Follow the trace

Evaluating physical and digital forensic findings given activity level propositions using Bayesian networks

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Part V

END MATTER

Nederlandse samenvatting

Volg het spoor

Het gebruik van Bayesiaanse netwerken voor het evalueren van fysieke en digitale sporen gegeven activiteitniveauhypothesen

Probleemstelling

Met de Likelihood Ratio (LR)-methode weegt een forensisch deskundige waarnemingen af tegen twee of meer hypotheses, rekening houdend met de context van de zaak. Dit resulteert in een maat voor de bewijskracht: de likelihood ratio. Forensisch deskundigen worden steeds vaker gevraagd om hun waarnemingen te evalueren gegeven activiteitniveauhypothesen (Evett *et al.*, 2002; Prinz *et al.*, 2024). Deze hypothesen gaan niet zozeer meer over 'wie is de donor van het spoor?' maar over de wijze waarop het spoor of sporenbeeld is ontstaan.

Deze evaluaties worden snel complex wanneer veel resultaten en diverse soorten informatie in de evaluatie moeten worden meegenomen. Daarom is een methode gewenst die het redeneren in zulke zaken gestructureerd vastlegt. Bayesiaanse netwerken bieden hiervoor een geschikt hulpmiddel (zie bijvoorbeeld Aitken *et al.* (2003); Dawid & Evett (1997); Garbolino & Taroni (2002); Taroni *et al.* (2014)). Na bestudering van de bestaande literatuur over het gebruik van Bayesiaanse netwerken voor het modelleren van evaluaties op activiteitniveau, zagen we drie openstaande onderzoeksrichtingen.

Ten eerste is het modelleren van Bayesiaanse netwerken complex en tijdrovend. Deze tijd is in de praktijk niet altijd beschikbaar. Daarom zou het waardevol zijn als deskundigen voorafgaand aan een zaak toegang hebben tot algemene modellen die met kleine aanpassingen kunnen worden toegepast in specifieke zaken. Deze modellen noemen we "template Bayesiaanse netwerken." Een dergelijk template bestaat al voor het evalueren van DNA-bevindingen gegeven activiteitniveauhypothesen. Dit template is overzichtelijk en is grafisch intuïtief door zijn verhalende structuur: het toont elk mogelijk pad van een (betwiste) activiteit naar de gevonden sporen op een sporendrager ('Volg het spoor'). Een dergelijk templatemodel ontbreekt echter nog voor de evaluatie van waarnemingen uit andere forensische disciplines.

Ten tweede kunnen verschillende forensische disciplines betrokken zijn bij een evaluatie op activiteitniveau. Het combineren van deze bevindingen op een logische, evenwichtige, robuuste en transparante manier (Willis *et al.*, 2015), zoals met de LR-methode, brengt uitdagingen met zich mee. Deze uitdagingen ontstaan doordat disciplines mogelijk met verschillende sets van subhypothesen werken en doordat hun waarnemingen al dan niet conditioneel afhankelijk zijn van elkaar (oftewel: de ene waarneming beïnvloedt mogelijk de kans op de andere waarneming) gegeven de zaakhypothesen. Ook dit type zaakwerk kan profiteren van het gebruik van Bayesiaanse netwerken.

Ten derde is er een verschil in de methoden voor bewijsinterpretatie tussen fysieke en digitale forensische disciplines. De LR-methode wordt in het digitale domein minder toegepast, ondanks het toenemende belang van digitaal onderzoek in forensisch zaakwerk. De vraag is of de methoden die in traditionele forensische disciplines worden gebruikt, zoals template Bayesiaanse netwerken en LR-methoden, ook toepasbaar zijn in digitaal forensisch zaakwerk of dat deze aangepast moeten worden.

Het overkoepelende doel kan worden samengevat als: 'het toegankelijker maken van activiteitniveau evaluaties en het beter op elkaar afstemmen van methoden voor het gebruik van Bayesiaanse netwerken in verschillende foren-

sische disciplines – inclusief het digitaal forensisch domein.'

Deel II: van 'idioms' naar zaakmodel

Na de introductie in Deel I, verkent Deel II de *idiom-based approach* (Neil *et al.*, 2000) voor het modelleren van Bayesiaanse netwerken om tijd te besparen en complexiteit te verminderen. *Idiomen* (vertaling van: idioms) functioneren als kleine bouwstenen van een groter netwerk. Veelvoorkomende denkstappen kunnen worden omgezet in idiomen en samengevoegd tot een collectie. Voor diverse vakgebieden zijn dergelijke collecties al eerder ontwikkeld. In Hoofdstuk 2 ontwikkelen wij er een voor de evaluatie van forensische sporen op activiteitniveau. Vervolgens presenteren we in Hoofdstuk 3 een template Bayesiaans netwerk dat we met behulp van deze collectie hebben gemaakt. Dit netwerk evalueert verschillende soorten overdrachtsbewijs gegeven uiteenlopende mogelijke sets van activiteitniveauhypothesen, en bouwt voort op eerder werk van Taylor *et al.* (2018) en Kokshoorn *et al.* (2017).

Deel III: Bayesiaanse netwerken en interdisciplinair forensisch onderzoek

Deel III onderzoekt hoe we Bayesiaanse netwerken kunnen gebruiken om verschillende soorten bewijs van verschillende disciplines te combineren op een gestructureerde en 'verhalende' manier. We gebruiken hiervoor een zaakvoorbeeld waarin DNA-sporen en vezelsporen zijn gevonden op een trui. In deze zaak wordt zowel de connectie tussen de trui en het delict als de relatie tussen de trui en de verdachte betwist.

In Hoofdstuk 4 ontwikkelen we een Bayesiaans netwerk voor dit voorbeeld met behulp van het template netwerk uit Deel II. Dit netwerk bevat *associatiehypothesen* (vertaling van: *association propositions*) die claims maken over of de trui al dan niet is gedragen door de dader tijdens het delict. Deze hypothesen betreffen dus de relevantie van de trui en maken het mogelijk om de evaluaties van DNA-sporen en vezelsporen op de trui te combineren gegeven

de relevante hypothesen in de zaak ('wie heeft wat gedaan?').

In Hoofdstuk 5 generaliseren we dit netwerk en transformeren het naar een template Bayesiaans netwerk. Dit template is toepasbaar voor het evalueren van diverse soorten forensisch bewijs in zaken waarin de activiteit en/of dader ter discussie staat én waarbij een onzekere relatie bestaat tussen de sporendrager en het delict.

Deel IV: Het digitale domein ontdekken

Deel IV onderzoekt hoe we de LR-methode breder kunnen toepassen in digitaal forensische wetenschappen om de interpretatiemethoden beter af te stemmen op fysiek forensische disciplines. In Hoofdstuk 6 tonen we aan dat de LR-methode effectief kan worden gebruikt in relatief eenvoudig zaakwerk met één waarneming: een stappentellermeting op een smartphone. We ontwikkelen een LR-methode die deze metingen interpreteert in zaken waar een gelopen afstand wordt betwist.

Hoofdstukken 7 en 8 demonstreren dat de LR-methode en Bayesiaanse netwerken ook toepasbaar zijn in complexere zaken met meerdere bevindingen, zoals bij een *hackverweer* (vrije vertaling van: *Trojan horse defense*). We hebben dit onderzoek opgesplitst omdat tijdens de ontwikkeling van het Bayesiaans netwerk bleek dat het formuleren van de juiste hypothese al zeer uitdagend was.

Hoofdstuk 7 illustreert hoe een deskundige relevante hypothesen kan formuleren voor verschillende betwiste situaties in hackverweer-zaken. We tonen aan dat deze hypothesen ook onbewuste handelingen van een individu kunnen omvatten en dat de digitaal forensisch deskundige met de juiste kennis bevindingen kan evalueren op basis van deze hypothesen. In Hoofdstuk 8 bouwen we stapsgewijs een Bayesiaans netwerk voor een praktijkvoorbeeld, waarbij we de template Bayesiaanse netwerken uit Deel II en III probleemloos toepassen.

Conclusie

Ons hoofddoel is probabilistisch redeneren toegankelijker maken in zaakwerk op activiteitniveau – zowel mono- als interdisciplinair en in fysieke en digitale forensische domeinen – voornamelijk met Bayesiaanse netwerken. Met praktijkvoorbeelden tonen we de concrete voordelen van de LR-methode en Bayesiaanse netwerken aan. Dit onderzoek heeft geleid tot een collectie van idiomen, twee breed toepasbare template Bayesiaanse netwerken, en een solide basis voor de toepassing van de LR-methode en Bayesiaanse netwerken in twee typen zaken in het digitale domein.

Author contributions

This thesis is based on five manuscripts for which I am the first author—four are published and one is currently (September 19, 2025) under review. This page provides an overview of these manuscripts, showing their connections to thesis chapters and clarifying each author's contributions.

Part II is based on:
Vink, M., & Sjerps M. J. 2023. A collection of idioms for modeling activity level evaluations in forensic science, *Forensic Science International: Synergy* **6**, 100331.

CRediT M. Vink: conceptualization, methodology, investigation, writing original draft, writing - review & editing. M.J Sjerps: conceptualization, methodology, supervision, writing review & editing.

Part III is based on:
Vink, M., De Koeijer, J. A., & Sjerps, M. J. 2024. A template Bayesian network for combining forensic evidence on an item with an uncertain relation to the disputed activities, *Forensic Science International: Synergy* **9**, 100546.

CRediT 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.

Part IV, Chapter 6 is based on:

Vink, M., Sjerps, M. J., Boztas, A., & Van Zandwijk, J. P. 2022. Likelihood ratio method for the interpretation of iPhone Health App data in digital forensics, *Forensic Science International: Digital Investigation* **41**, 301389[1].

CRediT M. Vink: conceptualization, software, methodology, validation, writing - original draft, writing - review & editing. M. J. Sjerps: conceptualization, methodology, validation, supervision, writing - review & editing. A. Boztas: conceptualization, resources, writing - review & editing. J. P. van Zandwijk: conceptualization, resources, writing - review & editing.

Part IV, Chapter 7 is based on:

Vink, M., Schramp, R., Berger, C. E. H., & Sjerps, M. J. 2025. Formulating propositions in Trojan horse defense cases, *Forensic Science International: Digital Investigation* **53**, 301915.

CRediT M. Vink: writing - review & editing, writing - original draft, Methodology, Investigation, conceptualization. R. Schramp: Writing - review & editing, Resources, Conceptualization. C. E. H. Berger: writing - review & editing, writing - original draft, investigation. M. J. Sjerps: writing - review & editing, supervision, investigation, conceptualization.

Part IV, Chapter 8 is based on:

Vink, M., Schramp, R., Kokshoorn, B. & Sjerps, M. J. 2025. The evaluation of evidence in Trojan horse defense cases using Bayesian networks. Manuscript submitted for publication.

[1]The authors' first names were incorrectly formatted in the official citation. The official citation is: Vink, M. M., Sjerps, M. J. M., Boztas, A. A., & Van Zandwijk, J. P. J. P. 2022. Likelihood ratio method for the interpretation of iPhone health app data in digital forensics, *Forensic Science International: Digital Investigation* **41**, 301389.

CRediT M. Vink: conceptualization, methodology, investigation, writing - original draft, writing - review & editing. R. Schramp: resources, writing - review & editing. B. Kokshoorn: methodology, writing - review & editing. M. J Sjerps: conceptualization, methodology, supervision, writing - review & editing.

Summary of modifications to published articles

In order to ensure coherence and consistency throughout this thesis, the following modifications have been made to the previously published articles that are included in this work:

General modifcations

Formatting adjustments

Layout, headings, and citation style have been reformatted to have a uniform style across the thesis. Abstracts have been excluded from the chapters and are summarized on one page. Moreover, all references and appendices from the original manuscripts are compiled into one reference list and one appendix section at the end of the thesis. The Supplementary material that accompanies the manuscripts can be accessed through the QR codes in Appendix A.

Language and terminology

Minor language edits and terminology unifications were applied to maintain consistency in vocabulary throughout the thesis.

Figure, table, and equation numbering

Figures, tables and equations have been renumbered to fit the sequential order within the thesis chapters.

Specific modifications

To Vink & Sjerps (2023)

I divided the paper into two parts: Chapter 2 focuses on the collection of idioms, while Chapter 3 addresses the template Bayesian network. Additionally, I have incorporated a fictive case example to demonstrate the application of the template model. Node names in some of the forensic idiom examples in Appendix B have been modified to maintain consistency with the terminology used in other Bayesian networks throughout this thesis.

To Vink *et al.* (2024)

This paper is divided into two parts: Chapter 4 describes the case model, while Chapter 5 elaborates on the template Bayesian network and variations to the case model.

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Marjan, ik leerde je kennen als docent forensische statistiek tijdens mijn masteropleiding Forensic Science. Je hebt mijn liefde voor forensische statistiek aangewakkerd. Toen er in 2020 een PhD-positie bij je vrijkwam, heb ik geen moment getwijfeld. Bedankt voor je vertrouwen en positiviteit, de boswandeling toen alles even moeilijk was, de talloze brainstormsessies over het formuleren van de juiste hypothese, en vooral je steun bij het vinden van mijn plek binnen het NFI. Ik bewonder je enorm, zowel als mens als wetenschapper. Het was een eer om jouw PhD-student te mogen zijn en een nog grotere eer om nu collega's te zijn.

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