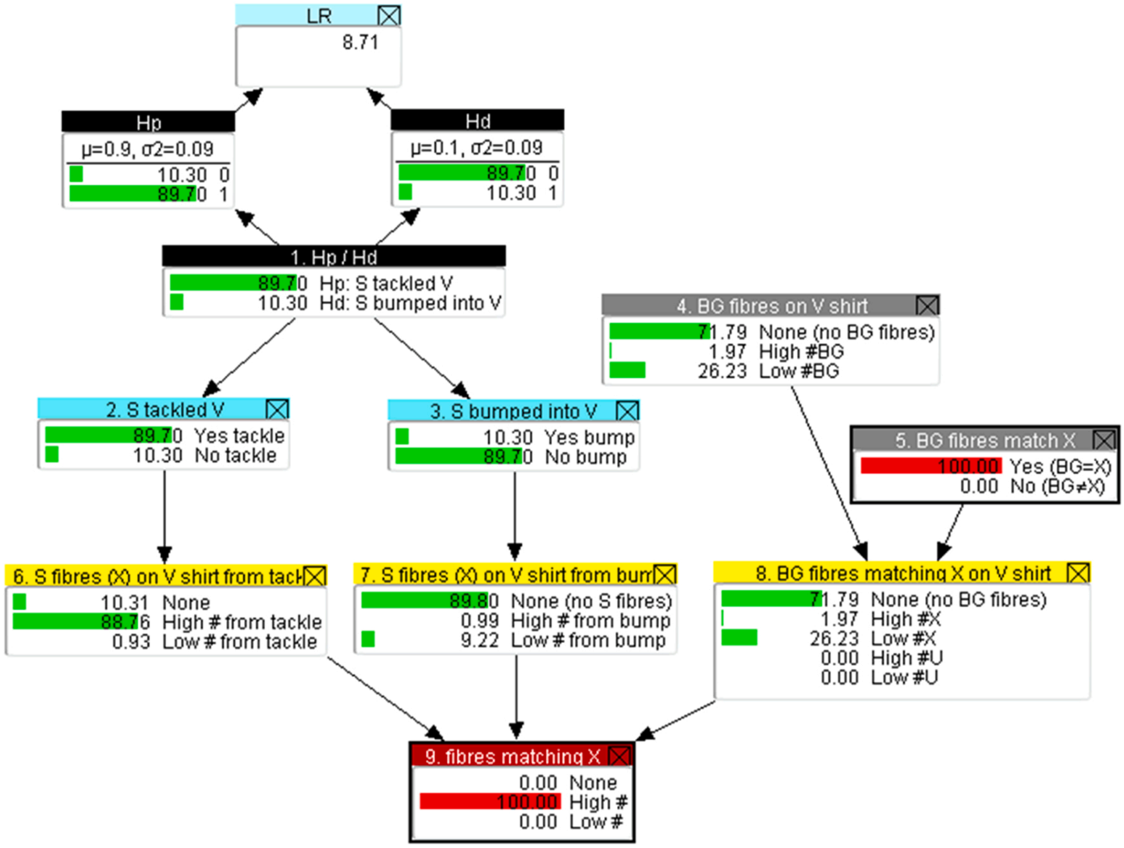

Fig. 7. BN returns LR = 8.7 when high number of fibres matching X are recovered on V's shirt node 5 is instantiated such that fibres matching X are present in the background environment. The network updates the probabilities in node 8 to indicate a higher probability (26.23 %) of recovering BG fibres matching X on V's shirt.

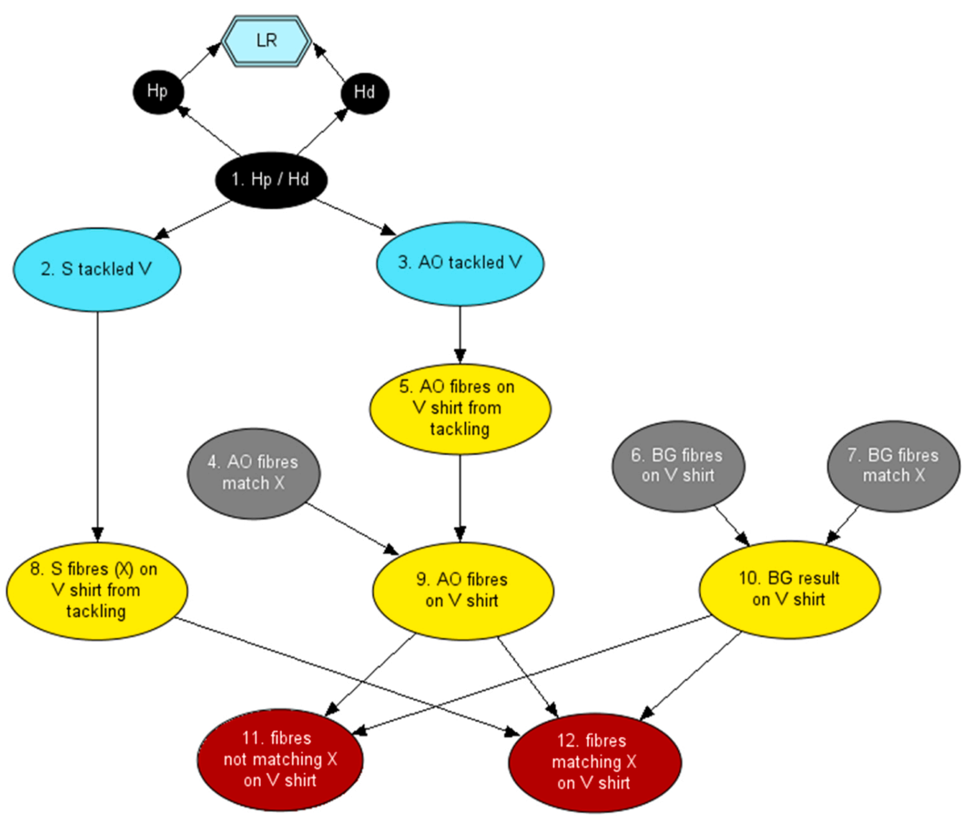

Fig. 8. Bayesian network constructed for Scenario C considering an alternate offender (AO).

Table 8
Summary table of the transfer and findings nodes and corresponding states for Scenario C, taking into consideration the presence of matching (=X) and non-matching (≠X) fibres.

Node	States
8. S fibres (X) on V shirt from tackling	None, High #X, Low #X
9. AO fibres on V shirt	None, High #AO=X, Low #AO=X, High #AO≠X, Low #AO≠X, Mixture
10. BG result on V shirt	None, High #BG=X, Low #BG=X, High #U(BG≠X), Low #U(BG≠X), Mixture
11. Fibres not matching on V shirt	None, High #U(≠X), Low #U(≠X)
12. Fibres matching X on V shirt	None, High #X, Low #X

A consolidated approach also shows great potential in supporting the evaluation of a combination of traces and collaborative interdisciplinary approach in casework.

The case scenarios presented have been intentionally designed as, although simplistic, they provide a starting ground for further development in practice. For example, only one-way transfer has been modelled in this paper, however, other mechanisms including two-way and secondary transfer are often relevant considerations to be addressed in casework. The network may also be extended to address other factors such as the location of recovered fibres. However, by limiting the number of mechanisms and focusing on considerations applicable across a broad range of situations, we aim to illustrate the BN construction process in a simple, clear and understandable manner. Adapting the network structure to consider additional factors may be grounds for future research.

The presented scenario assumes the suspect wore the garment of interest, establishing a direct link between the transferred fibres and the individual. However, in practical casework, the wearer of the garment may be another source of uncertainty that requires consideration. Taroni et al. [71] have demonstrated the importance of accounting for the relevance of the garment in activity level evaluation using conventional BNs. The narrative BNs developed in this work can be further extended to explicitly address this potential uncertainty.

Step 6 in BN construction involves assigning probabilities to the conditional probability tables within each node. The probability values used in these illustrative examples were informed by available literature and expert judgement; however, it is to be emphasised that these examples are illustrative. In practice, these can be further refined by incorporating data from directed empirical studies relevant to the specific circumstances, often limited by resource availability and casework pressures. Probability assignments drew on a combination of published data and experimental work by the authors under conditions analogous to the mock scenario [24,67,75]. A dedicated empirical study that more precisely mirrors the scenario, combined with practitioner feedback, would offer a valuable direction for future research. When data is limited or assigned values are based on uncertain assumptions or sources, conducting a sensitivity analysis is crucial. This models the impact of uncertainty on the LR, i.e. demonstrating how sensitive the network and LR calculations are to variations in probability values or data within each node. Whilst a detailed sensitivity analysis is beyond the scope of this paper, it is particularly important in casework to ensure the robustness of the evaluation [14], and practical guidance has been made available [76]. Presenting the case example BNs, their underlying probability tables and detailing the structuring of relevant reasoning processes serve as a foundational stimulus for further research into these critical aspects.

The LR values obtained in our scenarios may be considered relatively low (0.01 < LR < 100), corresponding to a weak to moderate level of support for the prosecution proposition according to established scales

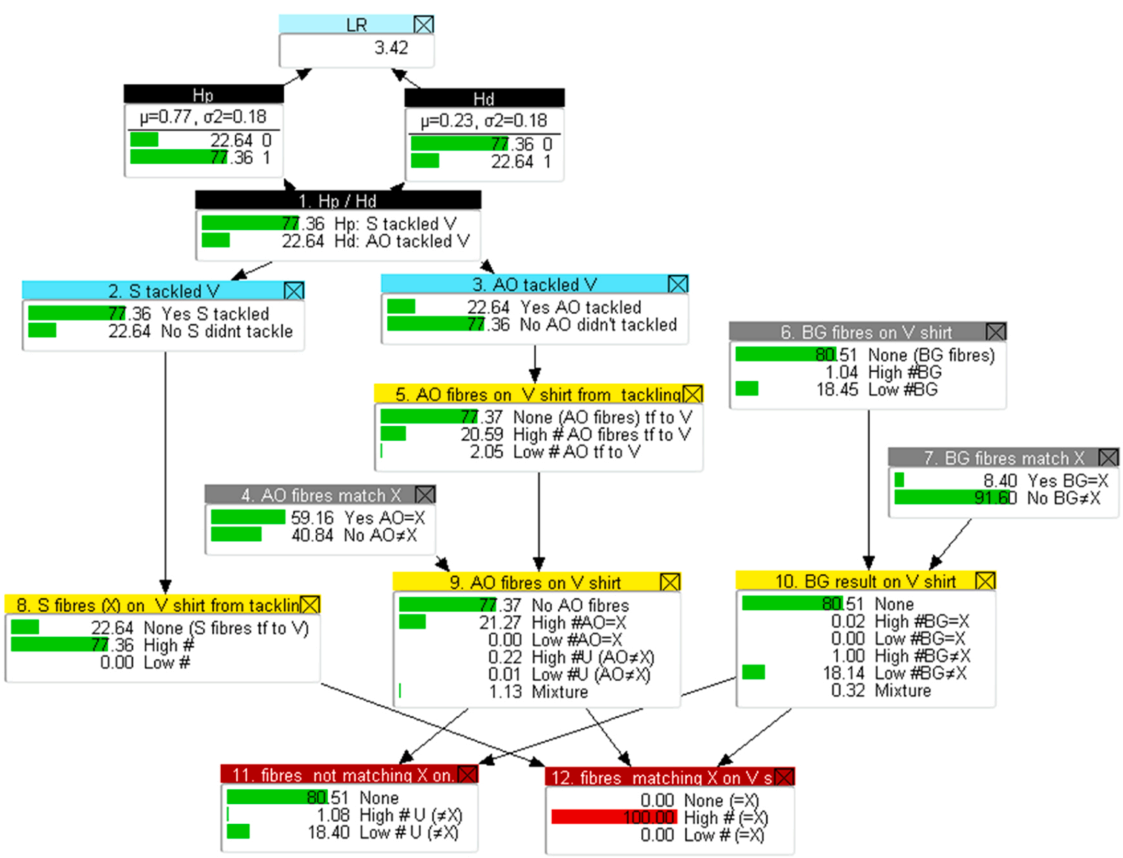

Fig. 9. Bayesian network returns LR = 3.4 when a high number of fibres matching X are recovered.

[14,69]. Notably, findings of comparable magnitude have also been reported in other studies in activity level evaluation across various trace types [61]. While this study applied widely cited interpretive guidelines, it is acknowledged that tailored, consensus-based verbal scales may be developed within laboratories or specifically for activity-level reporting. As such, the verbal level of support assigned to a given LR may vary across expert groups and jurisdictions, depending on local practices and thresholds [77,78]. Crucially, these modest LRs should not be equated with limited evidential value. Expert evaluation at the activity level addresses questions of closer primary interest to the Court, thereby limiting the risk of incorrectly transferring source-level conclusions to activity and offence without expert knowledge and guidance. Furthermore, the value of fibre evidence is additive; it contributes to the overall weight of evidence when considered alongside other findings in a case.

BNs inherently reflect the expert's understanding and perception of the domain at a given point in time. However, a key advantage of BNs lies in their flexibility; their structure and the assignment of probability values can be readily modified as new information emerges [79]. Furthermore, the influence of certain parameters on the likelihood of an outcome can readily be assessed and presented, thus enhancing the transparency of the entire evaluation process. This transparency aligns directly with fundamental principles in interpretation and evaluative reporting, reinforcing the critical need for forensic scientists to articulate their opinions in a clear, accurate and readily understandable manner for the Court as decision-makers, explicitly outlining the logical pathway leading to their conclusions. This clarity is particularly crucial when dealing with complex scientific and mathematical concepts, helping to avoid ambiguity and potential misinterpretation.

Despite advancements in the technical and analytical capabilities within forensic science, persistent challenges remain in interpretation rather than the technical aspects of analysis [74]. This echoes Kirk's observations from 1963, highlighting an ongoing historical trend where progress has been more focused on practical developments than on a deeper understanding of fundamental principles [80,81]. Indeed, as the volume and complexity of data increase, along with the multitude of various factors, their interdependencies and consideration of their relevance in given case circumstances continue to increase, these challenges in interpretation are set to increase. Consequently, it is to be stressed the need for a greater focus on the evaluating the trace in the context of circumstances to promote a more holistic and integrated approach to forensic evaluation [65].

Bayesian networks offer a powerful solution and valuable tool to address these existing challenges. However, a notable disparity is emerging in the representation and application of BNs across different forensic trace types. While forensic biology and other disciplines are increasingly embracing narrative-style BNs, developments in the textile fibre domain tend to pursue and illustrate the conventional BN approach [63,64]. This divergence occurs amidst a growing demand for activity level evaluations and discussions stressing the importance of a holistic, interdisciplinary and case-based approach to forensic science investigations [4,65,82]. This confluence of factors creates a strong impetus for a unified modelling approach. Such would facilitate the evaluation of a combination of diverse trace types within a single, coherent framework, given a unified set of activity-level propositions, thereby significantly enhancing interdisciplinary collaboration in casework [83]. Indeed, an increasing shift towards collaborative practices has been reported within institutions such as the Netherlands Forensic Institute [84].

Overall, this work presented provides a practical template to support practitioners in constructing narrative BNs for evaluating results of forensic fibre examination given questions of activity. By making the construction and reasoning process more accessible to experts and non-experts, this approach has the potential to improve the adoption and effective use of BNs in forensic casework. Ultimately, this contributes to enhancing the interpretation and value of fibre and microtrace evidence, fostering a more holistic and interdisciplinary approach to evaluation.

CRediT authorship contribution statement

Victoria Lau: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Xanthe Spindler:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Claude Roux:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2025.112586.

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