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A template Bayesian network for combining forensic evidence on an item with an uncertain relation to the disputed activities

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ABSTRACT

Most of the forensic evidence evaluations given activity level propositions are centered around an item which is assumed to be linked to an alleged activity. However, the relation between an item of interest and an activity may be contested. This study presents a template Bayesian network (BN) for the evaluation of transfer evidence given activity level propositions considering a dispute about the relation of an item to one or more activities. The template BN includes a set of association propositions that enables the combined evaluation of evidence concerning alleged activities of the suspect and evidence concerning the use of an alleged item in those activities. Since the two types of evidence are often from different forensic disciplines, the BN is especially useful in interdisciplinary casework. Throughout the paper, we use a fictive case example that captures the essence of cases for which the template model can be used. The template BN provides a flexible starting point that can be adapted to specific case situations and supports structured probabilistic reasoning by a forensic scientist.

1. Introduction

Evaluating *transfer evidence* [1] given *activity level propositions* [2] can be challenging due to various factors, such as the number of variables involved and their possible dependencies. Bayesian networks (BNs) have proven to be useful for modeling an expert's reasoning about complex events and for facilitating the derivation of likelihood ratios (LRs). In fact, many studies, e.g. Refs. [3–20], have published BNs as useful tools to support the evaluation of evidence considering activity level propositions.

Recently in 2023, Vink and Sjerps [13] presented a template model that originated from using the idiom-based approach to modeling BNs (see for example [21,22]). The template model is a generalization of the template model presented by Taylor et al. [11] for constructing BNs in forensic biology cases when considering activity level propositions. It also incorporates the ideas of Kokshoorn et al. [7] on propositions disputing the actor or activity in DNA evidence evaluation. In essence, the template model from Ref. [13] is a tool meant to be used by forensic experts for evaluations when the actor, the activity, or both are in dispute.

In the template model from Ref. [13], the item of interest (hereafter: item) is assumed to be used by the offender during an activity. But the latter might as well be an additional uncertainty. The uncertainty surrounding the connection between a crime stain or trace material and the offender (also referred to as the *relevance* of trace material), has been studied by various authors [1,5,23,24]. In 2012, Taroni et al. [25] applied this foundational work to evidence evaluations with BNs given activity level propositions. They state that "uncertainty about the item actually worn by the suspect thus represents an issue that current evaluative procedures at activity level do not account for" (p. 178). The authors present a case example in which fibers found at the crime scene match those from a pullover owned by the suspect. However, it is uncertain whether the suspect actually wore the pullover during the offense or not. In most recent work by Kokshoorn and Luijsterburg [26] and Taylor and Kokshoorn [20] case examples are mentioned where disputes over the relation between item and activity are currently taking place. In all case examples, the link between an item of clothing and the incident was uncertain and questions arose whether the item of clothing was worn during the offense or not.

The vast majority of the earlier research focuses on monodisciplinair evaluations. There is a growing demand to evaluate evidence given activity level propositions, including DNA and other types of evidence. Consequently, there is an increasing interest to evaluate a combination of different types of evidence given a single set of activity level

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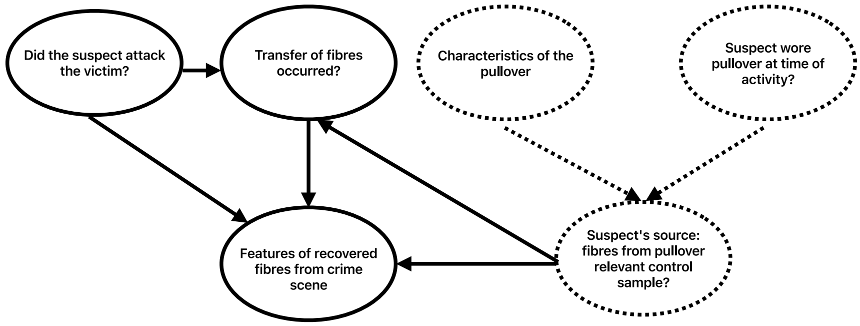
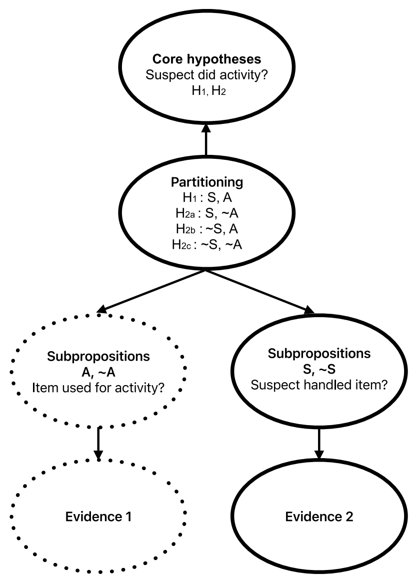


(a) Modeling the relation between suspect and a pullover in [25]



(b) Modeling the combination of two primary evaluations in [27]

Fig. 1. Various ways of modeling item—activity uncertainty. In (a) and (b), the modeling parts concerning item—activity are marked with dotted lines.

propositions. This increasing wish is confirmed by Kokshoorn and Luijsterburg [26] who report an increasing number of interdisciplinary collaborations in casework at the Netherlands Forensic Institute.

In 2020, De Koeijer et al. [27] published a study on combining evidential strength in interdisciplinary casework, with a specific focus on the uncertainty surrounding the relation between an item and an activity. The research states that assessing the value of evidence, given the connection between a suspect and an alleged activity, often requires multiple evaluations from one or several disciplines. These evaluations may concern a dispute over the relation between a person and an activity and/or a dispute over the relation between the item and a person or activity. Although the authors provide a framework for combining LRs from various disciplines, they do not present a model that includes the underlying evaluations of the different disciplines. To the best our knowledge, no template BN has been published that is sufficiently flexible to evaluate a combination of forensic evidence from different disciplines in cases with disputes about the actor and/or activity and/or the relation between an item of interest and an activity.

This research developed such a template model for evidence evaluations given activity level propositions. Since our focus is on reasoning and the qualitative structure of the BN, we do not aim to model every aspect of a case or provide probabilities for a specific case. Instead, our goal is to offer a flexible template model that can be adapted to various cases, promoting the uptake of BNs by forensic experts in casework. Therefore, our case examples will highlight certain parts of the case but will omit others. In Section 2, we will elaborate on the work of de Koeijer et al. [27] and Taroni et al. [10,25]. They previously modeled the uncertain relationship between an alleged item and an activity using a BN, which forms the basis of our work. In Section 3, we present a basic scenario involving a strangling incident. We start by modeling the evaluation of DNA traces found on a sweater, believed to have been worn by the offender during the incident, using the template model from Vink and Sjerps [13]. Section 4 will extend the fictitious case scenario with fiber evidence, proposing a case model that includes a dispute about the connection between the sweater and the alleged activity. In Section 5, we will generalize the case model and present an extended version of the template model from Ref. [13] that can be applied to a range of cases. Finally, Section 6 will demonstrate the flexibility of our template model by applying it to two more case variations. The BNs illustrated in Sections 3 to 6 are provided as Supplementary material.

Table 1
Summary of model choices by Taroni et al. [25], de Koeijer et al. [27], and current study.

	Focus	Questioned item—activity	Modeled as
Taroni et al.	Monodisplinary	Item being used by suspect at time of activity 1	Additional uncertainty in main evaluation given propositions addressing the actor
De Koeijer et al.	Interdisciplinary	Item being used by suspect or unknown during activity 1 or alternative activity 2	One of two primary evaluations that are combined to evaluate evidence considering propositions addressing the actor
Current study	Interdiscplinary	Item being used by suspect or unknown during activity 1 or alternative activity 2	Subevaluation within the evaluation given propositions addressing the actor and/or activity

2. The probabilistic relation between an item of interest and an activity

2.1. What is (un)disputed?

When evaluating transfer evidence given activity level propositions, the focus is usually on traces from items that are assumed to be related to an activity in the disputed propositions. For example, consider a stabbing incident with activity level propositions:

H_1: Mr. X stabbed Mr. Y.
H_2: An unknown person (other than Mr. X) stabbed Mr. Y.

One of the evaluations can be that of DNA traces on a knife of interest that is assumed to have been used by the offender to stab Mr. Y. The DNA expert will assign the probability of the findings given each proposition and report an LR.

In addition to the disputed actor in H_1 and H_2, the relation between the knife and the stabbing may also be questioned. In other words, it is uncertain whether the knife was used to stab Mr. Yand if the DNA traces on the knife can be connected to the actual offender. This uncertainty is likely to affect the evaluation of the DNA evidence under H_1 and H_2. This analysis draws on early foundational works such as Stoney [23], Evett [24], Garbolini and Taroni [5], and Taroni et al. [25]. We will demonstrate the influence of the uncertain relation between item and activity in Section 4.1.2.

Thus, a dispute about the relation between an item and an activity[1] refers to differing opinions on the involvement of a particular item in one or more activities, as stated in the propositions. We have now defined what is being disputed when we mention item—activity uncertainty. The following section discusses concepts from previous modeling establishments that will be applied in our proposed model.

2.1.1. Modeling uncertain item—activity relations: previous studies

Modeling the potential transfer paths of traces from an activity to an item requires the assumption that the item was used during the activity. If there is uncertainty in the item being used during the activity, it should be incorporated in the evaluation of evidence given activity level propositions. Few studies, such as those by Taroni et al. [25] and de Koeijer [27], have specifically focused on incorporating this uncertainty into modeling evaluations that consider activity level propositions (see Fig. 1).

Taroni et al. [25] present a case example in which fibers found at the crime scene match those from a pullover owned by the suspect. Although owned by the suspect, it is uncertain whether the pullover was worn by the suspect during the offense or not. They introduce a new unobserved variable, the *suspect's source*, that represents the characteristics of the garment that the suspect wore at time of the activity. If the pullover was worn at the time of the alleged activity, then the pullover equals the suspect's source and the fibers from the pullover are the "relevant" control sample. The uncertainty of the pullover being worn by the suspect is incorporated in the evaluation of the fiber evidence by conditioning Transfer of fibers occurred? and Features of recovered fibers from crime scene on suspect's source. As such, their model includes a primary dispute centering on the actor of the attack, with the connection between the pullover and the suspect treated as an uncertain factor. In summary, their model is monodisciplinary, focusing on fiber evidence and the connection between the pullover and the suspect rather than the pullover and the offender.

In 2021, Taroni et al. [10] expanded upon this work by including more possibilities of the transfer of (matching) fibers, such as through secondary transfer from suspect to unknown person to crime scene. This research is still monodisciplinary and addresses the issue of the suspect's pullover as a secondary dispute within the main dispute.

Another way of modeling is presented by De Koeijer et al. [27]. They illustrate a BN that separates the evaluation of evidence regarding suspect-activity relation into two subevaluations (Fig. 1b): "was the item used for the activity?" (left) and "did the suspect handle the item during the same time period as the alleged activity?" (right). The BN will yield a combined LR of the two subevaluations. In conclusion, their work is interdisciplinary, it concentrates on two primary evaluations that are eventually combined, and is suitable for cases where there is uncertainty about the use of the item in both activities considered.

Table 1 summarizes the differences between the two models in Refs. [25,27] and outlines the focus of this paper. Our approach differs from that of Taroni et al. [25] in that it evaluates evidence given item—activity propositions that include the relation between an item and the offender rather than solely the suspect during the incident. We believe this evaluation is a an additional evaluation within the primary evaluation. Since this evaluation might be conducted by a different forensic discipline than the primary one, our approach is interdisciplinary.

The distinction between De Koeijer et al.'s model [27] and the template model in the current study lies in our consideration of item—activity as an additional dispute in the primary evaluation. In De Koeijer et al., the evaluation of evidence given the item—activity relation is one of two primary evaluations that needs to be combined with a second evaluation of evidence concerning the suspect—item relation to draw conclusions about the probability of the combined evidence given the main propositions. We believe that the item—activity relation uncertainty introduces *association propositions*, as suggested by Evett [24][2], and that the uncertainty surrounding these association propositions could impact the evaluation of evidence given the activity level propositions addressing the actor and/or activity.

Last, what distinguishes our research from both previous studies is that our template model will be structured similarly to the template model from Ref. [13], which follows the ideas in Taylor et al. [11], with possible transfer paths from alleged activities to an item of interest.

In the following sections, we will recap and expand the template model from Ref. [13] to accommodate interdisciplinary casework. This model addresses disputes over the actor and/or activity, conditioned on disputes over the relation between items and contested activities.

[1] For readability purposes, we will sometimes refer to the relation between an item and an activity as 'item—activity'.

[2] Evett introduced association propositions to address the uncertainty concerning the relevance of a crime stain. For example, H_1: the crime stain came from the offender and H_2: the crime stain did not come from the offender.

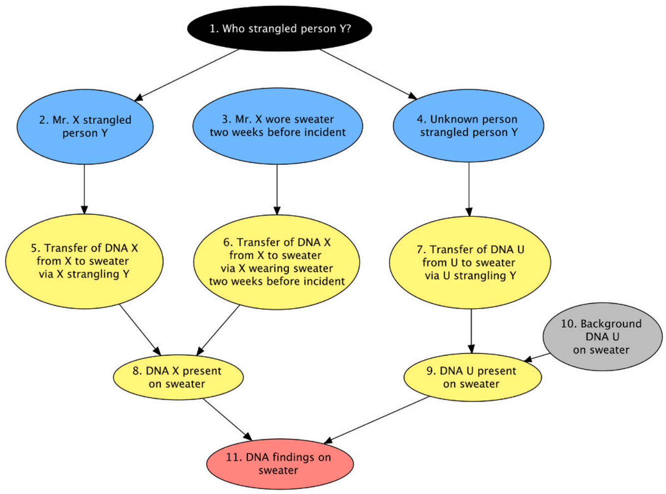


Fig. 2. Case model created using the template model from [13].

Table 2
The CPT for Transfer of DNA X from X to sweater via X strangling Y (5).

5. Transfer of DNA X from X to sweater via X strangling Y		
2. Mr. X strangled person Y	False	True
False	1	(1-p)
True	0	p

3. Recap of the template model from Vink and Sjerps [13]

The template model from Ref. [13] specifies various possible routes of traces from an activity to the item of interest (hereafter: item). Each path begins with an activity node concerning an activity that possibly leads to trace deposition. Following each activity node is a transfer node that specifies the expected transfer of a certain trace type to the item, given the activity specified in the parent activity node. Traces of the same type on the same item can be combined in an accumulation node. The model can be concluded with a case findings node that summarizes all case findings on the various items. We start with a fictive case example to illustrate the use of the template model from Ref. [13]. This fictive case example will be expanded upon throughout the paper.

3.1. Case scenario

Person Y was found strangled to death in her apartment. A blue sweater is found in one of the garbage bins outside the apartment. The sweater is analyzed for wearer DNA. A sample is taken from the inside of the sweater at the neck band. A database match leads to Mr. X, who becomes the suspect. The prosecution believes that Mr. X strangled person Y. Mr. X denies any involvement in the incident.[3] He claims the sweater is his, yet he donated it to a second-hand shop two weeks ago, and states that someone else (unknown to Mr. X) must have strangled person Y. The case considers the actor of the strangulation as disputed. It is assumed that the sweater was worn by the offender during the incident. Consider the following activity level propositions:

H_1: Mr. X strangled person Y.
H_2: An unknown person (other than X) strangled person Y.
I: Mr. X wore the sweater two weeks before the incident.

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

3.1.1. Case model

Fig. 2 shows the case example that has been modeled using the template model. The nodes are numbered and follow the color scheme from Ref. [11]: black for proposition nodes, blue for activity nodes, yellow for transfer and accumulation nodes, red for case finding nodes, and grey for root nodes. We constructed the BNs using the software Hugin Expert (www.hugin.com) and they are all available as Supplementary material. Furthermore, we only show some of the conditional probability tables (CPTs) in the text, the others may also be found in the BNs in the Supplementary material. The conditional probabilities in the CPTs are set by us and do not represent expert opinion. In a real case, the numbers should be set by a DNA expert.

Following the proposition node who strangled person y? (1) we define three activity nodes.

2. mr. x strangled person y
3. Mr. X wore sweater two weeks before incident
4. unknown person strangled person y

There are two paths following from the proposition node: one from mr. x strangled person y (2) and one from unknown person strangled person y (4). There is no directed link from the proposition node to Mr. X wore sweater two weeks before incident (3) as this activity is assumed to be true, irrespective of the identity of the strangler. Consequently, node 3 has a single state 'yes' with probability 1.

Second, we defined three transfer[4,5] nodes that capture the potential transfer of specific trace types to the sweater via the three subactivities.

5. transfer of dna x from x to sweater via x strangling y
6. Transfer of DNA X from X to sweater via X wearing sweater two weeks before incident
7. transfer of dna u from u to sweater via u strangling y

Table 2 shows the CPT of transfer of dna x from x to sweater via x strangling y (5) and includes the probability p, which is the probability of transfer of DNA of X from X to the sweater given that Mr. X strangled person Y[6]. The CPTs of the other transfer nodes (nodes 6 and 7) are structured similarly. Since two out of three activities may lead to the presence of DNA of X on the sweater, we use an accumulation node (8) to summarize the presence of DNA of X on the sweater. The two accumulation nodes are.

8. DNA X present on sweater
9. DNA U present on sweater

The presence of 'unknown DNA' may also be explained by 'background DNA'. We define background DNA as the presence of DNA of an unknown person due to another activity that has nothing to do with strangling person Y. For example, friends of Mr. X whom he met two weeks prior to the incident. This is modeled as a root node.

10. Background DNA U on sweater

We decided against adding a background node for the presence of DNA from Mr. X on the sweater because the possibility of DNA transfer

[4] These nodes also reflect the persistence and recovery of traces.
[5] Since the transfer of DNA of Y to the sweater is expected in equal amounts under both H_1 and H_2 we did not include this in Fig. 2. This does not imply that the transfer of DNA of Y is never important. For example, if no DNA features corresponding to Y's profile were observed, that should be a reason to question the assumption that the offender wore the sweater during the incident.
[6] The transfer of DNA considered due to wearing the sweater during the incident not so much the transfer of DNA from the alleged activity of strangling itself.

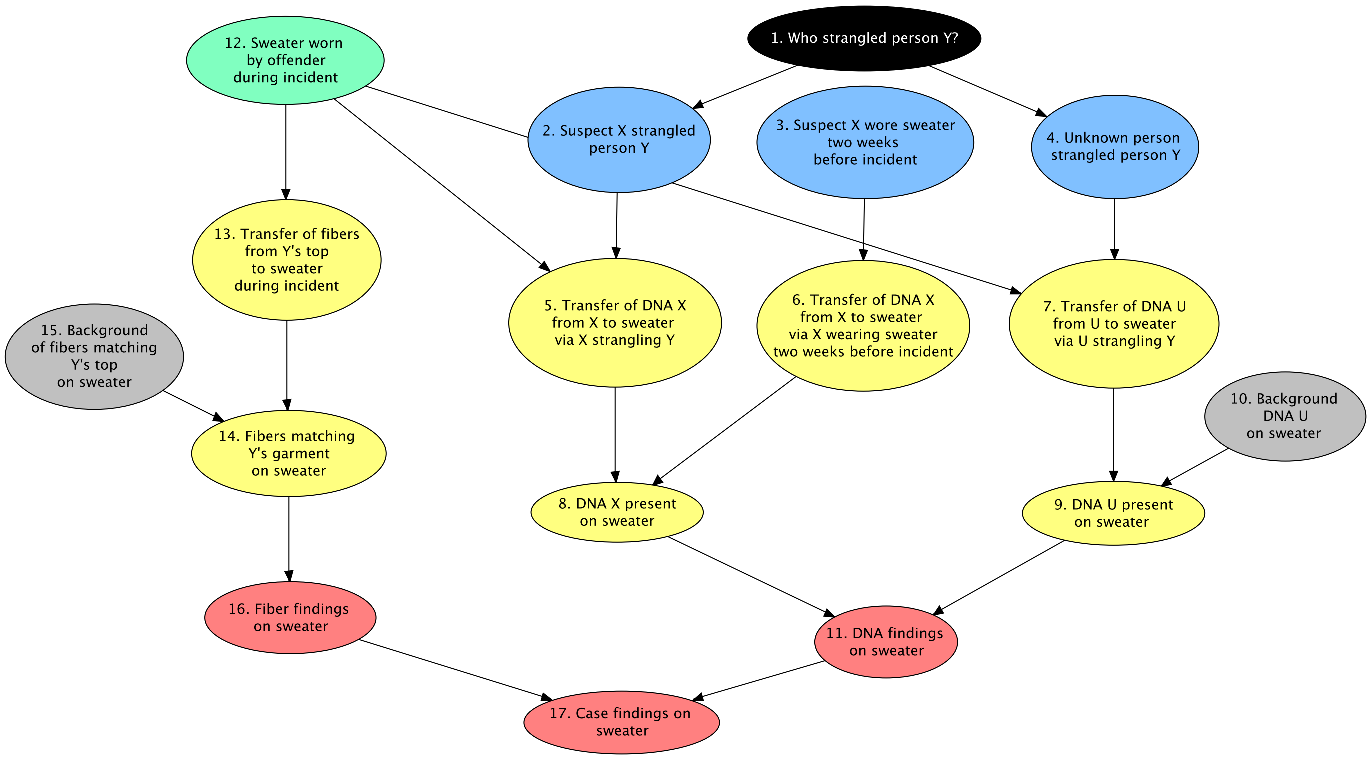


Fig. 3. Case model for the evaluation of fiber evidence and DNA evidence in a fictive case example. See footnote 7 for evidence that is excluded from the case model.

from Mr. X just by wearing the sweater two weeks before the incident could already explain the background presence of X's DNA. The transfer nodes (5,6,7), the background node (10) and the accumulation nodes (8, 9) have binary states 'True' or 'False' but can be further discretised to include DNA amounts. See Ref. [20] for case examples. If DNA amounts are used as states, a dependency may exist between transfer of dna x from x to sweater via x strangling y (5) and transfer of DNA X from X to sweater via X wearing sweater two weeks before the incident (6). This is due to information about Mr. X's shedding status.

The network is concluded with DNA findings on sweater (11). This node should be interpreted as DNA findings other than Y's DNA features. The states of this node are 'DNA of X only', 'DNA of U only', 'DNA of both X and U', and 'no DNA'.

In this scenario, observing a DNA profile corresponding to person Y or the suspect (X), often does not discriminate much between the propositions H_1 and H_2. It is the absence (or presence) of DNA features not corresponding to either person Y or suspect X, originating from an unknown person, that potentially becomes the main interest, as such absence is more likely given H_1 than given H_2 (vice versa for the presence of unknown DNA).

The LR from the network can be derived by instantiating H_1 and H_2 subsequently and dividing $P(E|H_1)$ by $P(E|H_2)$, where E equals the state of DNA findings on sweater. As we focus on structuring the case model rather than assigning the probabilities we do not yield an LR for the DNA evidence.

4. Modeling the evaluation of forensic evidence given propositions concerning item—activity

The involvement of the sweater is undisputed in the previous section. Yet the sweater may not have been worn by the offender at time of the incident. This section presents a revised version of the case example, demonstrating how to model the evaluation of evidence given propositions regarding the relation between an item and an activity. This evaluation will be incorporated into the case model shown in Fig. 2.

4.1. A fictive case example: continued

The police suspect that the sweater was worn by the offender during the strangulation. The defense questions this suspicion. The sweater is examined for wearer DNA[7] and foreign fibers. Several fibers are identified and compared to the clothing of person Y. Twenty of the fibers match the fabric from Y's top.

The activity level propositions remain unchanged[8]. However, in addition to the disputed actor, the link between the sweater and the incident, whether it was worn or not by the offender, is also being contested. The evaluation becomes interdisciplinary as both the fiber evidence and the DNA evidence are assessed. Repeating H_1 and H_2, and case information, I:

H_1: Mr. X strangled person Y.

H_2: An unknown person (other than X) strangled person Y.

I: The sweater belonged to Mr. X and he wore it two weeks before the incident.

4.1.1. Case model

Fig. 3 shows the case model for the modified case example including the questioned relation between the sweater and the incident. The right-hand side follows the different paths of DNA traces from the activity

[7] Of course, in a real case also DNA of Y on the sweater would be examined. Moreover, also Y's clothing may be searched for fibers possibly originating from the sweater. Other evidence may be collected too. In this section, we ignore this in order to keep focus and to highlight the combination with other evidence types (here fibers). In Section 6, we will explain how more complex situations can be handled.

[8] We set these propositions conforming to the guidelines in Ref. [28]. There are other options for setting the propositions, for example including the dispute over the relevance of the sweater in the propositions. We chose to exclude this dispute for reasons explained in Section 5.

Table 3
The CPT of Transfer of fibers from Y's top to sweater during incident (13).

13. Transfer of fibers from Y's top to sweater during incident		
12. Sweater worn by offender.	False	True
False	1	(1-q)
True	0	q

Table 4
The CPT for Transfer of DNA X from X to sweater via X strangling Y (5).

5. Transfer of DNA X from X to sweater via X strangling Y				
12. Sweater worn by offender..	False		True	
2. Mr. X strangled person Y	False	True	False	True
False	1	1	1	(1-r)
True	0	0	0	r

Table 5
The CPT for Transfer of DNA U from U to sweater via U strangling Y (7). In our case, probability r equals s as the shedder status of the suspect and the unknown person are assumed to be the same.

7. Transfer of DNA U from U to sweater via U strangling Y				
12. Sweater worn by offender..	False		True	
4. Unknown person strangled person Y	False	True	False	True
False	1	1	1	(1-s)
True	0	0	0	s

nodes to the case findings on the sweater. This construction is similar to the case model in Fig. 2. The case model is expanded to include nodes 12 to 17.

12. Sweater worn by offender during incident
13. Transfer of fibers from Y's top to sweater during incident
14. fibers matching Y's top on sweater
15. Background of fibers matching Y's top on sweater
16. fiber findings on sweater
17. Case findings on sweater

the structure in Fig. 1a) because the background information of the case will determine a prior probability that the sweater was worn by the offender during the incident. For example, in this case, the sweater was found in a garbage bin outside person Y's apartment. This information impacts the prior probability that the sweater was worn by the offender. Equal prior probabilities for H_3 and H_4 seem a 'neutral' choice but we see this differently. We believe it is acceptable for the forensic expert to provide the prior probabilities, as long as they clearly communicate to the fact finder how these priors influence the LR. The evaluation of DNA evidence can be influenced by updating these prior probabilities with forensic evidence. Moreover, we decided to give sweater worn by offender during the incident a green color instead of black to distinguish the association propositions from the main activity level propositions.

We can update the probabilities of sweater worn by offender during incident (12) using the fiber evidence found on the sweater. From sweater worn by offender during incident (12) follows a path to transfer of fibers from Y's top to sweater during incident (13)[10,11]. The CPT of transfer of fibers from Y's top to sweater during incident (Table 3) contains zeroes and ones except for two entries. The expert needs to assign the probability $q = P(\text{Transfer..} = \text{True} \mid \text{Sweater worn..} = \text{True})$ considering the case circumstances.

The path continues with fibers matching Y's top on sweater (14) and Background of fibers matching Y's top on sweater (15). The background of the fibers refers to the transfer, persistence and recovery of fibers that match person Y's top but do not come from that top. fiber findings on sweater (16) is a binary node and can be set to 'fibers matching Y' present to get the posterior probability of the link between the sweater and the strangulation.

The evaluation of the fiber evidence and the evaluation of the DNA evidence are combined using the assumption that if the sweater was not worn by the offender, the DNA traces on the sweater would not provide any information about who strangled person Y. Therefore, both transfer of dna x..x strangling person y (5) and transfer of dna u..u strangling person y (7) have an incoming link from the association node (12). The CPTs of these nodes (5,7) (Tables 4 and 5) are similar to the CPT from Table 2 but contain two additional columns of zeroes and ones. The CPTs contain the conditional probabilities, r and s:

$$r = P(5.\ \text{Transfer of DNA X..} = \text{True} \mid 12.\ \text{Sweater worn..} = \text{True},\ 2.\ \text{X strangled person Y} = \text{True})$$

$$s = P(7.\ \text{Transfer of DNA U..} = \text{True} \mid 12.\ \text{Sweater worn..} = \text{True},\ 4.\ \text{U strangled person Y} = \text{True}).$$

As mentioned in Section 2.1, we consider the question whether the sweater was worn by the offender during the incident as a subquestion in addition to the questioned relationship between the suspect and the strangulation. What follows from this are the following association propositions:

H_3: The sweater was worn by the offender during the incident.
H_4: The sweater was not worn by the offender during the incident.

And so, the case model in Fig. 2 is expanded starting with a proposition node sweater worn by offender during the incident (12)[9]. We decided to model the association propositions as a root node (similar to

In our case example, the shedder status of X and U is assumed to be equal and thus, so are probabilities r and s. The CPTs reflect our perspective on how the 'relevance' of the sweater can affect the evaluation of DNA evidence: the conditional probabilities assure that the probability of sweater worn by offender during incident can affect the strength of the DNA evidence given the activity level propositions in who strangled person y (1). Further details on the influence of the association node on the combined strength of evidence will be discussed in

[9] We sometimes refer to this node as association node.

[10] The transfer of fibers from Y's top to sweater is assumed to be independent of the actor. This means that the probability of fibers transferring from Y's top to the sweater is equal under both hypotheses, H_1 and H_2.

[11] Here we do not consider possible cross-transfer of fibers from the sweater to Y's top. We will elaborate on cross-transfer in Section 6.

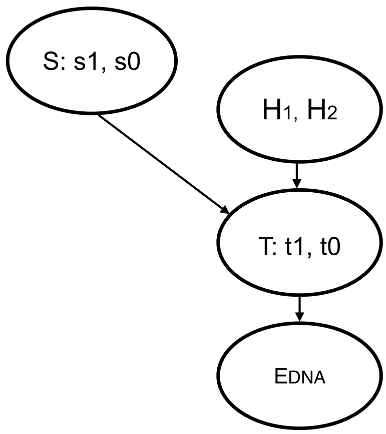


Fig. 4. Simplified model to illustrate the influence of sweater worn by offender during incident (12) on the transfer nodes.

section 4.1.2.

At last, we checked for *absolute support* [11] within the Bayesian network. Instantiating the activity level propositions consecutively does not provide the probability of the case findings being 0 or 1 and therefore, absolute support for any of the propositions will not happen within the network.

4.1.2. The influence of the association node on the combined LR

The impact of uncertain relations between traces (on items) and the strength of evidence has been previously demonstrated by Garbolino and Taroni [5], as well as by Taroni et al. [25]. Garbolino and Taroni [5] demonstrated that the derived LR reduces to one over the random match probability as the probability of relevance approaches 1. Moreover, Taroni et al. [25] showed that when the probability that the suspect wore the item during the activity is set to 1, the LR at activity level returns to its initial form - that is, with the categorical assumption that the suspect wore the item during the activity.

We want to illustrate the operation of sweater worn by offender during incident (12) in the model and its relative impact on the combined LR. Naturally, the combined LR of the fiber evidence and DNA evidence obtained from the BN will depend on the probabilities in sweater worn by offender during incident (12).

The probabilities affect the DNA evaluation through altering the transfer probabilities in nodes (5) and (7), as displayed in Fig. 3. This influence is symmetrical, implying that sweater worn by offender during incident impacts nodes (5) and (7) equally. Therefore, Fig. 4 provides a simplified model for illustrative purposes. Nodes H, T and E_{DNA} represent the DNA evaluation given H_1, Mr. X strangled person Y, and H_2, unknown strangled person Y. Node S represents the association propositions with probabilities s_1, the sweater was worn and s_0, the sweater was not worn.

We can *extend the conversation*, e.g. Refs. [5,29], to include the association propositions $s1$ and $s0$ as conditional in $P(T|H)$:

$$P(T \mid H) = P(T \mid H, s1)P(s1 \mid H) \; + \; P(T \mid H, s0)P(s0 \mid H)$$

Since there is no direct link between S and H, they are independent. This simplifies the equation to:

$$P(T \mid H) = P(T \mid H, s1)P(s1) \; + \; P(T \mid H, s0)P(s0) \tag{1}$$

Special case 1: sweater was not worn by the offender during the incident (S = s0).

If there is undoubtedly no relationship between the sweater and the offender during the incident, the DNA evaluation given H_1 and H_2 should become irrelevant. In this situation, we know that node S has true state $s0$ and that $P(T = t0 \mid H, s0)$ and $P(T = t1 \mid H, s0)$ become one and zero respectively. The true state of T is now known to be $t0$. Consequently, since H, T, and E are serially connected, T blocks the evaluative path between the propositions and the DNA evidence. In other words, given S = $s0$ and T = $t0$, the probability of H_1 and H_2 becomes independent of the DNA evidence obtained from the sweater:

$$P(H_1 \mid E_{DNA}, s0, t0) = P(H_1 \mid s0, t0)$$

$$P(H_2 \mid E_{DNA}, s0, t0) = P(H_2 \mid s0, t0).$$

And from Bayes' rule it follows that:

$$LR = \frac{P(E_{DNA} \mid H_1, s0)}{P(E_{DNA} \mid H_2, s0)} = 1.$$

Special case 2: sweater was worn by the offender during the incident (S = s1).

In this situation, we know that node S has true state $s1$ and Eq. (1) reduces to:

$$P(T \mid H) = P(T \mid H, s1).$$

This implies that the conditional probabilities $P(T = t1 \mid H, s1)$ and $P(T = t0 \mid H, s1)$ will have a value as if the assumption that the sweater was worn by the offender still holds. Therefore, the combined LR simplifies to the LR of the DNA evidence as in Section 3.

Eq. (1) shows that $P(T \mid H)$ is a weighted average of $P(t1 \mid H, s1)$ and $P(t0 \mid H, s0)$ in cases where $P(s1)$ is not zero nor one and $P(E_{DNA} \mid T = t)$ is a monotonic function of t. For such cases the combined LR ranges from 1 to the LR of the DNA evidence at activity level and each value of the combined LR depends on the probabilities in node S.

5. A template model for evaluating transfer evidence at activity level conditioned on the evidence evaluation given the item—activity propositions

This section generalizes the case model in Fig. 3 to form a template model that can be utilized in a variety of cases. Fig. 5 presents this template model. The template model evaluates transfer evidence given activity level propositions and includes disputes about the actor and/or activity, and a dispute related to item—activity. If any of these elements are not disputed, the template model can be adjusted accordingly. Node 13 to17[12] are added to the template model from Ref. [13] and represent the evaluation of evidence given item—activity propositions.

13. Item 1 links to activity 1?
14. Transfer of trace type 4 from A4 to item 1 via activity 1
15. Trace type 4 present on item 1
16. Background trace type 4 on item 1
17. Findings on item 1

These nodes evaluate the evidence given that item 1 can be linked to activity 1 or not. Item 1 links to activity 1? (13) is modeled as a binary root node with states 'True' and 'False'. The root nodes allow for prior probabilities to be set and for an evaluation of the findings on item 1 that can update these prior probabilities.

Recall from Section 2.1. that the specific relation between item and activity that needs to be assessed depends on the case circumstances. Therefore sweater worn by offender during incident (node 12 in Fig. 3) is generalized as item 1 links to activity 1? (13). Recall from Section 4.1.2. that Item 1 links to activity 1? influences the probabilities of transfer given H_1 and H_2. If the posterior probability P(13. Item links to activity 1? = True | 15. Trace type 4 present on item 1 = True) exceeds zero, information may flow between the activity level propositions and

[12] The numbering of the nodes differs slightly compared to the model in Fig. 3, due to an extra background node in the template.

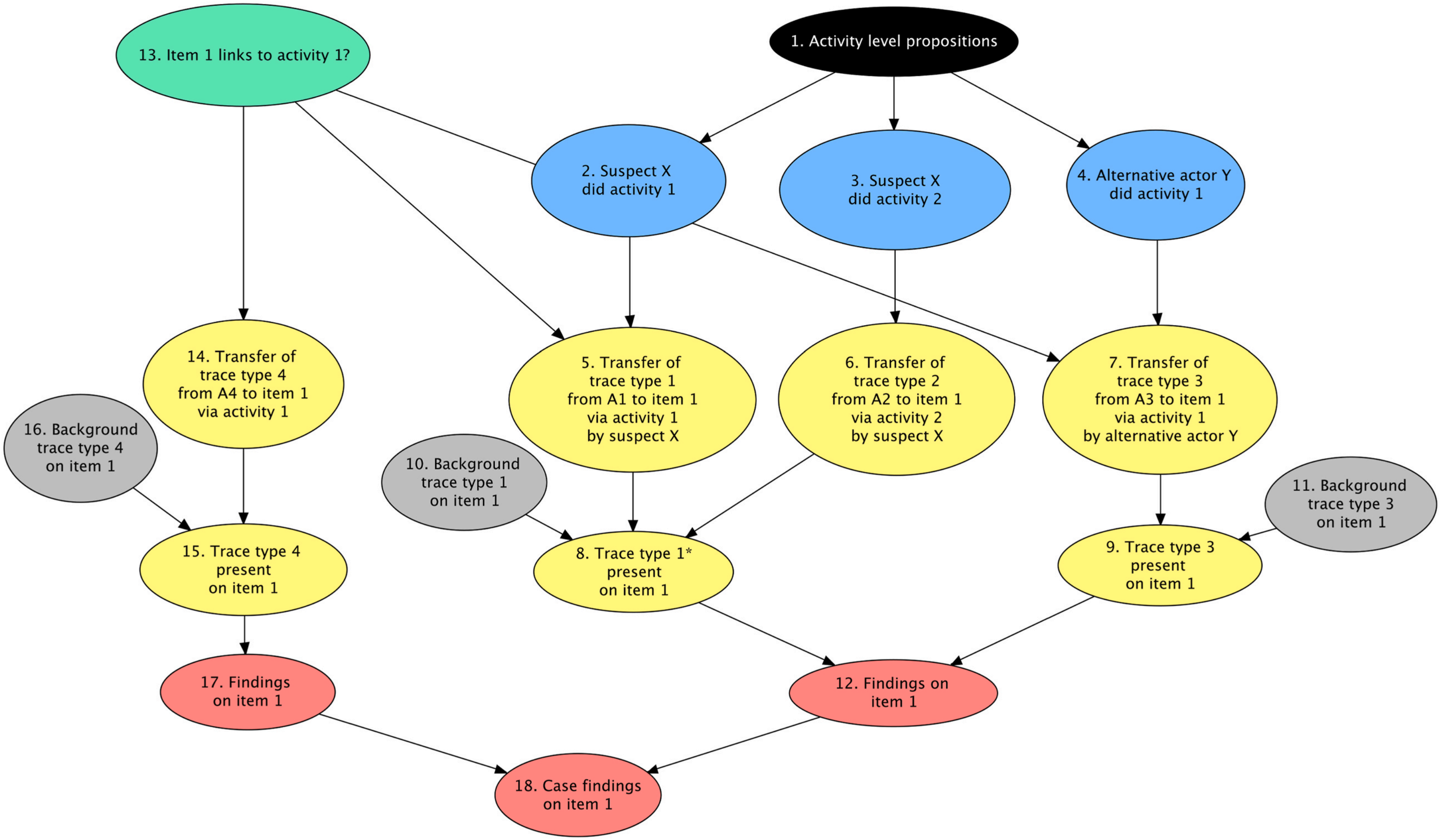
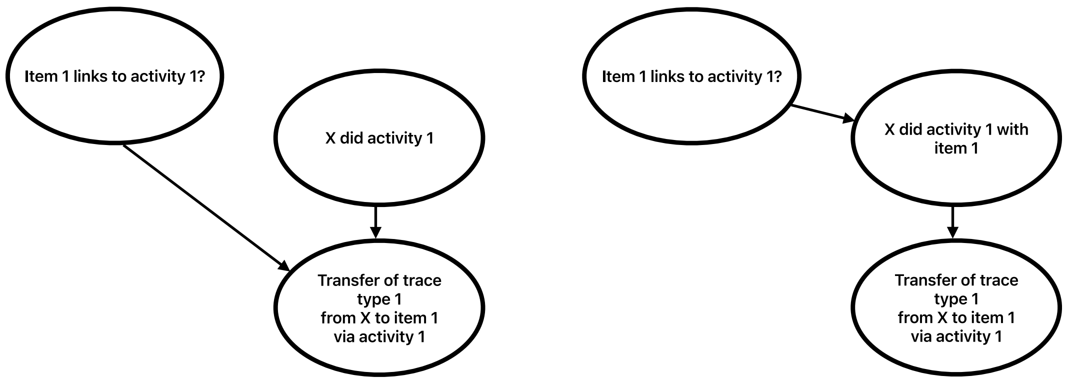


Fig. 5. Template model for the evaluation of transfer evidence at activity level including disputes over the actor and/or activity and a dispute over item—activity. *Trace type 1 and trace type 2 are the same and an accumulation node (node 8) can be used. If the trace types are not the same, new accumulation and background nodes (similar to nodes 8 and 10) should be introduced for trace type 2.



(a) Structure A (b) Structure B

Fig. 6. Two different modeling structures for combining the evaluations of the evidence given the relevance propositions and given the activity level propositions. Structure Ais the preferred method.

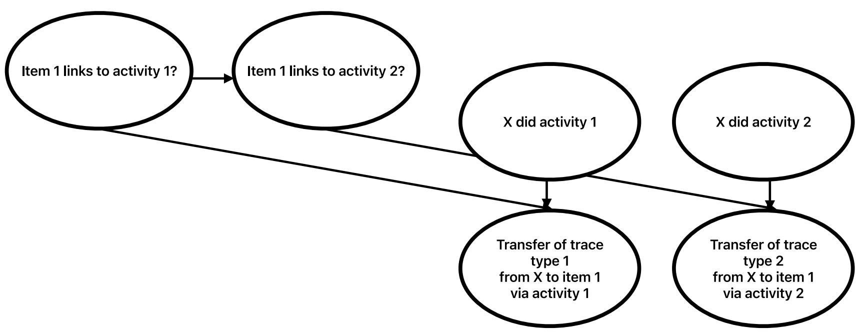


Fig. 7. Modeling structure with two disputed relations between one item and two (disputed) activities.

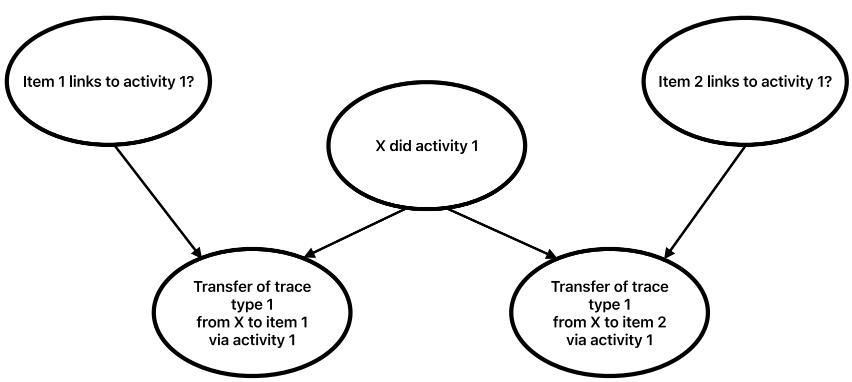


Fig. 8. Modeling structure with two disputed relations between two items and one (disputed) activity.

the case findings on the item.

Similar to the transfer paths leading from Activity level propositions (1) to Case findings on item 1 (18), a transfer path follows from item 1 links to activity 1? (13) to Case findings on item 1 (18). The child node of item 1 links to activity 1? (13) is Transfer of trace type 4 from A4 to item 1 via activity 1 (14)[13,14]. This node is followed by Trace type 4 present on item 1 (15).

[13] A4 is the 'donor' of trace type 4 and can be either an item or individual. The donor can be different from the donors in the other transfer nodes. The same holds for the trace type.

[14] Since item 1 links to activity 1 (13) is binary and already allows for only a single transfer path to follow, we decided not to use a blue activity node as a child node.

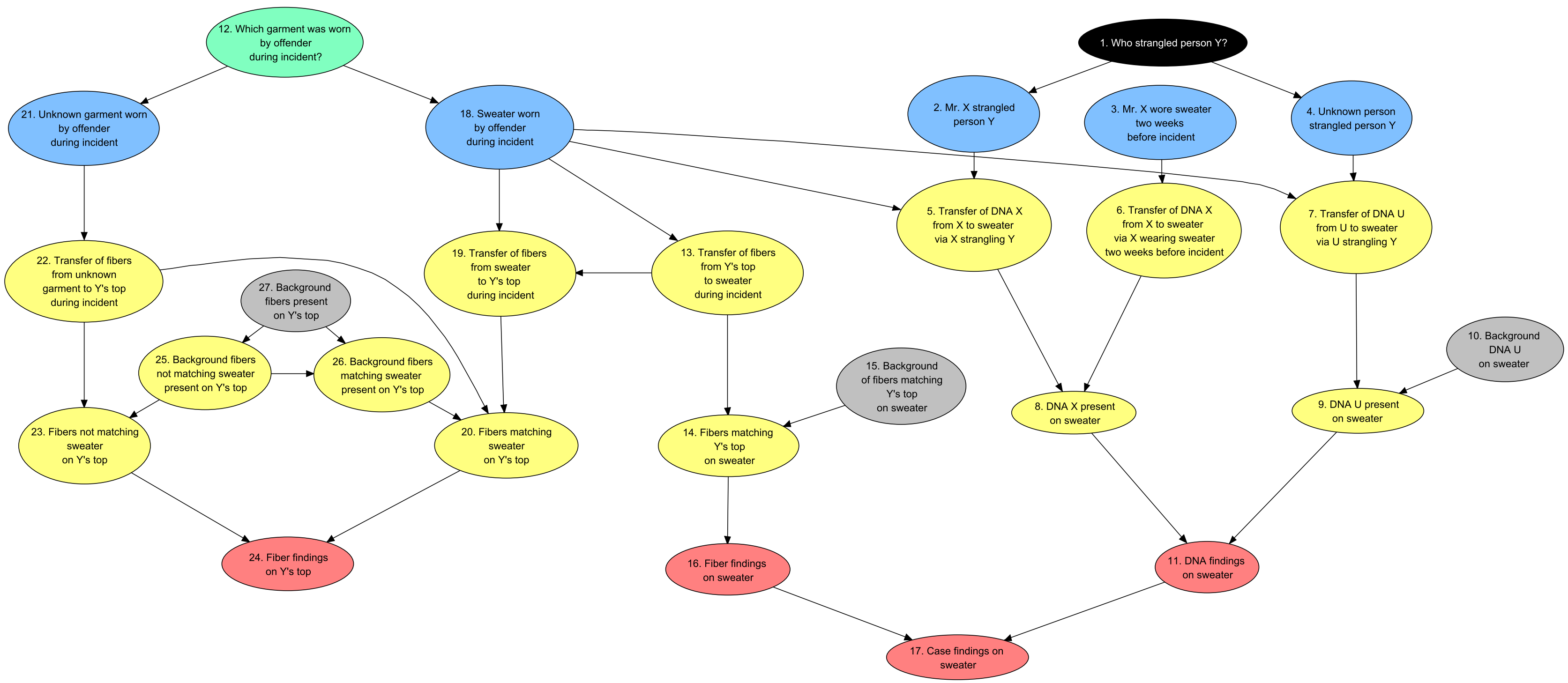


Fig. 9. Case model including cross-transfer from Y's top to the sweater and from the sweater to Y's top. See footnote 15 for evidence that is ignored in the network.

Table 6
The CPT of Transfer of fibers from sweater to Y's top during incident (19).

19. Transfer of fibers from sweater to Y's top during incident				
13. Transfer of fibers from Y's top to sweater..	False		True	
18. Sweater worn by offender..	False	True	False	True
False	1	(1-*t*)	1	(1-*u*)
True	0	*t*	0	*u*

We investigated two modeling structures to combine the evaluation of evidence given the propositions relating to the item—activity and given the activity level propositions (Fig. 6). Structure A contains directed links from item 1 links to activity 1? and X did activity 1 to Transfer of trace type 1 from X to item 1 via activity 1. Structure B includes a directed link from Item links to activity 1? to X did activity 1 with item 1.

We chose structure A because it is more flexible for multiple case scenarios than structure B. First, even if item 1 is not related to any activity, it is still possible for one of the activities to have occurred. Item 1 is simply not the item from which to draw an inference but other items may be. Structure A can handle this situation but structure B needs adaptation.

Second, if there are multiple items submitted for examination and their relation to an activity is also questioned, the expert only needs to add association nodes (similar to node 13) and transfer nodes (similar to node 14) to the network - no extra activity nodes are needed. Last, structure A is better suited for evaluating the evidence with regard to the main activity level question, that involves "who did activity 1?" or "what did Mr. X do?". The expert should be able to evaluate traces from multiple items and including the phrase "with item 1" in the activity node makes this impossible. Consequently, structure A is included in the template model through a parental relation of item 1 links to activity 1 (13) with the transfer nodes (5,7) that consider activity 1.

The template model is concluded with case findings on item 1 (18) that accumulates all the findings on item 1. The combined LR can be derived by instantiating H_1 and H_2 subsequently and by dividing the $P(E \mid H_1)$ by $P(E \mid H_2)$, where *E* equals 'case findings'. These conditional probabilities can be read from the CPT of case findings on item 1.

6. Variations to the template model

The template model in Fig. 5 illustrates a scenario in which one item of interest and one activity are disputed. And so, only the relation between item 1 and activity 1 is a possible dispute. There might also be a need to assess the value of evidence given the relation between the same item and another activity, or between another item and activity 1. In both cases, the expert can add a second root node representing the association propositions, as illustrated in Figs. 7 and 8. A similar transfer path as the one from item 1 links to activity 1? (13) to findings on item 1 (17) in Fig. 5 can be followed.

We suggest using an association node for every item for which the link to a certain activity is disputed. If multiple association nodes are being modeled, the expert should carefully investigate the possible dependencies between the association nodes - reflected by the directed link between them in Fig. 7. In addition, they should consider possible conditional dependencies concerning the association nodes and the transfer nodes and the subsequent changes in CPTs of the transfer nodes.

In the following sections, we will illustrate the flexibility of the template model in Fig. 5 by exploring two more potential variations of it. We will expand upon the fictive case twice more to show the modifications in modeling the evaluation of evidence given item—activity propositions.

6.1. Variation 1: cross-transfer of fibers between sweater and person Y's top

Just as fibers can transfer from person Y's top to the sweater, fibers can also transfer from the sweater to Y's clothing. The concept of *cross-transfer* has been studied in detail before by for example [3,30]. Imagine that Y's top was also collected for fiber examination[15]. If the sweater was worn by the offender during the incident, we would expect to find fibers matching the sweater on Y's top. Conversely, if the offender did not wear the sweater but some unknown garment, we would expect to find a group of fibers not matching the sweater[16] on Y's top. The presence of such non-matching fibers and the absence of matching fibers on Y's top would support the proposition that the sweater was not worn during the incident.

6.1.1. Case model

The case model from Fig. 3 is extended with nodes to include the cross-transfer of fibers between Y's top and the sweater (see Fig. 9). As we now explicitly consider an unknown garment as possibly being worn by the offender, we rephrased the association node (12) to: "Which garment was worn by the offender during incident?" with states 'the sweater' or 'unknown garment'.

The evaluation of fiber evidence on Y's top follows a similar structure as the evaluation of the fiber evidence on the sweater. However, we now have two possible transfer paths to Y's top instead of one. Therefore, two association activity nodes (18 and 21) follow from node 12 to distinguish these two transfer paths: one from the sweater to Y's top (nodes 18–20, 24) and one from an unknown garment to Y's top (nodes 21–24).

18. Sweater worn by offender during incident
19. Transfer of fibers from sweater to Y's top during incident
20. Fibers matching sweater on Y's top
21. Unknown garment worn by offender during incident
22. Transfer of fibers from unknown garment to Y's top during incident
23. Fibers not matching sweater on Y's top
24. Fiber findings on Y's top

In the case example, both matching and non-matching fibers can be found on Y's top. As a result, the four states of Fiber findings on Y's top (24) are: 'only fibers matching sweater', 'only fibers not matching sweater', 'both matching and non-matching fibers', and 'no fibers'.

Matching and non-matching fibers on Y's top could be from possible transfer activities or unrelated background fibers. Hence, the findings nodes 23 and 20 are conditioned on respectively.

25. Background fibers not matching sweater present on Y's top
26. Background fibers matching sweater present on Y's top

We added a root node with the prior probability of background fibers present (non-matching and/or matching) on Y's top to combine the two different kinds of background fibers on Y's top into one background probability node.

27. Background fibers present on Y's top

[15] We still neglect cross-transfer of DNA between the sweater and Y's top in order to highlight the essence of the example. We also disregard the possibility of background fibers on either the offender's garment or Y's top being transferred between them during the incident. For example, if both the blue sweater and Y's yellow top contain rare pink fibers, this could be important evidence.

[16] Sometimes referred to as 'non-matching' in this paper.

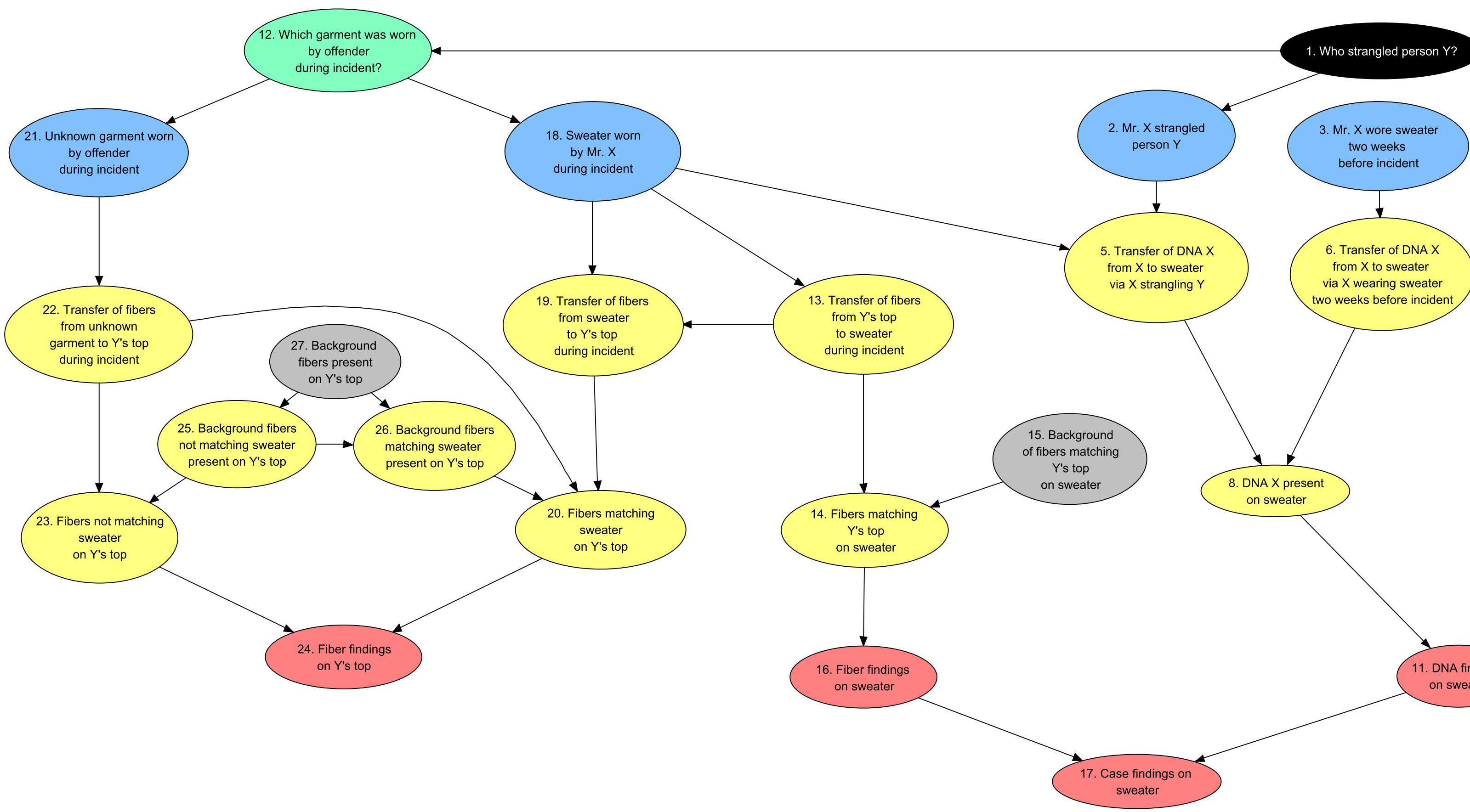


Fig. 10. Case model including cross-transfer and offender-specific item—activity propositions. See footnote 15 for parts of the evidence not shown in this BN.

We added a directed link from Transfer of fibers from Y's top to sweater during incident (13) to Transfer of fibers from sweater to Y's top during incident (19) to represent the dependency associated with cross-transfer. The probability of either transfer occurring is affected by the presence of the other transfer, and vice versa. Table 6 illustrates the CPT of Transfer of fibers from sweater to Y's top during the incident (19). The CPT contains the conditional probabilities, t and u:

$$t = P(19.\ \text{Transfer..from sweater..} = \text{True} \mid 18.\ \text{Sweater worn..} = \text{True},\ 13.\ \text{Transfer..from Y's top..} = \text{False})$$

$$u = P(19.\ \text{Transfer..from sweater..} = \text{True} \mid 18.\ \text{Sweater worn..} = \text{True},\ 13.\ \text{Transfer..from Y's top..} = \text{True}).$$

Table 7
The CPT for which garment was worn by the offender during incident? (12).

12. Which garment was worn by offender during incident?		
1. Who strangled person Y?	H_1: Mr. X	H_2: Unknown person
Sweater	0.5	0
Unknown garment	0.5	1

The final adjustment to the node dependencies is that fibers transferred from an unknown upper garment to Y's top during the incident are of unknown origin but could potentially match those from the sweater. Therefore, there is a directed link between Transfer of fibers from unknown garment to Y's top during incident (22) and the accumulation node Fibers matching sweater on Y's top (20).

6.2. *Variation 2: sweater could only have been worn by Mr. X if he was the offender*

Up to this point, we have focused on the connection between the sweater and the offender, either Mr. X or an unknown person. We now adjust the case example to a situation where only Mr. X could have worn the sweater during the incident. If another person strangled person Y, they must have worn something else. For example, in a situation where the garbage bin containing the sweater was not outside Y's apartment but in the Mr. X's apartment, and Mr. X claims to have last worn the sweater two weeks ago before putting it in the bin. If the connection between the sweater and the offender is questioned, the presence of matching fibers on Y's top can support the association of the sweater to the incident. This, in turn, strengthens the link between Mr. X and the incident, given that Mr. X is the only person who can be potentially connected to the sweater during the incident.

6.2.1. *Case model*

This additional case information results in three small changes in the structure of the BN (see Fig. 10)[17]. First, since it is undisputed that Mr. X is linked to the sweater and an unknown offender cannot be connected to it during the incident, the probability of DNA transfer from an unknown offender to the sweater during the event is zero. As a result, nodes 4, 7, 9, and 10, which represent the potential transfer path from an unknown person to the sweater, are excluded from the updated case model.

Second, the question shifts from whether the offender wore the sweater during the incident to which garment was worn by whom during the incident: the sweater by Mr. X or an unknown garment by Mr. X or an unknown person. Node 18 is changed to "sweater worn by *Mr. X* during the incident".

Last, we added a directed link from who strangled person y to which garment was worn by offender during incident (12) to account for the offender-specific item—activity relation. Table 7 displays the CPT for which garment was worn by offender during incident (12). The conditional probabilities indicate that only Mr. X could have worn the sweater at the time of the incident. If H_2 is true, an unknown person strangled person Y, and thus, an unknown garment must have been worn by the offender. If H_1 is true, Mr. X strangled person Y using either the sweater or an unknown garment. The prior probabilities of Mr. X wearing the sweater or an unknown garment during the incident are included in the CPT of which garment was worn by offender during incident (12). Here we assume equal prior probabilities but this is an assumption that should be further investigated. In contrast with the prior probabilities of sweater worn by offender during incident (12) in Fig. 3 we believe these prior probabilities are actually outside the expert's domain.

7. Final considerations

We have developed a template model that can be used to evaluate transfer evidence given activity level propositions in cases where there is a dispute about the actor and/or activity, and/or the relation between items and activities. The evaluation of evidence given item—activity propositions is a prerequisite for evaluating the evidence given the propositions at activity level. The evaluation may sometimes be carried out by a different forensic discipline and therefore the template model is particularly valuable in interdisciplinary casework. We believe that developing such template models, both here and elsewhere, will encourage the practical application of BNs in casework. This promotion is urgently needed, as forensic practice is lagging behind theory and the relevant court questions relate to activities rather than trace sources.

The dispute about the relation between item and activities are introduced as an association dispute concerning association propositions with prior probabilities. There is currently no consensus on how to deal with such prior probabilities in casework. We argued that the forensic expert can provide the prior probabilities as long as they explain to the fact finder how these priors influence the LR. For instance, an expert could use a range of priors and report their effect on the LR. Alternatively, one could select these priors in collaboration with the appropriate person(s). In any case, dealing with these prior probabilities cannot be avoided. This makes it an interesting topic for further research.

The template model provides a middle ground between a ready-to-use network and a generic network. The model is sufficiently specific to provide the forensic practitioner with a starting point but the model is also flexible enough to be used in a wide variety of cases. We acknowledge that the case examples provided in our research paper may appear simplified. We fully recognize the complexity and nuance intrinsic to real-world forensic cases. For example, in our case example,

[17] As in the previous section, we ignore some aspects of the DNA evidence, fiber evidence and disregard other possible evidence. See also footnote 15.

there may be fingermarks in Y's neck, video images from surveillance cameras, information from the suspect's mobile phone, analysis of the cell type of the DNA samples, and so on. By focusing on the essence of the problem, which is the combination of different type of evidence such as fiber and DNA evidence, and evaluating evidence given association propositions, we aim to demonstrate the potential of this model in a clear and understandable manner.

The forensic practitioner can consult the collection of idioms for modeling evidence evaluations given activity level propositions [13] to adjust and expand the template model. The work on using Object Oriented Bayesian Networks (OOBNs) for legal and forensic casework (e.g. Refs. [11,31–33]) may also be very useful in practice. For example when the evaluation includes multiple items of interest that all accompany an evaluation of similar modeling structure. While objects may not directly enhance readability, they can prevent large BN from being too overwhelming for the recipient.

BNs have proven to be very useful tools for the forensic expert to structure their reasoning, calculate the combined LR and for making their thinking explicit. But with great transparency comes many details and subtleties that increase complexity and so there is still debate about whether or not to use BNs in the communication with the court (see for example [20,34,35]). We believe that if one relies on a BN to calculate a LR, this should not be burried in the case file without any mention of it in the expert's report to the court. Instead, we suggest BNs as a structuring and probabilistic tool to assist in the understanding of complex reasoning under uncertainty.

In conclusion, our research bridges the gap between theoretical advancements and practical applications. It paves the way for a better understanding of reasoning about complex casework, enabling experts to write logical, transparent, balanced, robust, and not the least, clear reports for the court.

CRediT authorship contribution statement

M. Vink: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **J.A. de Koeijer:** Writing – review & editing, Resources, Conceptualization. **M.J. Sjerps:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fsisyn.2024.100546.

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