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The evaluation of fibre evidence in the investigation of serious crime

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The evaluation of fibre evidence in the investigation of serious crime

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RESUME

Les fibres textiles font l'objet d'expertises forensiques réalisées par de nombreux laboratoires servant le système judiciaire de par le monde. Si l'importance des fibres textiles pour dépister et poursuivre les auteurs de crime majeurs comme les homicides, les agressions sexuelles et le terrorisme, n'est plus à prouver, une mauvaise compréhension de la valeur probante de ce type d'indice dans l'investigation a résulté en une diminution de son utilité dans les affaires judiciaires.Les raisons à ce déclin incluent tant une mauvaise pré-évaluation des cas et des priorités de laboratoire, que des problèmes dans la rédaction des rapports d'expertise et l'interprétation des résultats. Du point de vue de la recherche, une augmentation des données empiriques est nécessaire afin de permettre de donner des réponses aux problématiques récurrentes tant dans la phase d'investigation des crimes graves mais aussi pour répondre aux questions posées lors du témoignage des experts au tribunal.

Cette thèse a pour but d'investiguer les lacunes existantes dans nos connaissances actuelles relatives aux facteurs influençant l'interprétation des fibres textiles en tant qu'élément de preuve. Le bénéfice potentiel d'un apport de connaissances pour l'évaluation de la preuve sera évalué. Les lacunes identifiées et considérées dans le cadre de ce travail de thèse concernent le manque de données publiées liées à deux scénarios provenant de cas pratiques précis traité par l'auteur, de même que celles existantes dans le contexte plus global de l'évaluation des fibres textiles. L'impact des données obtenues dans le cadre des études réalisées par l'auteur et d'autres groupes de chercheurs est évalué en utilisant des réseaux Bayesiens modélisant les deux cas pratiques cités précédemment. L'influence ou « sensibilité » de chacun des paramètres sur la force probante de l'indice fibre est aussi examinée.

Les résultats montrent que les données acquises par l'auteur lors de ces recherches ont un impact important au niveau de la pré-évaluation des cas ou de leur partie interprétative. Cependant, cet impact dépend du scénario spécifique du cas, des résultats obtenus lors de l'expertise et du choix de la proposition de la défense. Les résultats des analyses de sensibilité des différents paramètres (liés entres eux ou non) ont montrés que la méthodologie utilisée est utile pour fournir des informations sur les priorités à donner à de futures recherches, ceci non seulement dans le domaine des fibres textiles, mais aussi dans le domaine plus large des sciences forensiques.

Les implications de résultats obtenus dans le cadre de ce travail de thèse sont discutées du point de vue des praticiens et des perspectives futures sont explorées.

ABSTRACT

The forensic examination of textile fibres is routinely carried out by laboratories servicing the criminal justice systems of many countries worldwide. Despite its proven value in the detection and prosecution of the perpetrators of major crimes such as homicide, sexual offences and terrorism, there are still many misconceptions concerning its value in criminal investigations which has resulted in a decrease in its utility. Reasons cited for this situation include poor casework assessment, strategy setting as well as reporting/ interpretation. In terms of a driver for research, this translates into the need for more empirical data which can address recurring questions arising not only during the investigation of major crime, but also those encountered during court testimony.

This thesis investigates 'gaps' in key areas of our present knowledge of the factors influencing the interpretation of fibre evidence and assess these against the potential benefits in evidence evaluation. The 'gaps' considered in this thesis concern a lack of published data identified in the evaluation of evidence relating two specific real case scenarios encountered by the author, as well as a lack of, or incomplete data sets useful in a more global context in the evaluation of textile fibre evidence. The impact of data obtained from studies by the author and others is evaluated using Bayesian networks modelling these two case scenarios and the 'sensitivity' of the various parameters involved in evidence evaluation is examined.

The results show that the author's data has significant implications for case pre-assessment and evidence evaluation, however this is dependent upon the particular case scenario, examination outcome, as well as the choice of Hd propositions. The results of the sensitivity analysis of the various inter-relating parameters have also shown that the methodology employed is useful in informing and prioritising subsequent research strategies, not just in terms of fibre evidence but for forensic science in general.

The implications of the results from this thesis for the practitioner are discussed and future perspectives explored.

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1 INTRODUCTION AND PURPOSE

In this chapter, the misconceptions surrounding the utility of the forensic examination of textile fibres and the various factors concerning its poor uptake in serious crime investigations are identified and discussed. The differing approaches to the evaluation of this evidence type and the resistance to the adoption of a Bayesian framework are critically examined. The need for data concerning the fundamental processes governing the evaluation of fibre evidence is identified. Finally, the purpose of this thesis and its strategy in addressing these issues is provided.

The forensic examination of textile fibres is routinely carried out by laboratories servicing the criminal justice systems of many countries worldwide and contributes to the detection and prosecution of the perpetrators of major crimes. Despite this, its utility in criminal investigation is poorly understood and consequently uptake in major crime investigation is often confined to a 'last resort' scenario, when attempts to use other evidence types (e.g. DNA) have failed to progress the case. In many instances had it been employed at the beginning of an investigation, this would have provided a more effective outcome.

Reasons for poor uptake of this evidence type are cited by investigators through perceptions of poor evidential value, returned from time consuming, costly, examinations. These perceptions undoubtedly gained from personal experience, provide a damning indictment of the casework management of this evidence type.

1.1 Fibres under fire: The effectiveness of fibre examinations

A report into the effectiveness of the Forensic Science Service of England & Wales by *Ramsay, (1989)*, outlined a number of operational deficiencies resulting in poor value for money in the provision of forensic science (see *Chapter 2*). Whilst this report dealt specifically with England and Wales, *Grieve and Wiggins, (2001),* cited a number of issues similar to those identified in the Ramsay report, but which specifically aimed at improving the effectiveness of the forensic examination of fibres, globally. Whilst the authors cited streamlining the analytical processes as part of the solution, the key area they identified for improvement was through increasing the effectiveness of these examinations using better case assessment and interpretation processes;

'The future success of fibre examinations in forensic science is inextricably linked with enhancing the product – the report, and its impact..':

- Greater exchange of information between the analyst and investigator, particularly in identifying what the actual *purpose* of the examination is (i.e. what it is they hope to demonstrate or address through their examination) and ensure the examination strategy is *effective* in addressing this purpose.
- The accumulation of more data pertinent to evidence evaluation and interpretation ('the need for data').
- Use of logical evaluative reasoning (e.g. within a Bayesian framework) in the interpretation and reporting of results obtained from casework examinations.

1.2 The present situation and the way forward

Since the publication of Grieve and Wiggins' paper in 2001, what progress has been made in over a decade gone, in increasing the effectiveness and utilisation of forensic fibre examinations?

As a response to criticisms of various aspects of its service delivery, in the late 1990's the then state-run Forensic Science Service (FSS) of England & Wales introduced a likelihood ratio based framework for casework assessment and interpretation which became known as the '*CAI model*' *(Cook, Evett et al., 1998b)*. This framework is discussed in detail in *Chapter 2*.

From the terrorist events of September 2001 and beyond, there have been increased demands upon forensic science in general, to provide solutions to the problems faced by law enforcement communities throughout the world and this has been a key driver for many forensic science providers to improve all aspects of their service delivery.

Over the past 15 years, other forensic science providers in Europe have introduced similar likelihood ratio based frameworks to that introduced by the FSS, which consider the results of a given examination within the context of the circumstances peculiar to a specific case e.g. *Cook, Evett et al., (1998b), Johansson, (2009), ENFSI, (2015), Nehse, (2011) and Palmer,*

(2015b). Adoption of such a framework also appears to be taking place in Australia (*Roux, 2012*) and New Zealand (*Coulson, 2009*). The impact of a report by the *National Research Council, (2009)* in the USA (see below), has apparently resulted in some movement towards a more logical, evaluative style of reporting (*Koch, 2012, 2013*).

In other words, since the 1990's, there has been movement towards a more balanced, logical, transparent and robust method of interpretation and reporting of casework examinations. In Europe, reporting the results of fibre analysis only in terms of the strength of association between questioned fibres and a putative source (i.e. at *source level*) is becoming less and less acceptable.

Published data relating to fibre evidence can broadly be placed into the following two categories; those concerned with the development of analytical methods and those investigating the factors influencing the significance of fibre evidence *(Palmer, 2010a)*

Whilst there can be no doubt that the former is an extremely important aspect of fibre evidence, even the most sensitive discriminating analytical technique is rendered ineffective if its results cannot be applied to answer *specific case related questions* (*Houck, 1999, Palmer, 2010a, Roux, Talbot-Wright et al., 2015, Stoney and Stoney, 2015)*.

It is therefore no surprise that surveys of literature relating to research published relating to fibre evidence in the last 9 years (*Palmer, 2010a, Palmer, 2010b, Palmer, 2013*) show much of the research initiative over this period has been focused towards accumulating data which can be used in the interpretation process of casework, (e.g. transfer and persistence studies, colour block studies, target fibre studies) particularly when a Bayesian framework is employed. This aspect of the literature is the subject of *Chapter 3*.

Despite the move towards a Bayesian based framework, the practice identified by *Grieve and Wiggins, (2001)* of submitting cases for fibre examinations ***"in the hope that something of significance will emerge"*,** or being instructed by the police to '*do a full forensic examination*' as cited by *Jackson and Jones, (2009)*, is still, in this author's experience, continuing. *Robertson and Roux, (2010)* state;

"Put simply, there is little point in conducting trace evidence examinations if they are either scientifically poorly based or if the outcome of such analysis does not contribute in some way to the justice process".

In addition, there is still a school of thought that in order for a scientist to maintain impartiality within the forensic context, only minimal information regarding a submitted case should be provided to the scientist. Proponents of this approach argue that to do otherwise, could result in 'cognitive bias' being consciously or unconsciously introduced by the scientist, resulting in unsafe conclusions being drawn from the results of forensic casework analysis. This view is exemplified by the publications of *Dror, (2013) and Dror, Kassan et al., (2013).* The authors of these papers argue that in order to mitigate such bias, forensic scientists should be [kept blind] to ***'contextual information'***. *Butt, (2013)*, argues that whilst 'managing exposure' to information which may be considered 'extraneous' to a forensic scientist's role in a given case may be desirable; ***'the reality is that a limited amount is oftentimes required to allow examiners to perform their role'***.

Concerns regarding 'bias' were also raised in a report published in 2009 by the National Research Council (NRC); *"Strengthening Forensic Science in the United States: A Path Forward",* which highlighted the need for improvement in virtually all areas of the service delivery of forensic science to its criminal justice system, *National Research Council, (2009) , Chapter 4, p112, Paragraph 2*;

"Throughout scientific investigations, the investigator must be as free from bias as possible, and practices are put in place to detect biases (such as those from measurements, human interpretation) and to minimize their effects on conclusions."

Champod, (2014a), argues that ***"the perceived risks [of cognitive bias] are only postulated and have never been measured"*** and there is a danger that attempts to mitigate such risks could undermine the very processes they seek to protect – balanced, impartial, robust evidence evaluation.

To limit access to information relating to the circumstances of a particular case is to disregard the most fundamental factor governing the interpretation of forensic evidence – namely its *context sensitivity*. The context sensitivity of forensic evidence means that; whilst the use of a particular approach and evidence type may be highly probative and effective in one specific case, the contrary may be true for another.

In contrast to the view of the above authors, *Jackson, Jones et al, (2006)*, argue that;

***"*[propositions that have been addressed]...*should be formulated from the framework of circumstances in the case and through dialogue between parties in the criminal justice system"*.**

The key to the elimination of cognitive bias is not through an information vacuum, but through a thorough understanding of the case circumstances so that a proper case assessment where our expectations of an examination outcome in a particular scenario ('*framework of circumstances'*) are declared through strategy setting, *before* a particular examination occurs. This process was described by *Jackson, Jones et al., (2006)*, as '*detachment*' and is discussed in more detail in *Chapter 2*.

In the current economic climate where there is a drive to reduce turnaround times, as well as provide greater effectiveness and better 'value for money' in forensic casework, a full understanding of the cogent issues in a case, also allows a much more time and resource efficient examination strategy to be developed, producing results that are logical, balanced and which can be robustly assessed against issues of prosecution and defence perspectives.

It is still common practice for many examiners to restrict the reporting of the significance of their findings by solely addressing how likely it is that a questioned sample could have originated from a putative source (*Bommarito, 2009*, *Smith, 2011*). This approach, often termed '*frequentist*' in nature, only considers the significance of the findings from a '*source level*' perspective and does not address the context sensitivity of the findings within the framework of circumstances of the case itself.

Whilst addressing 'source level' issues is an important part of the evaluative process inherent within a Bayesian framework (*Cook, Evett et al., 1993*, *Cook, Evett et al., 1998b, Grieve, 2000a, Drotz, 2006, Nordgaard, Ansell et al., 2012, Vooijs, Vergeer et al., 2015)*, reporting this in the absence of conditioning by case specific information and context, the significance of the evidence (in either an adversarial or inquisitorial legal system) is likely to be woefully understated, (more dangerously) overstated, or, wrongly dismissed as irrelevant. *Houck, (1999)*, states;

"***Context is, in fact, the crucial component to a grasp of the significance of trace evidence. Without context, we are communicating mere facts with no foundation of meaning…".***

This practice of reporting in the United States was (and still is) exemplified by the *National Research Council, (2009)* report, which identified the need for improvement in the interpretation and reporting of laboratory results. The report was particularly critical of the widespread practice of reporting results of laboratory examinations at source level and in particular the vague nature of the wording routinely employed in these reports;

Chapter 6, p185-186, Paragraph 3:

"There is a critical need in most fields of forensic science to raise the standards for reporting and testifying about the results of investigations. For example, many terms are used by forensic examiners in reports and in court testimony to describe findings, conclusions, and the degrees of association between evidentiary material (e.g., hairs, fingerprints, fibres) and particular people or objects. Such terms include but are not limited to "match," "consistent with," "identical," "similar in all respects tested," and "cannot be excluded as the source of." The use of such terms can have a profound effect on how the trier of fact in a criminal or civil matter perceives and evaluates evidence. Yet the forensic science disciplines have not reached agreement or consensus on the precise meaning of any of these terms."

The report went on to make specific reference regarding the way forward in this respect;

"Although some disciplines have developed vocabulary and scales to be used in reporting results, they have not become standard practice. This imprecision in vocabulary stems in part from the paucity of research in forensic science and the corresponding limitations in interpreting the results of forensic analyses. Publications **[relating to the Bayesian Approach]** ***provide the essential building blocks for the proper assessment and communication of forensic findings."***

It also identified a key part of the interpretative process;

Chapter 6, p188, Paragraph 2:

"In evaluating the accuracy of forensic analysis, it is crucial to clarify the type of question the analysis is called to address."

The report had touched upon this crucial aspect in an earlier chapter;

Chapter 4, p112, Paragraph 1:

"The scientific method presumes that events occur in consistent patterns that can be understood through careful comparison and systematic study. Knowledge is produced through a series of steps during which data are accumulated methodically, strengths and weaknesses of information are assessed, and knowledge about causal relationships is inferred. In the process, scientists also develop an understanding of the limits of that knowledge (such as the precision of the observations), the inferred nature of relationships, and key assumptions behind the inferences. Hypotheses are developed, are measured against the data, and are either supported or refuted".

Similar criticisms were made of the case reporting style in England & Wales by *Ramsay, (1989),* which subsequently led to the development of the CAI model in the 1990's.

In part 2 of a paper by *Grieve, (2000b) ,* the results of survey initiated in 1997, showed that 77% of respondent examiners in North America had little or no knowledge of the use of Bayes theorem as an interpretative tool in the evaluation of fibres evidence. Possible reasons for reluctance connected with the adoption of a Bayesian approach to evidence interpretation were cited as;

- A lack of awareness of the explanatory literature available
- An antagonistic mind set generated by the impression that the approach is too complicated or mathematical
- Not knowing how to apply Bayes theorem in practical casework
- Criticism that case scenarios dealt with in the literature are not realistic.

Although this survey relates to 1997, it is this author's opinion that the possible reasons cited for poor uptake in a Bayesian approach to interpretation of fibre evidence are still valid as explanations for these particular findings identified by the *National Research Council, (2009)* report. An initiative by the European Network of Forensic Science Institutes (ENFSI) to develop a standard for the formulation of evaluative reports *(ENFSI, 2015)*, has produced responses by member institutions which reflect similar attitudes in Europe (*Champod, 2014b)*. *Nordgaard, Ansell et al., (2012),* are of the opinion that;

'***Forensic scientists may be sceptical to the logical approach to evidence evaluation…because a majority of forensic cases are still such that no explicit reference data exists with which estimations of likelihoods [ratios] can be done. It is however important to realise that the lack of explicit reference data does not disqualify the use of the logical approach, nor even the use of a likelihood ratio***'**.**

1.3 Misconceptions of the Bayesian approach

Critics of the use of a Bayesian framework in trace evidence investigation, often cite the lack of calculated data (such as allelic frequencies used to obtain match probabilities for reporting DNA results) as a major stumbling block to its application (*Houck, 1999, Bommarito, 2009, Smith, 2011, Bodziak, 2012, Nordgaard, Ansell et al., 2012 , Palmer, 2015b*).

Since the worldwide textile industry is in a constant state of flux due to factors such as economics, changing fashion, seasonal requirements, etc., it is virtually impossible to provide stable frequency data in the same way that can be provided in DNA evidence. The situation is further compounded that there are almost infinite possible combinations of dye, generic fibre class and morphology.

The fundamental difference between DNA evidence and fibre evidence is that; data relating to the prevalence of the former is fixed in time, whilst the latter is not.

Houck, (1999) pointed out that the fundamental difference in the nature of these evidence types means that (as far as *source* level evaluations are concerned) they must be treated with different statistical approaches. ***'One size does not fit all'.***

As previously stated, there is a huge diversity in fibre/ class/ colour/ morphology and it is this very feature which has been shown to be significant. The purpose of addressing *source level* issues is to provide a probability assignment of how likely the findings are due to an adventitious match (i.e. what is the probability that a particular analyte has originated from a source other than that in question?). In the absence of 'fixed' data such as allelic frequencies used in the calculation of DNA match probabilities, probability can be *assigned* using data obtained from the following types of studies;

- Fibre population studies: which provide estimates of the relative frequencies of different fibre type/ colour combinations, *at the generic level*, on particular surfaces/ substrates (e.g. car seats, skin).
- Target fibre studies: provide estimates of the probability of finding a *specific* fibre type, morphology and colour combination, *at the generic level*, on a random surface.
- Colour block studies: provide information on the ability of a scheme of analysis to discriminate between ostensibly similar fibres of a given generic fibre/ colour combination.

The difference between these studies and the information they provide in allowing source level determinations to be assessed is discussed fully in *Chapter 3*.

Misconceptions regarding the availability and use of relevant data for fibre evidence would therefore appear to be due to what *Houck, (1999)* described as;

***'[limiting] a discipline by requiring it to fit into a preordained [mathematical] model'*.**

In other words, there would appear to be a lack of understanding of how a Bayesian framework caters for both the *calculation* of a probability based on empirical data (e.g. allelic frequencies) and the *assignation* of a probability based not only on data, but personal experience and expert judgement. This issue is explored by *Aitken, Berger et al., (2011)* in response to a UK court of appeal challenge *R v 'T', (2010).* The authors' state;

'*…the foundation of the Bayesian paradigm…is that the logic works equally well with purely epistemic probabilities as it does with aleatory probabilities…this is what is 'Bayesian' about the Bayesian approach*'.

The misconceptions/ confusion regarding the Bayesian framework are similarly discussed with reference to *R v 'T', (2010)* by *Robertson, Vignaux et al., (2011).*

These misconceptions concerning use of assigned and calculated probability in a Bayesian framework (*Smith, 2011, Bodziak, 2012, Aitken, Berger et al., 2011, Robertson, Vignaux et al., 2011)* are undoubtedly the main reason that, since the publication of the *National Research Council, (2009)* report, its adoption in reporting fibre evidence in the USA, has still not been fully implemented *(Oein, 2014)*. This would also appear to be the reason for its somewhat variable application in Europe (*Johansson, 2009, Nehse, 2011, Champod, 2014b, Palmer, 2015b*).

Whilst the *National Research Council, (2009)* report identified some cogent issues for improvement in the evaluation and reporting of the results of forensic analysis, its authors also exemplified a lack of understanding of *source* and *activity* level issues;

National Research Council (2009), Chapter 4, p122, Paragraph 3:

"A somewhat obvious cognitive bias that may arise in forensic science is a willingness to ignore base rate information in assessing the probative value of information. For example, suppose carpet fibers from a crime scene are found to match carpet fibers found in a suspect's home. The probative value of this information depends on the rate at which such fibers are found in homes in addition to that of the suspect. If the carpet fibers are extremely common, the presence of matching fibers in the suspect's home will be of little probative value"

This statement exemplifies a general misconception amongst practitioners and judiciary alike that the Bayesian Approach per se, must *solely* involve the use of empirically derived

frequency (*Houck, 1999, Bommarito, 2009, Smith, 2011, Bodziak, 2012, Nordgaard, Ansell et al., 2012, Champod, 2014b, Palmer, 2015a*).

Bodziak, (2012), states;

'*...formulating a likelihood ratio on notional and estimated data contribute[s] nothing toward assuring a more accurate conclusion, but seriously risks misleading the examiner and jury*'.

Responses noted by *Champod, (2014b)*, relating to the production of the ENFSI guidelines for evaluative reporting in forensic science *(ENFSI, 2015)*, include comments exemplified by;

'..there are [a], lack of standards, appropriate databases or adequate validation studies to perform a probabilistic assessment of findings using likelihood ratios' [and] 'assessment of likelihood ratios by verbal predicates is subjective and therefore inconsistent in many cases with the objective assessment of the evidence'.

An informal survey of ENFSI-ETHG membership by this author *(Palmer, 2015b)* revealed similar comments regarding '*subjective inference'* and '*lack of data*' amongst institutions that do not employ a Bayesian framework in their reporting. However, some of those who criticised the use of likelihood ratios, did state that they formulated their conclusions within "***the context of the specific case under consideration*".**

Whilst the probability of encountering matching fibres by chance is an important consideration in the above case scenario quoted by the *National Research Council, (2009)* report, one needs to evaluate this information within the *context specific nature* of the case, e.g.; how is it alleged the fibres were transferred to the suspects home, what activity at the scene is under question, what is the relationship between the victim and the suspect and what are the alleged time scales involved? This illustrates another misconception that source level estimates can be used to directly address activity level issues *(Palmer and Booth, 2010)*.

Jackson, Jones et al., (2006), argue that the following are key factors in the evaluation of forensic evidence;

- Knowledge of the framework of circumstances in a given case with formulation of appropriate propositions
- Casework experience
- Knowledge of inter and intra-sample variation of evidential materials

- Knowledge of published data such as transfer and persistence and background occurrence of evidential material

To address activity level on source level data is to ignore highly relevant issues of transfer and persistence likely to be of interest to the court. In many cases, the issue of whether or not recovered fibres have originated from a putative source is not disputed, but the activity resulting in its transfer is. In the case of the Ipswich serial killings for example *(Palmer, 2008)*, it was accepted by the defence that the fibre collectives found on each of the dead women had originated from the suspect and his environment, however, the issue of *when* these had been transferred was the principal source of dispute. Likewise, *Bennett, Roux et al., (2010)*, describe a homicide by strangulation, where transfer and persistence data relating to the fibre evidence was the contested aspect of the evidence evaluation.

However, despite the misconception and resistance to its uptake, as stated previously, the *National Research Council (2009)* report does appear to have been the driver for a subsequent change towards a more logical, evaluative reasoning style of reporting in the USA (*Koch, 2012*, *Koch, 2013)*.

The issues discussed in his section have been (and continue to be) exemplified by various court of appeal rulings in the UK, which are described in detail in *Chapter 2* of this thesis.

1.4 The need for data – the present situation

Whilst many may argue that much of the *National Research Council (2009)* report is not applicable to the provision of forensic science in Europe, one aspect it identified is globally applicable, namely the difficulty in producing relevant research;

Chapter 6, p187, Paragraph 1:

"....the forensic science disciplines suffer from an inadequate research base: Few forensic scientists have the opportunity to conduct research, few academics are positioned to undertake such research, and, importantly, the funding for forensic research is insufficient."

The report also highlighted a funding bias towards research related to DNA profiling;

Chapter 6, p187, Paragraph 2:

"..it has been only in recent years that the National Institute of Justice has taken interest in funding forensic science research, but the majority of these funds have been awarded to reduce case backlogs, especially for cases that involve the analysis of DNA.."

Whilst there may be a funding bias towards DNA related research, research relating to fibre evidence continues to be carried out, despite the fact that many practitioners in operational laboratories find it increasingly difficult to obtain support and resources due to operational demands on their time and (perhaps more importantly), budgetary constraints. The present economic situation at the time of writing (where austerity measures have been implemented world-wide), makes the situation even more difficult in terms of funding research and encouraging international collaboration *(Palmer, 2013)*.

The decision by the UK government to close its state run Forensic Science Service (FSS) of England and Wales in 2011, has been a major cause of concern, as this organisation, at its peak, was a proliferate source of research in all aspects of forensic science.

As a consequence of this decision, forensic science provision in England and Wales* is now provided on a commercial basis. The current commercial 'market' for forensic science provision in these countries involves forensic casework being broken down into commodity based components, each of which is offered for tender by commercial providers. Contracts tend to be awarded principally on cost, rather than the expertise profile of the provider. This coupled with cuts to police budgets, in-house resourcing of forensic examinations has resulted in an ever shrinking 'market', where the customer is also effectively the competitor. Consequently, commercial forensic science providers in England and Wales are enduring smaller and smaller profit margins and not surprisingly pure research is of low priority, and likely to be driven according to 'business need' (*Nic Daeid, 2011*, *Home Office Committee for Science and Technology, 2012, 2013, Gallop and Brown, 2014)*.

In the absence of the FSS, the burden of research in the UK has now been placed on Universities *(Silverman, 2011)*, however, despite initiatives such as the formation of a *Forensic Science Special Interest Group* (SIG) to promote funding for such research in the UK, **"[these initiatives]** ***will require time and effort…especially as the funding landscape remains so competitive*****"** *(Research Councils UK, 2013)*. At the time of writing, there is still no ring-fenced funding for research in Forensic Science.

Since the demise of the FSS and the commercialisation/ commoditisation of forensic science provision in England & Wales, **'[the]** ***CAI developer's interest in maximising the customer's own value for money is understood to contradict the need for business leaders to maximise profits, particularly in a competitive economic environment'*** *(Lawless and Williams, 2010)*. In other words casework assessment has (ironically) become cost, rather than value driven.

The current situation in England and Wales, is therefore, in many ways worse than that depicted by *Grieve and Wiggins* in 2001, however, the strategies and solutions they identified over ten years ago (particularly the need for data) are still (if not even more) relevant.

What is clear is that no single evidence type can stand alone in the investigation of major crime, whilst it can be argued that fibre evidence can and does provide compelling evidence in its own right, it (like other evidence types) very often complements other evidence types and provides additional added value, not just in terms of summated evidential value, but also in terms of the nature of the information it provides e.g. answering questions of '*when*', '*where*' and '*how*'. This 'added value' can therefore be defined both quantitatively and qualitatively.

In order to continue to provide value and increase the effectiveness of fibre examinations (whether in a commercial or state-run environment), there is a clear need for a more robust, transparent approach to casework assessment and interpretation through a greater understanding of the significance of the various underlying processes and the complex interdependencies that exist between them.

*At the time of writing, forensic science in Scotland and Northern Ireland remains under state provision.

Robertson and Roux, (2010), argued that;

"***The challenge for the current and next generation of forensic managers is to not lose sight of forensic science as a holistic subject and support the trace evidence examiners to develop a sounder knowledge base through enhanced and properly targeted R&D*".**

Globally then, the present challenge is to continue to address the need for data, specifically by targeting research in areas where there are limitations and/or deficiencies of our knowledge of the underlying processes governing the significance of fibre evidence to improve casework assessment and interpretation and increase the effectiveness of this evidence type.

1.5 Purpose of work

As stated previously in this chapter, the current challenge relating to the forensic examination of fibres (and indeed other evidence types) is to improve the effectiveness of these examinations, by providing a more robust framework of casework assessment, strategy setting and interpretation. In terms of a driver for research, this translates into the need for more empirical data which can address recurring questions arising not only during the investigation of major crime, but also those encountered during court testimony.

The purpose of this study is therefore to identify, evaluate and address 'gaps' in key areas of our present knowledge of the factors influencing the interpretation of fibre evidence and assess these against the potential benefits in evidence evaluation.

These 'gaps' can be defined as;

- Lack of published data identified in the evaluation of evidence relating two specific real case scenarios encountered by the author
- Lack of, or incomplete data sets useful in a more global context in the evaluation of textile fibre evidence.

The intention of this work is that it will inform a more effective casework assessment and strategy framework, ultimately allowing more robust interpretation and conclusions to be drawn from the results of examination in the defined circumstances.

1.6 Strategy

In order to achieve this, the following strategy has been adopted;

1.6.1 The Bayesian framework in forensic casework (Chapter 2).

In this chapter, the background and rationale behind the introduction of a Bayesian framework to underpin the assessment and interpretation processes of forensic evidence is given, key concepts are defined and practical aspects of its application are discussed. In addition, the use of Bayesian networks to model a specific case scenario and evaluate the complex inter-dependencies of factors involved in the interpretation process is introduced

and defined as a key evaluative tool in this thesis and is demonstrated to be the most appropriate method for assessing the impact of data and areas of 'sensitivity' within the complex inter-dependencies of factors governing the significance of fibre evidence in a given case scenario.

Finally, judicial challenges to the application of the Bayesian framework in forensic science are discussed.

1.6.2 Literature review (Chapter 3)

A comprehensive, up to date, literature review relating to the key factors influencing the interpretation of fibre evidence is carried out in *Chapter 3*. This chapter will consist of a review of current literature, specifically relating to factors important in the evaluation of fibre evidence, namely; transfer and persistence ('t' values), the probability of an 'adventitious' fibre match ('γ' values) and the presence and size of non-matching fibre collectives ('b' values) recovered from the recipient item. The importance of data relating to these factors and their use in a Bayesian framework will be introduced in Chapter 2 and discussed more fully in *Chapters 4, 5 and 6*.

This review will also identify areas where there is a gap, or a need for refinement, in our understanding of a particular factor relating to the evaluation of fibre evidence. This exercise will therefore also serve to inform the strategy and planning of future research.

1.6.3 Validation of Bayesian network architecture (Chapter 4)

In Chapter 4, 'Hugin Researcher™'*(Hugin Expert A/S, Aalborg, Denmark, as a 'compact model representation for reasoning under uncertainty'),* a commercially available Bayesian network software package, will be used in 'simple' casework scenarios involving one-way and two-way fibre transfer evidence. The likelihood ratios generated by these Bayesian networks will be examined for congruence with those calculated according to published formulae used to model the same casework scenarios, with the same conditional probability data.

The aim of this chapter is therefore to 'validate' the underlying structural components of the Bayesian network architecture, for subsequent use in modelling the more complex casework scenarios in *Chapters 5 & 6*.

1.6.4 Fibre evidence on skin: The Ipswich serial killings (Chapter 5)

In order to fully evaluate the value and impact of the work in addressing the areas of knowledge deficiency identified in the literature review, two real major crime scenarios encountered by the author will be used for this purpose. The two real case scenarios were chosen by the author as they each presented particular challenges, not only in terms of issues of interpretation of the findings, but also in terms of assessing and implementing an effective examination strategy.

The data sets drawn from the literature search will be included according to the relevance for each case scenario (i.e. transfer and persistence ('t' values), the probability of an 'adventitious' fibre match ('γ' values) and the presence and size of non-matching fibre collectives ('b' values)).

Chapter 5, will consider the first of the two real case scenarios chosen by the author, which involved the serial killings of five women around the town of Ipswich, in the county of Suffolk, England in 2006. This chapter will detail the circumstances of the case and the aspects of fibre transfer and persistence which proved to be crucial in evaluating the findings for the court. In addition, the lack of published data relevant to this case will be identified and the impact of data from subsequent research by the author to address this, will be evaluated.

The Bayesian network software package ('*Hugin Researcher™*') 'validated' in *Chapter 4*, will be used to model the case scenario for the purpose of comparing and evaluating the impact of the 'new' data sets on the interpretation of the fibre evidence in this case.

1.6.5 Fibre evidence in head hair: A bank robbery (Chapter 6)

Chapter 6 will consider a series of bank robberies were masks (balaclavas) were recovered from 'getaway' vehicles used in the commission of these crimes. Although a number of suspects were identified and apprehended, the police did not attempt to recover any potential fibre evidence from these individuals. Using data from the authors studies and that identified in the literature review (*Chapter 3*), the potential utility of fibre evidence in this case (and other similar cases) will be evaluated and an investigative strategy proposed.

The Bayesian network software package ('*Hugin Researcher™*') 'validated' in *Chapter 4*, is used to construct a model for this case scenario which will incorporate the complex

interdependencies of the various factors and data sets important in the initial assessment and subsequent interpretation.

Since the graphical user interface of '*Hugin Researcher*^{TM} ' allows an easy and rapid inclusion or exclusion of a particular data set, the impact of new data sets from the author's studies on the overall Likelihood Ratio (LR) driven by the case circumstances are assessed.

'Sensitivity analysis' is also performed to determine which factor(s) has the most influence on the resulting likelihood ratio.

2 FORENSIC SCIENCE AND THE BAYESIAN FRAMEWORK

In this chapter, an overview of Bayes theorem is provided along with the history of its application in the casework assessment and interpretation model instigated by the (then) state run Forensic Science Service of England and Wales. Key definitions regarding the application of the Bayesian framework in the evaluation of textile evidence are given and practical applications are discussed. Finally, challenges to the application of the framework by the judiciary in England and Wales, which exemplify global misconceptions regarding Bayes theorem, are discussed.

2.1 Bayes Theorem

Bayes theorem, was named after Thomas Bayes (1701-1761) who first proposed a theorem dealing with conditional probabilities. His work was further developed and published by *Laplace, (1814)*. This theorem essentially provides a means of updating a degree of belief on a given proposition in the light of new information or evidence.

This method is employed in a number of applications, where 'reasoning under uncertainty' is required e.g. medical diagnoses, stock market analysis and risk analysis, to name a few.

Over the past two decades, it has been introduced and developed as a framework for the interpretation and evaluation of forensic evidence as it is very useful in dealing with the evaluation of findings in the light of two competing propositions (i.e. the defence and prosecution propositions). Before its demise in 2011, The Forensic Science Service (FSS) in England & Wales was the major proponent of the use of this framework in operational forensic casework.

2.2 Introduction of the Bayesian Framework in Forensic Science

In the mid-late 1980's, the then state-run Forensic Science Service (FSS) of England & Wales was experiencing a number of operational difficulties with its service delivery (*Ramsay, 1989*):

- Significant casework backlogs and unacceptable turnaround times
- Poor communication between the Police and the scientists
- Carrying out lengthy and often ineffective examinations resulting in 'inconclusive' conclusions
- Criticism of the use of confusing or ambiguous language in statements and reports
- Poor 'value for money'

In the late 1990's, the FSS proposed and instigated a new approach to casework assessment and interpretation based upon the principles of *Bayesian* inference *(Cook, Evett et al., 1998b)*, which was designed to streamline and improve the deficiencies in its service delivery. The casework, assessment and interpretation (CAI) model as it became known, continued to evolve and was used routinely in casework until the closure of the FSS in 2011 *(Lawless and Williams, 2010)*. Its specific use in the forensic examination of fibres has been demonstrated by *Evett, Cage et al., (1987)*, *Cook, Evett et al., (1993)*, *Cook, Evett et al., (1998b), Champod, Evett et al., (2004)*, *Champod and Taroni, (1996)*, *Champod and Taroni, (1999), Jackson,*

Jones et al., (2006), Jackson and Jones, (2009), Palmer and Booth, (2010) and *Champod and Taroni (pending).*

2.3 Definitions

The basic concept in Bayes theorem is that of *conditional probability*; whenever a statement of probability (P) of an event A is given it is given under the condition of other known factors. This can be exemplified by the statement: "*given the event B, the probability of the event A is x*".

The notation for this is $\mathrm{P(A|B)} = \mathrm{x}$

Bayes theorem is:

$$\mathrm{P(A|B)} = \frac{\mathrm{P(B|A)P(A)}}{\mathrm{P(B)}}$$

This defines the relationship between the probabilities of A and B and the *conditional probabilities* of A given B and B given A.

Where;

- $\mathrm{P(A)}$ is the prior probability i.e. the initial degree of belief in A
- $\mathrm{P(B)}$ is the prior probability i.e. the initial degree of belief in B
- $\mathrm{P(A|B)}$ is the posterior probability i.e. the degree of belief in A given B

In a forensic context, where the probabilities of two competing propositions (events) need to be considered (i.e. Hp = the prosecution version of events and Hd = the defence version of events) through conditioning by the findings from an examination (E), and contextual information (I), Bayes theorem can be rearranged where the prior and posterior probabilities for each proposition are ratios, commonly referred to as 'odds' and the quotient of the probability of the evidence given the proposition becomes the *likelihood ratio*.

$$\frac{\mathrm{P(Hp|I,E)}}{\mathrm{P(Hd|I,E)}} = \frac{\mathrm{P(E|Hp,I)}}{\mathrm{P(E|Hd,I)}} \times \frac{\mathrm{P(Hp|I)}}{\mathrm{P(Hd|I)}}$$

Posterior odds Likelihood Ratio Prior Odds

Prior (contextual) information can be accounted for by conditioning the probabilities on this throughout the equation. The likelihood ratio (LR) therefore becomes a measure of how much the evidence favours the prosecution and defence propositions, i.e. how our initial belief (prior odds) is updated by the evidence (LR), to a new / final belief (posterior odds).

Where the LR >1 the probability of Hp is increased, where LR < 1 the probability of Hd is increased.

In simple terms the likelihood ratio can be expressed as;

$$\mathrm{LR} = \frac{\text{Probability of the findings if the prosecution proposition is true}}{\text{Probability of the findings if the defence proposition is true}}$$

The Bayesian approach therefore allows us, in the face of new forensic observations (i.e. outcomes of examinations) to update a probability which describes our personal state of belief regarding an event which is conditioned by relevant information.

2.4 Propositions and hierarchical setting

Given that the Bayesian framework is conditioned upon a pair of competing propositions (Hp & Hd), it is crucial that these are appropriate and reflect the case circumstances being addressed.

Cook, Evett et al., (1998a) and *Evett, Jackson et al., (2000b),* proposed a 'hierarchy of propositions' designed to assist in effective proposition and strategy setting. This 'hierarchy' describes three increasing levels of contribution to the court, defined as 'source', 'activity' and 'offence' level propositions.

An example of source level propositions is;

- The fibres on Mr A's (the suspect) clothing came from Mr B's pullover (Hp)

- The fibres on Mr A's clothing came from someone else's pullover (Hd)

An example of activity level propositions is;

- Mr A (the suspect) assaulted Mr B who was wearing the pullover (Hp)
- Mr A was present at the scene, but did not assault Mr B (Hd)

Offence level propositions deal directly with the issue of guilt or innocence;

- Mr A (the suspect) murdered Mr B (Hp)
- Someone else murdered Mr B (Hd)

Since it is the role of the jury (in an adversarial legal system) and the judge(s) (in an inquisitorial legal system) to establish guilt or innocence, offence level propositions are generally not considered or addressed in proposition setting by the forensic scientist.

The ability to move beyond source level propositions to address activity level propositions will depend on a number of factors such as; the case circumstances (*the framework of circumstances*), the nature and relevance of the exhibits submitted, the experience of the scientist and the background data available. Ideally, activity level propositions should always be used when specialist knowledge of factors such as the transfer and persistence characteristics of a specific analyte of trace evidence have an important contribution to the understanding of a particular alleged activity *ENFSI, (2015)*.

The 'basic' likelihood ratio calculation outlined above, can be further refined to encompass data from factors which impinge upon the probability assignments of the observations given Hp or Hd when considering *activity level* propositions. In a 'simple' one-way fibre transfer case probability assignments will be conditioned by factors relating to; transfer, persistence and recovery ('t' values), the probability of an 'adventitious' fibre match ('γ' values) and the presence and size of non-matching fibre collectives ('b' values) recovered from the recipient item in question. Such a refinement is described by *Evett, (1984)*, *Aitken and Taroni (2004)* and *Champod and Taroni, (pending),* and is expressed as;

$$\mathrm{LR} = \frac{(\mathrm{b}_0\mathrm{t}_\mathrm{n})+(\mathrm{b}_1\gamma_\mathrm{b}\mathrm{t}_0)}{(\mathrm{b}_0\gamma\mathrm{t}'_\mathrm{n})+(\mathrm{b}_1\gamma_\mathrm{b}\mathrm{t}'_0)}$$

Where:

t_n is the 'transfer probability' under Hp, that a given number of fibres have been transferred from a donor to a recipient surface.

t_0 is the 'transfer probability' under Hp, that no fibres have been transferred from a donor to a recipient surface.

t'_n is the 'transfer probability' under Hd, that a given number of fibres have been transferred from a donor to a recipient surface.

t'_0 is the 'transfer probability' under Hd, that no fibres have been transferred from a donor to a recipient surface.

b_0 is the probability of recovering no foreign fibre groups (FFG) distinguishable from the donor item, on the recipient surface.

b_1 is the probability of recovering one foreign fibre group (FFG) distinguishable from the donor item, on the recipient surface.

γ and γ_b are the probabilities of finding similar fibre collectives sharing the same characteristics as the fibres comprising the suspect's pullover, in alternative garments from potential offenders or as background fibres on car seats, respectively. In the majority of circumstances these two values can be considered the same.

The derivation and application of these values in a Bayesian framework concerned with the evaluation of fibre evidence, is described in greater detail in *Chapters 3, 4, 5 and 6*.

2.5 Verbal scales

Whilst the likelihood ratio provides a method of evaluating the impact of the findings with respect to the prosecution and defences stances, understanding this process may be difficult for a lay person (most usually for whom a report is intended). It is now standard practice for those employing a Bayesian framework in casework assessment and interpretation to translate the likelihood ratios obtained from this process, into an equivalent verbal scale such

as that described by *Evett, Jackson et al., (2000a*), *Association of Forensic Science Providers, (2009*) and *Nordgaard, Ansell et al., (2012)*, for the purposes of reporting.

. Value of Likelihood Ratio	Verbal Equivalent
>1-10	Weak support
10-100	Moderate support
100-1000	Moderately strong support
1000-10000	Strong support
10000-1000000	Very strong support
>1000000	Extremely strong support

Table 2.1: Verbal scale and likelihood ratio equivalence *Association of Forensic Science Providers, (2009)*

Level	Value of Likelihood Ratio	Verbal Equivalent
+4	>1000000	Extremely strong support for Hp
+3	6000-1000000	Strong support for Hp
+2	100-6000	Support for Hp
+1	6-100	Support to some extent for Hp
0	0.17-6	No support for Hp or Hd
-1	0.17-0.01	Support to some extent for Hd
-2	0.01-0.00017	Support for Hd
-3	0.00017-0.000001	Strong support for Hd
-4	<0.000001	Extremely strong support for Hd

Table 2.2: Verbal scale and likelihood ratio equivalence *Nordgaard, Ansell, et al, (2012*)

Tables 2.1 & 2.2 show the standardised verbal scale and likelihood ratio equivalence employed in the UK and Sweden respectively. Whilst each takes a slightly different approach in terms of their use in reporting casework, the underlying framework is analogous *(Nordgaard, Ansell et al., 2012)*.

Whilst verbal scales are generally regarded amongst many practitioners as being the most pragmatic solution in communicating the strength of evidential findings to a lay person, their utility has been the subject of some debate (*Mullen, Spence et al., 2014*, *Jackson, Evett et al., 2014*). In addition, recent studies by *Martire, Kemp et al (2014)* and *Martire and Watkins (2015)* provide evidence that their use may be counter-productive in informing the lay person of the intended opinion of the expert concerning the significance of the evidence.

Despite these concerns, the *Association of Forensic Science Providers, (2009)* verbal equivalence scale shown in *Table 2.1*, will be used when assigning levels of 'strength' to the results from the Bayesian networks in *chapters 5 & 6*, used to model the relevant casework scenarios.

2.6 Expectations, propositions and strategy setting

In many respects, the misconceptions resulting in reluctance by many fibre practitioners to adopt the Bayesian approach (or indeed its misapplication), may be due to the manner by which it has been promoted to them, i.e. using DNA based examples and/ or statistics beyond the ability of the intended end user. However, as already stated, one does not need to use very accurate frequency data such as allelic frequencies, or complicated statistical equations in order to use this approach as a means of formulating, defining and quantifying our expectations in a case and subsequently testing these against empirical observations.

One way of applying this approach is through the use of an '*expectation matrix*' to assist in the pre-assessment process of casework, i.e. *before a particular examination strategy has taken place*. This approach, which represents a fairly crude method of applying the Bayesian *framework* to fibre casework and interpretation, nevertheless allows the practitioner to define

their expectations of the outcome of their examinations, if each of two competing propositions was true. Formulating (adequate) propositions lead to a more precise definition of the questions being asked of the practitioner and serves to inform the conditional factors within a given framework of circumstances. The outcome of the subsequent examination is then evaluated against the initial expectations for each proposition. This approach allows the examiner to obtain a clearer 'line of sight' in formulating their examination strategy and evaluating subsequent findings against the specific case circumstances and the defence and prosecution stances (*Palmer and Booth, 2010*).

For example;

Consider a case where an armed robbery at a bank has taken place. Witnesses describe a man wearing a balaclava leaving the scene in a car. Witnesses also took details of the cars registration number. The 'getaway car' was subsequently found abandoned some distance from the scene of an armed robbery and a balaclava was found in the front passenger foot well. A suspect was arrested a day later and tapings taken from his hair. The suspect denies ever wearing a balaclava or having anything to do with the robbery. In this case two competing propositions can be defined;

1. The suspect wore the balaclava at the time of the robbery (Hp)

2. Someone else wore the balaclava at the time of the robbery (Hd)

In assessing such a case, data in the literature can provide expectations of particular outcomes from the examination – with regard to the activity based propositions. These 'expectations' can be expressed as probability values, however, it is important that these figures are not regarded as 'tablets of stone' and that *they merely act as a means of quantifying the thought process and are not quoted with the same level of precision as for DNA match probabilities.*

Based upon examples from the literature relating to the persistence of fibres in head hair (*Ashcroft, Evans et al, 1988, Salter and Cook, 1996*), the results of population studies *(Palmer and Oliver, 2004)* and target fibres studies *(Palmer and Chinherende, 1996)*, our *expectation matrix* may resemble that shown in *Table 2.3*:

Potential Outcome (No. of Fibres)	P(E|Hp)	P(E|Hd)	LR
Many matching fibres (>10)	0.9	0.0001	9000
Few matching fibres (<10)	0.099	0.0099	10
No matching fibres	0.001	0.99	0.001

Table 2.3: Basic 'expectation matrix' for casework assessment and interpretation

Again, it needs to be emphasised that the probability values are only orders of magnitude higher, based upon the practitioner's *expectations* with reference to the literature and their own experience. In the above example, it can be seen that the assigned probability estimates, produce likelihood ratios (LR's) that are several orders of magnitude higher that many fibres would be found in the suspect's hair had he been wearing the balaclava, at the time of the offence rather than if he had not. *This immediately tells us that applying fibre examination in this case is worth doing, as well as giving indications of the potential value of examination outcomes.*

Finding for example, 20 fibres in the suspect's hair matching the balaclava would therefore provide a high level of support for the prosecution proposition (Hp). On the other hand, finding no fibres would provide a high level of support that a person other than the suspect had worn the balaclava (Hd).

This process is referred to as '*detachment*' by *Jackson, Jones et al., (2006),* who argued that this was necessary; ***'if a scientist is to offer a balanced, robust, evaluation'*.**

Through the use of data from transfer and persistence studies and personal casework experience, this particular approach assists the practitioner in progressing from source to activity level propositions. It also assists the practitioner in developing;

- a clearer line of sight in developing an effective examination strategy.
- a more logical, transparent, robust interpretation and conclusion.

The underlying process of '*detachment*' in this approach, also addresses and mitigates concerns expressed by *Dror, (2013)*, *Dror, Kassan et al., (2013)*, *Butt, (2013)* and *National Research Council, (2009)*, regarding cognitive bias.

However, the limitation with this 'matrix based' format is that it does not provide transparency regarding the logic and knowledge base used in the application of this particular method;

In the case cited, the probability assignments provided regarding the expectation of numbers of fibres found, are actually based upon the contribution of a number of inter-related parameters (e.g. transfer and persistence studies, population/ target fibre studies, analytical discrimination, etc.), some having a greater impact than others depending on the case circumstances. Whilst these are undoubtedly evaluated in the mind of the experienced examiner, this particular format does not lend itself to providing a clear line of sight of the case specific 'high impact' parameters and their inter-relationships.

Since the aim of this thesis is to perform an impact and sensitivity analysis on the various interdependent factors relating to the assessment and interpretation of fibre evidence, the use of this 'expectation matrix' is therefore, not fit for this purpose.

2.7 Bayesian Networks

The use of 'Bayesian Networks' to model complex probabilistic inter-relationships in forensic casework is well documented (*Hepler and Weir, 2008, Jensen, 1996, Jensen and Nielsen, 2007, Taroni, Biedermann et al., 2004, Sironi, 2009, Champod and Taroni, 2014, Taroni, Biedermann et al.,2014*). The advantage of Bayesian networks over the above 'matrix based' format is that they can be constructed to model a particular case scenario with the complex inter-dependent factors important to the evaluation of the results in the light of the prosecution and defence propositions included with much greater transparency. Probability values can then be assigned and the impact of these individually and collectively on the likelihood ratio, can be readily and instantly assessed.

It is for these reasons, that the use of these is employed in the evaluation of the study data in this thesis. The description, use and validation of Bayesian networks and the software package (*'Hugin Researcher™'*) used in constructing these for this purpose of this thesis, is dealt with in *Chapter 4*.

2.8 Challenges of the Bayesian framework

Over the past few years there have been a number of court of appeal rulings in the UK which have essentially related to a challenge of the logical, evaluative, reasoning processes involved in the Bayesian framework.

Whilst none of these cases involved fibre evidence per se, they exemplify much of the 'global' misconceptions regarding the Bayesian framework outlined in Chapter 1.

The most recent, *successful* challenge of the Bayesian framework in the English court of appeal, featured the case of *R v 'T', (2010).* Before looking at the rulings in this case in more detail, it is necessary to consider two other court of appeal rulings in which similar but unsuccessful challenges to the Bayesian framework were made; *R v Reed and Reed, (2009)* and *R v Weller, (2010)*.

2.8.1 R v REED and REED (2009)

David and Terence Reed were brothers convicted of the murder of Peter Hoe in 2006. Amongst the evidence against the accused were two pieces of plastic found at the crime scene which were linked to two separate knives believed to have been used to kill the deceased. One of the pieces of plastic from the crime scene provided a DNA profile matching that of Terence Reed, the other piece provided DNA profiles matching David Reed and that of the deceased.

The substance of this appeal was not on the question of the 'matches' of the DNA, but on the admissibility of the reporting scientists' evidence evaluating the likelihood of various possible scenarios of transfer of the appellants' DNA to the items in question. In the absence of any explanation by the appellants for the presence of their DNA on the incriminating items, the reporting scientist considered a number of possible scenarios;

- Primary transfer when the knives were brought to the crime scene by the appellants, and subsequently broken.
- Primary transfer to the knives, the knives then brought to the crime scene by another person or persons.
- Secondary transfer through the appellants touching another person who subsequently transferred the appellants DNA to the knives whilst taking these to the crime scene.
- Secondary transfer through the appellants shaking the hands of the deceased at some prior occasion, the deceased subsequently transferring the appellants DNA to the knives.

The first of these possibilities was considered to be the most likely, according to the reporting scientist.

It was submitted by counsel for the appellants that the evaluation of likelihood of a particular deposition by the reporting scientist could not be justified, as there was no published research to sustain that opinion.

In considering the prosecution and defence arguments, the court of appeal judges concluded that;

"*The issue was whether any evidence could be admitted which enumerated the possibilities of how DNA came to be on the knife fragments and if so, whether these possibilities could be evaluated*"

"[The experience of the expert(s) employed by the defence] did not extend to examining the scene of the crime and relating that examination to the evaluation of the circumstances of transfer of unidentified material"

"..in our view, a forensic scientist with scenes of crime experience…can properly use knowledge of the scene of the crime and other agreed circumstances to evaluate those possibilities by reference to [their] experience and scientific research undertaken."

" *..in our view.. as a witness can express an opinion on the possibilities with suitable caveats, then logic dictates it will not only be possible to give some evaluation* [of each of the possibilities] *but essential to do so..*"

"*..it is not logical.. to say that an expert could never give such evidence once it is accepted that the possibilities can be enumerated* [in other evidence types]"

***"..it is difficult to envisage the circumstances being set out…or defined by a set of rules because the circumstances in which such evidence can be given are likely to be so variable*."**

In other words, the logical evaluation of forensic evidence by an expert can be carried out in the absence of published data, provided the expert has suitable operational experience and their opinion is formulated within a defined framework of circumstances or context sensitivity of the case with suitable caveats.

On this basis, the original conviction was upheld and the appeal rejected.

2.8.2 R v WELLER (2010)

On the 30th November 2006, Peter Weller was convicted of sexual assault by digitally penetrating the vagina of a 16 year old girl at a party.

The circumstances were that the victim was very drunk at a party, became unwell and was helped to a bedroom by Peter Weller. The victim maintained it was there in the bedroom, that Weller inserted his finger into her vagina. The appellant maintained that he helped the complainant into bed, pulled the hair out of her eyes to prevent her further vomiting on it and put her in the recovery position.

Fingernail clippings from the left hand of the appellant were swabbed and a mixed DNA profile, the major component being attributable to the appellant with a minor component matching that of the complainant was found. Nothing of significance was found on the nail clippings from the right hand of the appellant.

It was common ground at the original trial and at the appeal, that DNA from the complainant was indeed present on the fingernail clippings of the appellant, but, there were five possibilities for its presence;

1. From the appellants primary contact with the complainants hair
2. From the appellants primary contact with the complainant when he put her to bed and/ or moved her into the 'recovery' position.
3. From primary contact with the complainants vomit

4. From the appellants primary contact with the complainant by inserting his fingers into her vagina

5. By secondary contact due to the appellant picking up the complainants clothing (especially her knickers).

At the original trial the reporting scientist evaluated these possibilities and it was her opinion that there was 'strong support' for the view that the DNA transfer was due to digital penetration rather than the other mechanisms proposed.

The appeal was based upon the contention that there was insufficient scientific reliability for an expert to express an opinion based upon an evaluation of each of these possibilities. Counsel for the appellant further contended that the state of [published] scientific knowledge was such that the original reporting scientist (and also that employed by the original defence team) should not have expressed the evaluative opinions that they did.

The submissions by the appellant were based upon the reports of a witness;

"[*who*] *had published a large number of papers in areas of cell biology and molecular biology…However [was] a scholar, not man of practical experience in DNA*"

This expert testimony referred to a published paper on the transfer and persistence of DNA under fingernails which it was claimed demonstrated it was not safe to evaluate the possibilities presented in this case.

In contrast, the crown called on the evidence of an expert;

"*who had the benefit of an enormous amount of knowledge of a scientific nature not derived from published papers, but from day to day work carried out which showed the scientific position that had been reached in practical work*."

His evidence contradicted that of the appellant not only in the conclusions drawn from the cited paper, but also by reference to unpublished research and direct casework experience carried out by himself and his colleagues.

After hearing the evidence from the crown and the appellant, and reviewing the published material themselves, the judges rejected the appeal for the following reasons;

"*The problem* [is that the witness for the appellant]*… simply did not have that practical day-to-day experience of work that necessarily is unpublished, but from which it is possible to draw scientific conclusions*".

"..the evidence given [by the crown] was logically compelling because an examination of logic of the various possibilities would show that it was realistic to make an evaluation in this case."

"*It is unrealistic to examine a field of science of this kind only by reference to published sources…evaluating evidence will be entitled to take into account the experience of the experts and if their experience is challenged* [to do this by] *cross examination."*

"*What this appeal demonstrates is that if one tries to question science purely by reference to published papers and without practical day to day experience* [in] *which others have reached a judgement, that attack is likely to fail, as it did in* [this] *case."*

In other words, published data is only one part of the process of logical evaluative reasoning inherent in a Bayesian framework.

2.8.3 R v 'T' (2010)

The original conviction of 'T' was based upon the presence of a footwear mark at a homicide crime scene which was deemed to have been made by a pair of training shoes found in the accused's home. The substance of the appeal was; the validity of a footwear database used to estimate the probability of encountering a particular brand and the admissibility of the use and calculation of likelihood ratios in forming an evaluative opinion of how likely it was that the trainers in question were those which left the mark at the crime scene.

Despite the testimony of the reporting scientist that the limitations of the data provided by the database was tempered by his own experience and judgment in providing an evaluative opinion, this appeal was upheld and a number of rulings were made by the judges which appeared at odds with rulings from *R v Reed and Reed* and *R v Weller*. This judgement has had lasting implications for the casework assessment and interpretation model.

The judges upheld this appeal principally on the grounds of 'uncertainty of data' despite the fact that all statistical methods operate within that exact premise;

"the fact that there is no reliable statistical basis does not mean a court cannot admit an evaluative opinion…..it can do so where there is some other sufficiently reliable basis for its admission"

"In R v Weller evaluative evidence was also admitted on the basis of work done by forensic experts where no database exists..[there was not] any question of a statistical database or use of a likelihood ratio"

In fact the use of a Bayesian framework was employed in both the *R v Reed and Reed* and *R v Weller* cases *(Clayton, 2010)*.

Despite the *R v 'T' (2010)* ruling, similar more recent challenges to the admissibility of evaluative opinion have failed on the basis predicted by the *R v Weller (2010)* ruling. In 2013 the court of appeal in the cases of *R v Dugosz, Pickering and MDS, (2013)* ruled;

***'..evaluative evidence is admissible provided the judge is satisfied that the expert giving the evidence has a proper basis for giving the evaluative evidence based upon his or her experience..'*.**

Whilst none of the cited rulings apply specifically to fibre evidence, they nonetheless exemplify (in the UK at least), the general inconsistency in the understanding of the Bayesian approach and the processes of logical, evaluative reasoning in general.

3 REVIEW AND CRITIQUE OF PUBLISHED DATA

In this chapter, a review and critique of the present data sets available in the literature is performed to evaluate the degree of knowledge concerning the various important factors (defined in chapter 2) governing the evaluation of textile fibre evidence. From this exercise the 'gaps' in the relevant datasets are identified and the results of research to address this can be evaluated and the strategy for future research is informed.

Since the purpose of this thesis is to identify, evaluate and address 'gaps' in key areas of our present knowledge of the factors influencing the interpretation of fibre evidence, this literature review is therefore principally focussed on studies/ data concerned with; transfer and persistence, fibre population and target fibres studies and background fibre populations.

These will serve to inform the 't', 'γ' and 'b' probability assignments (as described in *Chapter 2)* which will be used in the Bayesian network models employed for the purposes of impact and sensitivity analysis in *Chapters 5 & 6.*

3.1 Transfer and persistence ('t' values)

The mechanisms of the transfer and persistence of fibres have been comprehensively studied over the years, using various donor and recipient surfaces encountered in forensic casework. Such studies have produced valuable data often allowing the practitioner to provide an estimate of the degree, nature and time frame of the contact responsible for an observed fibre transfer, within the context of a particular case scenario. However, despite this, there are still a number of gaps in our knowledge of this area, which have subsequently been identified through questions and problems posed in operational casework.

3.1.1 Clothing and footwear

Initial studies in the 1970's relating to clothing in 'person to person' contact scenarios *(Pounds and Smalldon, 1975a, Pounds and Smalldon, 1975b, Pounds and Smalldon, 1975c)*, in the early 1980's *(Robertson, Kidd et al., 1982)* and the early 1990's (*Lowrie and Jackson, 1991)* demonstrated that a large loss of transferred fibres (c.80%) could be expected from a recipient garment in the first few hours following transfer. The nature and duration of contact, nature of recipient and donor surfaces and post transfer activity were identified as important factors in determining transfer and persistence characteristics.

Akulova, Vasiliauskiene et al., (2002), studied the effect on fibre persistence on clothing during normal outdoor wear. This study showed that 75% of transferred fibres were lost during the first 8-10 hours of wear and that after 16 hours of wear, between 5-10% of transferred fibres remained. It was found that public transport accelerated the rate of loss.

A case of a double child homicide was cited by *De Wael, (2009)*, where numerous crime relevant fibres were also recovered from the clothing of the victims after immersion in water. The factors governing the persistence of transferred fibres on clothing which had been immersed in water were investigated by *Lepot, Vanden Driessche et al., (2015)* who confirmed that significant numbers of transferred fibres were likely to persist even if the donor garment was immersed in water, the level of persistence however was dependent on the structure of the knitted recipient garments. A more recent study by *Lepot, Lunstroot et al., (2015)* showed that crime relevant fibres are likely to persist on garments even after immersion in running water.

An investigation by *Schnegg, Gueissaz et al., (2015)* into the transfer characteristics of fibres from clothing to knives during stabbing events, showed that fibres were readily transferred to knives and that redistribution of fibres from different layers of clothing could enable a sequence of events to be determined. Shedding capacity, textile construction, dimensions of the blade, as well as blade type, were found to be important factors.

Comparatively little research has been carried out concerning the persistence of transferred fibres to footwear, however, *Roux, Langdon et al., (1999)* demonstrated that although automotive carpet fibres could be transferred to footwear, the majority were lost in the first 5 minutes with none persisting after 30 minutes. A similar study by *Robertson and de*

Gamboa, (1984) investigating the transfer of domestic carpet fibres to footwear, found again that transferred fibres were rapidly lost, unless they physically stuck to the footwear (for example due to chewing gum being present on the sole).

Bennett, Roux et al., (2010), cited a case study illustrating the importance and significance of fibre transfer in homicide inquiries. In April, 1995 the body of a young woman was found in a suburb of Sydney, Australia. The body was fully clothed and bore a number of injuries to the neck, face and fingers. There were no signs of sexual assault and she appeared to have been strangled. The only physical evidence located at the scene was a number of dark, coarse fibres adhering to the soles of her shoes. The source of these fibres was found to be the carpet of a 1991 Honda CRX that belonged to the suspect. Almost all other possible sources of these fibres were eliminated.

At trial, the source of the fibres was not disputed by the defence. Instead the issue became how long these fibres had persisted on the shoe soles. A number of experiments were conducted to investigate the factors influencing the transfer and persistence of carpet fibres to shoe soles and the results of these experiments became a critically important part of the prosecution.

3.1.2 Car interiors

Similar studies over the subsequent years have been investigated using another common forensic casework scenario – that involving clothing to car seat contacts (*Robertson and Lim, 1987, Cook and Jackson, 1984, Roux, Chable et al., 1996, Lowrie and Jackson, 1994, Grieve and Biermann, 1996b, Sermier and Massonnet, 2009, Coyle, Jones et al., 2012*). The results of these studies show that generally fibres are readily transferred to cars seats and (where the donor and recipient textiles are optimal) *vice versa*. They also demonstrated that because of the ‘semi closed environment’ of the seats, transferred fibres are likely to persist for long periods of time. The long persistence of such fibres, result in a ‘pool’ conducive for subsequent secondary transfers.

Scott, (1985) demonstrated that automotive carpet fibres could be readily transferred to garments during contact. The degree of transfer was governed by the texture of the recipient garment as well as the fibre type comprising the carpet.

3.1.3 Washing

The effects of washing recipient garments on the persistence of transferred fibres have been studied by *Grieve, Dunlop et al., (1989), Palmer, (1998)* and *Szewcow, Robertson et al., (2011)*. The results of all these studies show that significant numbers of transferred fibres are likely to persist on garments following washing/ laundering.

3.1.4 Head Hair

In contrast to studies involving clothing and car seats, the transfer and persistence of fibres in head hair has been the subject of only a limited number of studies i.e. *Ashcroft, Evans et al., (1988), and Salter and Cook, (1996)*. These studies demonstrated that there is a definite window of persistence of fibres in head hair, ranging from 3 -7 days depending on whether the hair is washed or not. The results of these studies provided a very useful means of justifying fibres examinations on items such as balaclavas used in the commission of an armed robbery, which have been discarded at the scene, or left in a getaway car. In such a situation the norm is for investigators to present a discarded item to the laboratory for DNA testing. Whilst this in itself can be useful, situations have arisen in court where the accused maintains that whilst he may have worn the questioned item at some time in the past, he had no knowledge of the garments recent whereabouts and did not wear it at the time in question. Scientifically there is currently no means of countering/ addressing this defence using DNA evidence.

The studies relating to the persistence of fibres in hair, showed that provided the suspect was arrested within 7 days, had the police taped the hair of the suspect at that time, the presence of fibres matching the questioned garment in the suspects hair would not only show evidence of an association, but this would be incongruous with the defence proposition.

Whilst these studies provided the basis of a methodology for investigating this type of crime, their use is limited to situations where suspects are identified within this timeframe – which is usually *not* the situation. The literature relating to this particular aspect of transfer and persistence made no recommendation or provision of assistance regarding the use of fibre evidence outside the quoted time scales (i.e. 1 week).

Anecdotal information concerning this situation was provided by *Clayson and McKnight, (2001),* who reported a case where fibres from a questioned garment had been secondarily transferred from a suspects head, to their bedding.

Whilst such an approach undoubtedly provides a solution to the limitations of looking purely at direct contact between head hair and a balaclava, further studies fully investigating the potential of head hair for the secondary transfer of different fibre types and the subsequent expectations of recovery in these scenarios, was required in order to provide operational guidance and data for subsequent meaningful interpretation.

A study by *Palmer and Banks, (2005)* was carried out to address this issue and the impact and implications of its findings are assessed and discussed in relation to a real casework scenario in *Chapter 5*.

More recently, homicide cases have been reported where significant fibre evidence had been recovered from the victims' hair, despite deposition/ immersion in water for significant periods of time (*Palmer, 2008*). Such findings ostensibly appear contrary to expectations in such cases, however since no experimental work had been carried out at the time of these crimes to investigate what parameters are important in such scenarios, it was difficult to establish exactly what the expectations in such circumstances should be. In an attempt to address this issue, a survey of ETHG members was carried out by *De Wael, (2010)*. According to the respondents of the survey, estimations of persistence ranged between 0-80%, after 2 hours, 0-50% after 2 days and less than 25% after 2 weeks. The survey confirmed the need for research in this area.

3.1.5 Skin and Fingernails

Like hair, there is a paucity of data relating to the transfer and persistence characteristics of fibres on skin (including hands and fingernails).

A study by *Marshall, (2005)*, regarding the persistence of fibres on hands showed that transferred fibres would be expected to persist for only minutes. Preliminary results of a study by *Almazrooei, Hemmings et al., (2012),* indicate that the majority of fibres found on hands are from sources extraneous to the recipient. A recent study by *Hong, Han et al., (2014)* demonstrated that transferred fibres can persist even after hand washing and towel drying. Since our hands are subject to frequent movement and come into repeated contact

with a multitude of items on a daily basis, the results of these studies (to date) would appear to confirm our expectations concerning fibre persistence on them. Nevertheless, there is a clear need for more data regarding this aspect.

McBride and Brown, (2005), studied the persistence of fibres under fingernails. The results obtained were highly variable but suggested that fibres could persist for a number of hours, depending on variables such as nail length. These authors also performed a population study on the fibres found, which were in accordance with those performed on other substrates (see below). Again, there appears to be a need for more studies concerning this recipient substrate.

Whilst the above studies concerned themselves with very specific areas of anatomy, skin in general is also considered by many to be a non-retentive surface for fibres and consequently it is the author's experience that this is the reason that fibre recovery is often not attempted on the naked bodies of homicide victims who have been deposited at outdoor locations and exposed to the weather. The expectation that fibres will not persist on naked bodies deposited outdoors appears contrary to anecdotal evidence regarding recovery of fibres from just such a crime scene, documented by *Palmer, (2008).*

Krauss and Hildebrand, (1996) investigated the persistence of fibres exposed to outdoor conditions using small sections of pig skin as a human stimulant. The results of this study showed that significant numbers of fibres were still present after 14 days and that rain, not wind was the main factor in their persistence. Whilst the experimental design of this study was generally good, the method of seeding fibres onto relatively small surfaces areas of the substrate raised questions over the conclusions relating to the wind, as well as the nature of the rate of fibre loss.

Since the scenario of a naked body outdoor deposition can potentially employ fibres as an intelligence tool, the limitations of this study are that; it does not address how long transferred fibres would be expected to persist on skin prior to death, nor does it address the significance of the presence of particular fibre collectives – both important factors in evaluating fibre evidence in terms of its intelligence and corroborative value in these particular case circumstances. In addition, the conclusions of the existing study relating to the effect of wind seemed counter -intuitive and it was felt this aspect needed further investigation.

This study also identified another area of deficiency in our knowledge concerning the persistence of fibres on skin, namely that in the absence of data concerning the retention of fibres on the skin of living individuals there will always be difficulty in assessing the significance of finding fibres on the skin of the victim of a homicide deposited outdoors – particularly were estimations of the nature and time period of contact are required. This will be exemplified by reference to a specific casework example.

The widespread assumption that skin is a non-retentive surface and that transferred fibres will only persist on it for short time frames on a living individual seems to be based more upon intuition rather than on empirical data, since there was virtually no published studies relating to this.

The gaps in our knowledge of this area have been identified through questions arising from operational casework and these were highlighted in a high profile case in the UK, where the victims of a serial killing had been deposited outdoors for several days during severe weather conditions *(Palmer, 2008)*. In order to address these issues the author and co-workers carried out a number of related studies; *Palmer and Burch, (2009)* and *Palmer and Polwarth, (2011)*.

The contribution and impact of these studies are further discussed and assessed with reference to the above case in *Chapter 7*.

3.2 Chances of adventitious fibre matches ('Rarity')

3.2.1 Fibre population studies ('γ' and 'b' values)

So-called 'fibre population studies' provide a means of estimating the relative frequency of a particular fibre type/ colour combination at *a very generic level* (e.g. 'blue', 'nylon') on a particular item or surface (substrate). Whilst the generic nature of these studies means the absolute frequency data of a particular colour and type combination is of limited value, the data relating to the *relative* frequencies of different colour/ type combinations can be a useful starting point in assessing the evidential value of a fibre collective found on an item of interest.

Existing published data from fibre population studies carried out on a number of different substrates (*Fong and Inami, 1986, Grieve and Biermann, 1997a, Roux and Margot, 1997b, Massonnet, Schiesser et al., 1998, Cantrell, Roux et al., 2001, Watt, Roux et al., 2005, Was-Gubala, 2009b, Lazic, Caron et al., 2012)* demonstrates that the relative frequencies of the different fibre type/ colour combinations is largely concordant between different substrates, but that the absolute numbers present on each (unsurprisingly) differ.

Biermann and Grieve, (1996a) and *Biermann and Grieve, (1998)*, constructed a database of fibre compositions of mail order garments in Germany, as a contribution to estimating fibre frequency data. The results of this endeavour were broken down according to garment type, but were broadly concordant with those obtained from the above population studies.

Given that skin and hair are frequently of interest in the investigation of major crime, the fact that no studies have been carried out on these to confirm or refute accordance with data obtained from other substrates is surprising. In intelligence led homicide investigations where debris from hair and skin is examined for the presence of fibre collectives, it is clearly of importance to be able to recognise those which 'stand out from the background'. In order to test whether or not fibre population frequency data relating to hair and skin was in accordance with that obtained from other substrate, studies by the author; *Palmer and Oliver, (2004)* and *Palmer and Burch, (2009)*, were carried out and again, the impact of the data obtained from these studies will be discussed and assessed using casework scenarios. A summary of fibre population studies to date is given in *Table 3.1.*

Study	Substrate	Most Common
Fong & Inami (1986)	Garments	Red acrylic (8.1%) Blue cotton (7.7%)
Grieve & Biermann (1997a)	Outdoor surfaces	Grey-black Cotton (23.8%) Blue Cotton (13.3%)
Roux and Margot (1997a)	Car seats	Grey-black Cotton (17.3%) Blue Cotton (16.4%)
Massonnet, Schiesser *et al* (1998)	T-shirts	Grey-black Cotton (24%) Blue Cotton (14%)
Cantrell, Roux et al (2001)	Cinema seats	Grey-black Cotton (33.4%) Blue Cotton (29.6%)
Palmer and Oliver (2004)	Head hair	Grey-black Cotton (26%) Blue Cotton (23%)
Watt, Roux *et al*, (2005)	Washing machines	Black cotton (26.9) Blue cotton (20.2%)
Was-Gubala (2009b)	Public transport	Grey-black Cotton (25%) Blue Cotton (15%)
Palmer & Burch, (2009)	Human skin	Grey-black Cotton (37%) Blue Cotton (17%)
Lazic, Caron *et al*, (2012)	Cinema seats	Black cotton (46%) Blue cotton (20%)

Table 3.1: Summary of findings from fibre population studies

3.2.2 'Colour block' studies ('γ' values)

Although fibre population studies provide fibre frequency data only at a *very generic level* (e.g. 'blue' and 'nylon'), this is either ignored or misunderstood by many practitioners and members of the criminal justice system alike. Consequently this often results in the evidential value of a particular fibre type/ colour combination being woefully understated.

Colour block studies concern themselves with the discrimination of particular fibre type/ colour combinations (e.g. 'black' cotton, 'blue' polyesters) using the full battery of comparative tests available to the examiner. In many respects these are a 'follow on' from data from population studies as they seek to establish to what degree specific fibre type colour combination can be discriminated from the generic level.

Over the past 10-20 years there have been a number of such studies carried out; *Grieve, Dunlop et al., (1990), Cassista and Peters, (1997), Grieve, Dunlop et al., (1989), Grieve, Biermann et al., (2001), Grieve, Biermann et al., (2003), Grieve, Biermann et al., (2005), Biermann, (2007), Buzzini and Massonnet, (2013)*, *Buzzini and Massonnet, (2015)* and *Jones and Coyle, (2010)*. These studies both reflect and chart the improvements over this time, afforded by the increased discrimination, reliability and functionality of available analytical instrumentation. The main advantage from these developments is the ability to examine smaller analytes with an increased degree of discrimination.

This means that we are now, more than ever, using a combination of tests, able to more reliably distinguish between two ostensibly similar textile materials. Unfortunately, many of the approaches to fibre examination still carry over thinking and dogma which predates these technological developments. Given the current drive to decrease turnaround times and provide more robust interpretation in fibre examinations as exemplified by *Grieve and Wiggins, (2001)*, the need to redress our thinking and question dogma in the light of 21st century advances is greater than ever.

This situation is perhaps best exemplified by the approach of many examiners to casework involving blue cotton fibres *(Palmer and Booth, 2010)*. This fibre type/ colour combination is one of the most frequently encountered in casework and this is reflected in virtually all of the fibre population studies published to date. This situation has been taken by many to mean that their prevalence negates any meaningful conclusions to be drawn from their presence

in casework situations. This flawed thinking is undoubtedly due to misinterpretation of fibre population studies which seek to obtain frequency data at a very conservative, generic level i.e. ‘blue’ cotton.

Since there is a vast variability in the shade and hue of the dyes employed to produce a ‘blue’ colour, this is the same as saying that all blue cars are common – yet as anyone who has had to paint damaged paintwork on their blue car will tell you, finding an exact colour match for that particular vehicle is far from straightforward. The discrimination afforded by the current range of microspectrophotometers capable of operating into the UV range of the electromagnetic spectrum offer much better discrimination, particularly when used in combination with other techniques, yet this does not seem to have been factored into the interpretative processes of many, nor do the results of the so called ‘Target Fibre Studies’.

The studies of *Grieve, Dunlop et al., (1990)*, *Grieve, Biermann et al*, (*2001*) assessing the discrimination of the most commonly encountered coloured cotton fibres (black blue, red) illustrated that microscopy alone offered very poor discrimination, but that this was considerably increased when visible range MSP was carried out in combination. In the years following this study, more discriminating instrumentation capable of operating from the visible into the UV range has been introduced into many operational forensic laboratories. The results obtained by *Biermann, (2007)*, showed that the discrimination afforded by UV-Visual range MSP in combination with microscopy provided meant that these fibre types can be reliably distinguished – contrary to popular belief. Since the discriminating power of microscopy alone in the comparison of the most commonly encountered cotton fibres has been shown to be of limited value (*Grieve, Biermann et al*, *2005)*, it is now time to question the dogma still held by many practitioners that the application of microscopy should always be used as the ‘first test’ in a fibre comparison sequence.

Further investigation of the discrimination of blue cotton fibres by UV-Vis MSP alone, carried out by the author and co-workers in 2007 and subsequently published *Palmer, Hutchinson et al., (2009)*, not only corroborated the results of the previous studies regarding the discrimination of blue cotton, but also provided a sound scientific justification for modifying the scheme of analysis to use MSP as the ‘first test’ for these particular fibre colour/ type combinations. These conclusions were supported by *Buzzini and Massonnet, (2015)*, who investigated the discrimination power of particular analytical methods when employed in

comparisons using a number of different coloured acrylic, wool and cotton fibres. Their results illustrated that the optimal analytical sequence differs according to which particular fibre type and colour combination is under consideration.

Software applications allowing the display of the 1st derivative of MSP spectral data are available in many laboratories. Whilst this technique potentially allows further discrimination between fibres displaying subtle differences in dye colour *(Coyle, 2002)*, a study critically evaluating its application by *Wiggins, Palmer et al., (2007)* demonstrated that caution should be applied in its use in situations where there is a demonstrable high inter and intra fibre variation within a given control, as this is likely to result in false exclusions.

A summary of published colour block studies to date is shown in *Table 3.2.*

Study	Colour Block	Microscopy	MSP	Raman	TLC
Grieve, Dunlop, et al (1990)	Blue Cotton Red Cotton Black Cotton	0.14 (f) 0.33 (f) 0.25 (f)	0.0017 (f) 0.0067 (f) 0.17 (f)		
Grieve, Biermann et al (2001)	Black cotton Dyes	–	Sulphur Black 1 0.13 (DP) Direct Black 22 0.89 (DP) Reactive 0.93 (DP)		
Grieve, Biermann et al (2003)	Orange Cotton Green Cotton		0.930 (DP) 0.998 (DP)		
Grieve, Biermann et al (2005)	Blue Polyester		0.00009 (f)		
Biermann (2007)	Blue Cotton Red Cotton	–	0.9996(DP) 0.00023 (f) 0.9995(DP) 0.0003 (f)	–	–
Buzzini and Massonnet (2015)	Blue Acrylic Black Acrylic Red Acrylic Blue Cotton Black Cotton Red Cotton Blue Wool Black Wool Red Wool	0.98 (DP) 0.88 (DP) 0.96 (DP) 0.94 (DP) 0.82 (DP) 0.38 (DP) 0.96 (DP) 0.62 (DP) 0.86 (DP)	0.98 (DP) 0.80 (DP) 0.92 (DP) 0.93 (DP) 0.86 (DP) 0.58 (DP) 0.98 (DP) 0.91 (DP) 0.98 (DP)	0.84 (DP) 0.73 (DP) 0.73 (DP) 0.70 (DP) 0.69 (DP) 0.52 (DP) 0.72 (DP) 0.82 (DP) 0.94 (DP)	0.86 (DP) 0.84 (DP) 0.75 (DP) 0.56 (DP) 0.66 (DP) 0.10 (DP) 0.89 (DP) 0.89 (DP) 0.83 (DP)
Palmer, Hutchinson et al (2009)	Blue Cotton	–	0.89/ 0.96* (DP) *Vis MSP/UV-Vis MSP	–	–
Jones and Massonnet (2009)	Light Blue Cotton Dark Blue Cotton		0.59 (DP) 0.93 (DP)	0.89 (DP) 0.70 (DP)	
Jones and Coyle (2010)	Blue Nylon Flock		0.974(DP)		

Table 3.2: List of Published Colour Block Studies

3.2.3 Target fibre studies ('γ' values)

Whilst colour block studies provide a means of quantifying the discriminating power of the comparison tests employed in sub- categorising/ distinguishing between fibres belonging to a particular generic fibre type/ colour, they do not *in themselves,* provide an estimate of how

likely it is that a fibre of a particular morphology, colour, dye type and chemical composition will be found on a random surface by chance (i.e. ‘adventitiously’).

'Target fibre’ studies on the other hand, whilst not necessarily case specific, do provide a more accurate evaluation of how likely it is to encounter a particular non-ubiquitous fibre type/ colour combination on a random surface by chance.

Studies of this nature have involved searching clothing for the presence of a particular fibre type (‘target’) whose morphology, colour, chemical and dye characteristics had been previously fully defined at the laboratory e.g.; *Cook and Wilson, (1986), Cook, Salter et al., (1993), Bruschweiler and Grieve, (1997)* and *Wiggins, Drummond et al., (2004)*. More recently, such studies performed on garments have featured more specific fibre target types such as flock *(Jones and Coyle, 2011)* and fluorescent (‘high visibility’) fibres *(Coyle, Shaw et al, 2013)*.

Similar studies have been carried out looking for a variety of target fibre types on car seats *(Jackson and Cook, 1986),* cinema seats *(Palmer and Chinherende, 1996),* public house seats *(Kelly and Griffin, 1998)* and head hair *(Cook, Webb-Salter et al., 1997)*.

The results of these target fibre studies are summarised in *Table 3.3.*

The results of these studies consistently show that the probability of finding significant numbers of a particular fibre type/ colour combination on a random surface is low.

The results of these studies have been confirmed in ‘the field’ by the results obtained from casework examinations, where numerous environments have been searched for sources of multiple target fibre types, the sources subsequently being found to be confined to a single, specific environment (*Palmer, 2005, Palmer, 2008, R v Hall, 2011*).

Whilst the data from these studies is undoubtedly useful for addressing source level propositions, the time and resources required are too high for these to be carried out on a regular basis. Whilst the use of cars and clothing in such studies do provide important data, the number and these substrates examined in the relevant studies are fairly limited in terms of encompassing potential contact with the huge number and variation of textiles in the population.

The study of *Palmer and Chinherende, (1996)*, involved a different approach to previous studies, by sampling of a substrate which had been subjected to innumerable contacts from huge number of random textile items in the population. To this end, in one part of this study, the authors chose cinema seats as recipient surfaces to search for a red acrylic target fibre relating to a garment available for purchase in the UK. The advantage of this methodology is that the data obtained, will encompass a larger sub-set of the population without more time and resources being used. Since this particular study, this approach has been adopted by other workers e.g. *Kelly and Griffin, (1998), Bruschweiler and Grieve, (1997) and Jochem, (2012).*

A recent target fibre study by *Palmer, Burnett et al., (2015)* extended the sampling within a large urban environment to sample seats from cinemas, buses and public houses to establish the prevalence of black acrylic and blue polyester target fibres (two of the most commonly encountered fibres in casework). The experiment was designed to maximise the chances of encountering adventitious matches with these specific target fibres. Despite this, none were found. This study also pointed out that only (including this study) three target fibre studies have been conducted over the last 11 years. In addition, the authors point out that much of the early studies (pre-2000) were carried out using instrumentation of inferior discrimination to that subsequently available. Consequently the results of these studies may understate the probability of encountering adventitious matches.

Study	Substrate	Sample Size	Target Fibres	Number Found
Cook and Wilson, (1986)	Garments	335	Blue wool (1) Blue nylon Blue acrylic Red acrylic Blue wool (2)	9 0 0 2 1
Jackson and Cook, (1986)	Car seats	108	Red wool Brown polyester	37 8
Cook, Evett *et al*, (1993)	Garments	56	Blue wool Pink cotton Blue cotton Grey polyester	62 4 1 0
Palmer and Chinherende (1996)	Cinema Seats Car seats	67 66	Red acrylic Green cotton Red acrylic Green cotton	14 3 0 6
Bruschweiler and Grieve (1997)	Garments	435	Red acrylic	2
Cook, Webb-Salter *et al*, (1997)	Head hair	100	Blue wool Green acrylic Grey acrylic (1) Grey acrylic (2)	20 2 15 0
Kelly and Griffin, (1998)	Pub seats	80	Blue wool	9
Wiggins, Drummond *et al*, (2004)	Garments	58	Blue wool Black polyester Grey polyester Blue acrylic	11 0 1 4
Jones and Coyle, (2010)	Garments	100	Black polyester flock Blue-grey nylon flock Grey-brown nylon flock Orange nylon flock Green nylon flock Black nylon flock Grey nylon flock	6 0 0 0 12 0 0 0 0
Coyle, Shaw *et al*, (2013)	Garments	52	Fluorescent Yellow Polyester	0
Palmer, Burnett *et al* (2015)	Cinema Seats Bus Seats Pub Seats	30 40 53	Black Acrylic Blue Polyester	0 0

Table 3.3: List of published target fibre studies

3.2.4 Background fibre populations ('b' values)

Whilst the number of fibres matching a putative source is an important factor in the evaluation of source (and activity) level propositions, it has been argued that such findings need to be evaluated within the context of the number of non-matching 'foreign fibre groups' (FFG) present on the recipient item, the greater the number of these groups, the greater the chance of an adventitious match (*Grieve and Dunlop, 1992, Champod and Taroni, 1996, Roux, Chable et al.,1996, Coulson, Elliot et al., 2006)*.

Grieve and Dunlop, (1992), pointed out that using 'average values' for data used in evaluating fibre evidence within a Bayesian framework, could have implications for the accuracy of likelihood ratio estimations. However, these authors did concede that it is impractical for a caseworker to obtain data specific to each and every case they examine. In this study, using underwear, they demonstrated that reasonable estimates of background FFG using only stereomicroscopy, could be obtained within what they considered to be a reasonable timescale (50 minutes – 7 hours). Their estimates of FFG ranged from 10-101.

Given current drives to reduce turnaround times in forensic casework, it is debatable whether the times quoted for this exercise would be deemed 'reasonable'.

In a study involving car seats *Roux, Chable et al.,(1996)* found that very few FFG contained numbers compatible with those of the 'crime related' group. From their examinations, they considered it to be "*highly probable (0.95) for at least one FFG with a number of fibres comparable to the crime related group to be found on a seat."* Whilst they acknowledge that FFG are an important consideration, they also argue that their presence should not '*preclude the value of* [fibre evidence obtained] from *a car seat*'. They also suggested that examination of FFG on tapings from a non- crime relevant area of the car (e.g. back seats) may inform the relevance of those found on the crime relevant areas.

Champod and Taroni, (1996), used a number of case scenarios to examine and evaluate the effect of various parameters involved in evaluating fibre evidence using the Bayesian framework. In particular the study illustrated the effect of the probability of the presence of FFG on the resultant likelihood ratios. These factors are further discussed and used in the 'validation' of the Bayesian network in *Chapter 4* of this study.

The paucity of data regarding the prevalence of FFG on garments (and other substrates) is illustrated by *Coulson, Elliot et al., (2006)*. These authors performed a 'pilot study' using a single white T-shirt to estimate the number and size of FFG present. The results of this study identified 1983 distinct FFG, 75% of these groups consisting of a single fibre and 11 groups consisting of over 100 fibres. Since this study only used comparison and fluorescence microscopy, the authors rightly state that the inclusion of instrumental analyses would most likely reduce the number of large groups and increase the number of smaller groups.

Given the clear lack of data regarding background probability estimations for FFG, it would seem that tempering the results of these studies with casework experience, would seem the most pragmatic approach in assigning background probability estimates for the Bayesian network models.

3.3 Summary

The review of the current literature has identified a number of areas where our knowledge regarding important factors in the interpretation of fibre evidence is incomplete from a global or case type specific perspective.

From a *globa*l perspective, little progress has been made in the past 10 years in terms of target fibre studies to encompass a wider range of target fibres which may assist in source level evaluation of case relevant fibres. Recent and previous work by the author has sought to address this issue, however, it is evident from the studies to date that future work is needed to encompass a better range of fibre type colour combinations encountered in casework (not only with Target fibre studies, but also with colour block studies).

In addition, it is evident from this exercise, that there is a huge paucity of data concerning the number and size of extraneous fibre populations on various substrates encountered in casework.

The relevance of such knowledge is discussed in detail in *Chapters 4-7.*

In terms of *case type specific data* gaps in the published transfer and persistence data concerning hair and skin have been identified and addressed by the author. The utility of such data is investigated and evaluated in *Chapters 5 and 6* and implications for the practitioner are discussed in *Chapter 7*.

As well as having significance for the practitioner in terms of casework assessment and interpretation, the gaps identified inform the priorities of further research strategies and this is specifically discussed in *Chapter 7.*

4 VALIDATION OF THE BAYESIAN NETWORK ARCHITECTURE

The following chapter describes the validation and structure of the Bayesian network architecture used to model the complex real casework scenarios under consideration in Chapters 5 and 6. The important parameters (e.g. transfer probability and match probability) used in the architecture are defined and maximum likelihood estimates (MLE's) are provided for these parameters for different 'simple' case scenarios involving one-way and two-way fibre transfers. The likelihood ratios for each scenario outcome were calculated by hand and found to be congruent with the output of Bayesian networks created to model these scenarios.

4.1 Aim of this chapter

Since the purpose of this thesis involves the use of a Bayesian Network to model complex casework scenarios for the purpose of impact analysis of new data, the aim of this chapter is to 'validate' the underlying structural components used in the network architecture. To this

end, equations used for the calculation of likelihood ratios associated with various fibre transfer scenarios, have formed the basis for the construction of Bayesian networks to model these scenarios. The likelihood ratios obtained for the 'hand calculations' have then been checked for congruence with the output from the Bayesian networks. Maximum likelihood estimates have been used in these calculations rather than data directly derived from studies, since they are probabilistic estimates informed from study data as well as casework experience.

4.2 Bayesian networks

Bayesian networks provide a method of describing (or *modelling*) a particular aspect of the world (*domain*) in which there are various states that are subject to uncertainty. One simple example of such a domain is medical diagnosis. A physician will consider a patients' symptoms and their medical records in order to establish a diagnosis of their illness (e.g. how likely it is that a runny nose is due to a cold, as opposed to an allergy). Such models as the name suggests, employ Bayesian reasoning through the use of conditional probabilities (see *Section 2.3*). Probabilities are assigned to the parameters (or observations) conditioning a particular state of a domain in question, and the likelihood of a particular state outcome, given a set of observations, can be determined.

The advantage of Bayesian networks is their adaptability, in that as our knowledge of a particular aspect of the model under consideration grows or changes, the probability assignments relating to the various conditioning parameters can easily be updated. This adaptability also allows us to address 'ignorance' within a particular domain by considering 'what if' scenarios.

Whilst Bayesian networks can be constructed 'on paper', they are more commonly constructed using computer software applications.

'Hugin Researcher™' is such a commercially available Bayesian network software package which employs a graphical user interface to allow a visual construction of a particular model/ architecture under examination and is marketed as a decision making tool. It is described by the manufacturer, Hugin Expert A/S of Aalborg, Denmark, as a *'compact model representation for reasoning under uncertainty' (www.hugin.com)*. The graphical structure of

Bayesian networks allows the description and modelling of possible dependent relationships between different components of the problem under investigation. The uncertainties present are represented through conditional probabilities which can be aleatory or epistemic in nature and these form the basis for the cause / relationship interactions between the various components.

The underlying Bayesian algorithms of such systems, use these conditional probabilities to calculate the probability of different events or hypothesis given a series of specific observations e.g. differential diagnosis based upon the results of clinical chemistry.

As well as medicine, Bayesian Networks are used in a number of applications;

- Industrial (diagnosis and repair of complex machinery),
- Economic (credit application evaluation, risk analysis)
- Military (early warning systems, situation assessment)

The construction, use and applications of Bayesian networks is described in considerable detail, for example by *Jensen, (1996)* or *Pourret et al (2008)*.

It has been demonstrated that these networks are well suited for the assessment and interpretation of forensic casework scenarios, where there are a number of complex, inter-related factors involved rendering any calculation of likelihood ratio, by hand, problematic. Furthermore, the graphical component of these systems allow the user to concentrate on finding the appropriate structural representation of a problem, whilst the underlying statistical calculations are performed 'behind the scenes' *(Biedermann, Taroni et al., 2009)*. It is the investigation of this last aspect which this chapter will deal with.

4.3 Validation of underlying network components

For this purpose, the casework scenarios and probability calculations described by *Champod and Taroni, (1999)* and *Champod and Taroni, (pending)* have been employed.

4.3.1 Scenario 1A (one- way transfer)

A stolen car is used in the commission of a robbery on the day of its theft and abandoned one hour later. Later that night, the car is located by the police and potential fibre evidence is recovered from its seats (comprising polyester fibres) using tapings. The owner of the vehicle lives alone and has never lent the car to anyone.

A suspect is apprehended the next day and a red woollen pullover worn by him is seized. The suspect denies any involvement in the incident and states he does not know the owner of the car, or driven the car in question.

Laboratory examination of the fibre tapings from the car, demonstrated the presence of a distinct fibre collective comprising a large number (*n*) of red wool fibres. Through a process of elimination involving the clothing of the owner, no other groups of fibres 'foreign to the car' have been noted on the tape lifts.

The 'foreign' red wool fibre collective are further examined and subsequently found to be indistinguishable from the fibres comprising the suspect's pullover. The suspect was apprehended independently of this information. The competing propositions can be considered as;

Hp: The suspect, wearing the red pullover, drove the car.

Hd: The suspect did not drive the car.

Champod and Taroni, (pending) define and describe the likelihood ratio (LR) calculation in this scenario as:

$$\mathrm{LR} = \frac{(\mathbf{b_0 t_n}) + (\mathbf{b_1 \gamma_b t_0})}{(\mathbf{b_0 \gamma t'_n}) + (\mathbf{b_1 \gamma_b t'_0})} \approx \frac{\mathbf{t_n}}{\boldsymbol{\gamma} \mathbf{t'_n}}$$

Where:

$\mathbf{t_n}$ is the 'transfer probability' under Hp, that a given number of fibres have been transferred from the suspects pullover to the car seat. For this exercise a value of 0.95 has been assigned.

t_0 is the 'transfer probability' under Hp, that no fibres have been transferred from the suspects pullover to the car seat. For this exercise a value of 0.05 has been assigned.

t'_n is the 'transfer probability' under Hd, that a given number of fibres have been transferred from the offenders pullover (i.e. not the suspect's) to the car seat. For this exercise a value of 0.05 has been assigned.

t'_0 is the 'transfer probability' under Hd, that no fibres have been transferred from the offenders pullover (i.e. not the suspect's) to the car seat. For this exercise a value of 0.05 has been assigned.

b_0 is the probability of recovering no foreign fibre group (FFG) distinguishable from the garments of the owner, on the driver's seat. For this exercise a value of 0.9 has been assigned. This is a *background transfer probability*.

b_1 is the probability of recovering one foreign fibre group (FFG) distinguishable from the garments of the owner, on the driver's seat. For this exercise a value of 0.1 has been assigned. This is a *background transfer probability.*

γ and γ_b are the probabilities of finding similar sized fibre collectives sharing the same characteristics as the fibres comprising the suspect's pullover, in alternative garments from potential offenders or as background fibres on car seats, respectively. In the majority of circumstances these two values can be considered the same. For this exercise a value of 0.02 has been assigned to each variable.

Parameter	Probability
t_n	0.95
t_0	0.05
t'_n	0.05
t'_0	0.05

$\mathbf{t_{other}}$	0.9
$\mathbf{b_0}$	0.9
$\mathbf{b_1}$	0.1
$\boldsymbol{\gamma}$ & $\boldsymbol{\gamma_b}$	0.02

Table 4.1: Summary of probability assignments for each variable

These values are summarised in *Table 4.1*.

In this scenario, the probability of finding a foreign fibre group is small ($b_1 = 0.1$). Likewise the probabilities of finding no fibres from the suspect or offender respectively have been considered to be equal and small (t_0 & $t'_0 = 0.05$) as have the chances of obtaining an 'adventitious match' with the suspects clothing ($\gamma = 0.02$).

In this instance, the background fibre transfer probabilities produce a minimal contribution (0.0001) to both the numerator and denominator, when calculating the likelihood ratio and their effect is therefore minimal in terms of expressing the strength of evidence (using a verbal equivalence scale). The likelihood ratio in this instance can effectively be simplified to;

$$\mathbf{LR} = \frac{(\mathbf{b_0 t_n})}{(\mathbf{b_0 \gamma t'_n})} = \frac{\mathbf{t_n}}{\boldsymbol{\gamma} \mathbf{t'_n}} = \mathbf{950}$$

Without this simplification, including the background transfer probabilities in the LR calculation, we obtain

$$\mathbf{LR} = \frac{(\mathbf{b_0 t_n}) + (\mathbf{b_1 \gamma_b t_0})}{(\mathbf{b_0 \gamma t'_n}) + (\mathbf{b_1 \gamma_b t'_0})}$$

$$= \frac{(0.9 \times 0.95) + (0.1 \times 0.02 \times 0.05)}{(0.9 \times 0.02 \times 0.05) + (0.1 \times 0.02 \times 0.05)}$$

$$= \frac{(0.855) + (0.0001)}{(0.0009) + (0.0001)}$$

·The difference between the likelihood ratios by the exclusion of these variables is about 100, supporting the derivation that in this instance the probability of a foreign fibre group contribution is negligible and can effectively be ignored in this scenario.

Figure 4.1 shows the network structure described by *Champod and Taroni, (2014)* employed in the model of the case scenarios involving one-way fibre transfer scenarios. The architecture of this network is underpinned by the expression;

$$\mathrm{LR} = \frac{\mathrm{P(Y|X, T, Hp)} \cdot \mathrm{P(T|X, Hp)} \cdot \mathrm{P(X|Hp)}}{\mathrm{P(Y|X, T, Hd)} \cdot \mathrm{P(T|X, Hd)} \cdot \mathrm{P(X|Hd)}}$$

The resultant probability assignments for each node in this expression are shown in *Table 4.2.*

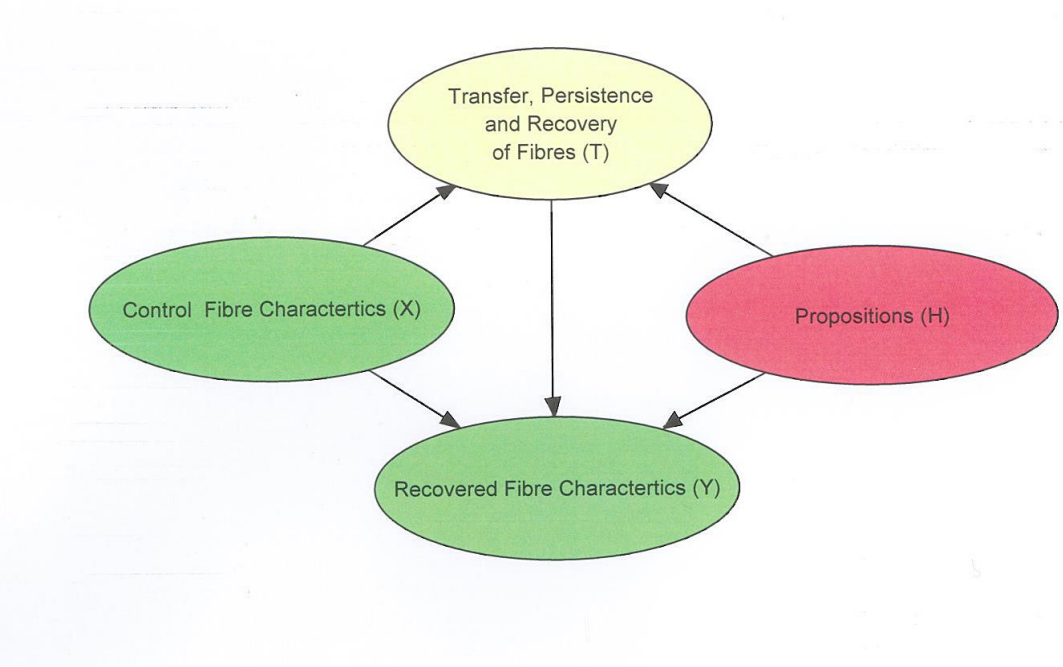


Figure 4.1: Bayesian network structure for one way transfer of fibres (pullover to car seat)

The assumptions in this scenario are; that the chances of the donor garment shedding large numbers of its constituent fibres are high, all the recovered red wool fibres are indistinguishable from the suspects garment and that the chances of encountering other fibres not attributable to the owner are very low.

Conditional Probability Table for Node T				
	Hp		Hd	
State	**X**	**≠ X**	**X**	**≠ X**
$\mathbf{t_0}$	t_0 **0.05**	**0.333**	t_0' **0.05**	t_0' **0.05**
$\mathbf{t_n}$	t_n **0.95**	**0.333**	t_n' **0.05**	t_n' **0.05**
$\mathbf{t_{other}}$	$1 - t_0 - t_n$ **0**	**0.333**	$1 - t_0' - t_n'$ **0.9**	$1 - t_0' - t_n'$ **0.9**

Conditional Probability Table for Node Y under Hp						
	$\mathbf{t_0}$		$\mathbf{t_n}$		$\mathbf{t_{other}}$	
State	**X**	**≠ X**	**X**	**≠ X**	**X**	**≠ X**
y	$b_1\gamma_b$ **0.002**	**0.5**	b_0 **0.9**	**0.5**	**0**	**0**
≠ y	$1 - b_1\gamma_b$ **0.998**	**0.5**	$1 - b_0$ **0.1**	**0.5**	**1**	**1**

Conditional Probability Table for Node Y under Hd						
	$\mathbf{t_0}$		$\mathbf{t_n}$		$\mathbf{t_{other}}$	
State	**X**	**≠ X**	**X**	**≠ X**	**X**	**≠ X**
y	$b_1\gamma_b$ **0.002**	$b_1\gamma_b$ **0.002**	$b_0\gamma$ **0.018**	$b_0\gamma$ **0.018**	**0**	**0**
≠ y	$1 - b_1\gamma_b$ **0.998**	$1 - b_1\gamma_b$ **0.998**	$1 - b_0\gamma$ **0.982**	$1 - b_0\gamma$ **0.982**	**1**	**1**

Conditional Probability Table for Node H	
State	**Probability**
Hp (The suspect wearing the pullover drove the car)	0.5
Hd (The suspect did not drive the car)	0.5

Conditional Probability Table for Node X	
State	**Probability**
X	0.5
≠ X	0.5

Table 4.2: Probability assignments for each node of the Bayesian network structure shown in Figure 4.1, according to *Champod and Taroni (2014). Where X is when the recovered fibres are indistinguishable from the control fibres and ≠X is when the recovered fibres are different from the control fibres.*

If we assume the case circumstances are correct and the provenance of all background fibre collectives is known, the network calculates the following likelihood ratio by dividing the posterior probabilities on Hp and Hd respectively (shown in *Figure 4.2).*

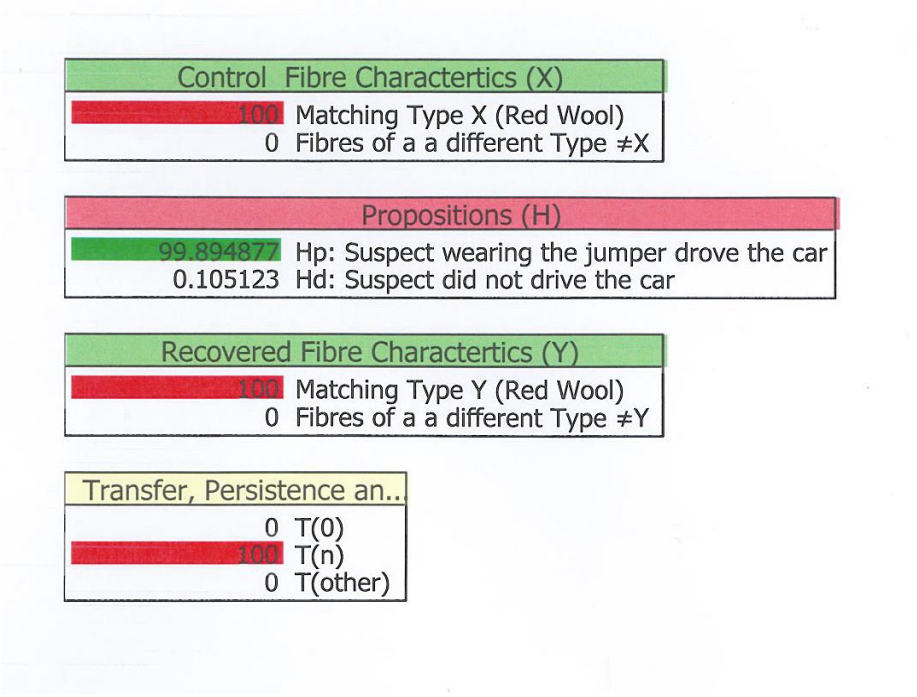


Figure 4.2: Bayesian network likelihood ratio where 100% of recovered fibres match those of suspect item and the presence of unassigned fibre collectives are not considered. LR = 950.

In demonstrating the effect of the low probability of finding other non-matching foreign fibre populations $\frac{(b_1\gamma_b t_0)}{(b_1\gamma_b t_0')}$ the network calculates the following likelihood ratio in *Figure 4.3;*

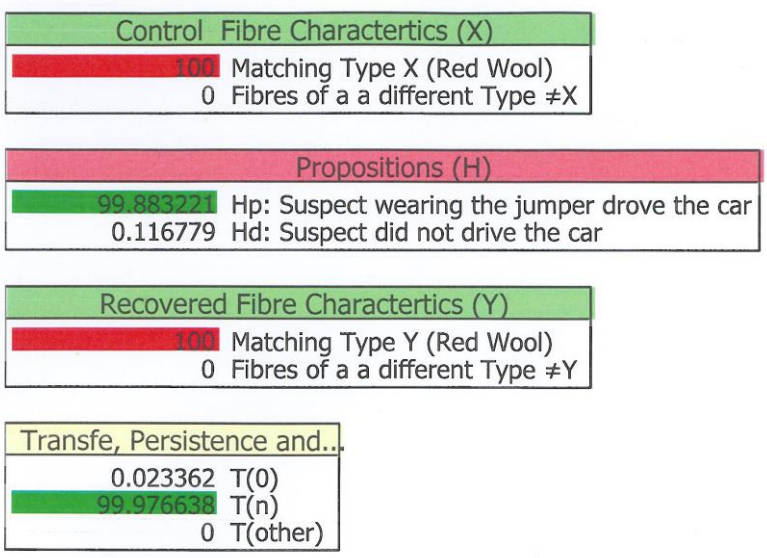


Figure 4.3: Bayesian network likelihood ratio where 100% of recovered fibres match those of suspect item and the presence of unassigned fibre collectives are not considered *(i.e. by assigning* b_0 *as 0.9 and* b_1 *as 0.1). LR = 855.1*

The likelihood ratios provided by the Bayesian network in *Figures 4.2 and 4.3* are in accordance with those obtained by direct calculation. However, in real casework, it is highly unlikely that the provenance of background populations of fibres would be known and assumptions that their effect be ignored may mislead.

4.3.2 Scenario 1B (one-way transfer)

Let us now consider a similar scenario to that above, with the exception that the car in question has been bought second or third hand. Clearly in such a scenario there are bound to be a number of fibre collectives that cannot be attributed to the current owner and whose provenance cannot be ascertained.

In such a situation we can therefore assign the probability of recovering no foreign fibre group (FFG) distinguishable from the garments of the owner, 'by chance', on the driver's seat (b_0) as 0.1 and the probability of recovering at least one foreign fibre group (FFG) distinguishable from the garments of the owner, 'by chance', on the driver's seat (b_1) as 0.9.

The probabilities assigned to the other variables are exactly the same as in the previous scenario shown in *Table 4.2*.

However, unlike the previous scenario, in this case the contribution of the background terms $\frac{(b_1\gamma_b t_0)}{(b_1\gamma_b t_0')}$ now provides a significant contribution to the overall LR calculation.

To determine the effect the background transfer probabilities now have on the calculation of the likelihood ratio, we again employ the equation;

$$\mathbf{LR} = \frac{(\mathbf{b_0 t_n}) + (\mathbf{b_1 \gamma_b t_0})}{(\mathbf{b_0 \gamma t_n'}) + (\mathbf{b_1 \gamma_b t_0'})}$$

$$= \frac{(0.1 \times 0.95) + (0.9 \times 0.02 \times 0.05)}{(0.1 \times 0.02 \times 0.05) + (0.9 \times 0.02 \times 0.05)}$$

$$= \frac{(0.095) + (0.0009)}{(0.0001) + (0.0009)}$$

$$= \mathbf{95.9}$$

If we then remove the effect of $\frac{(b_1\gamma_b t_0)}{(b_1\gamma_b t_0')}$ *then the likelihood ratio reverts to* 950 *– as in the previous scenario.*

The effect of a high probability of finding foreign fibre collectives in the car thus has the effect of an approximately ten-fold reduction on the likelihood ratio.

The assumptions in this scenario are; that the chances of the donor garment shedding large numbers of its constituent fibres are high, all the recovered red wool fibres are indistinguishable from the suspects garment and that the chances of encountering other fibres not attributable to the owner are high.

The Bayesian network structure is the same as for scenario 1A, however, the node probability assignation for Y is amended to take account of the new values of b_0 and b_1 (which now become 0.1 and 0.9 respectively). All other probability assignments remain unchanged.

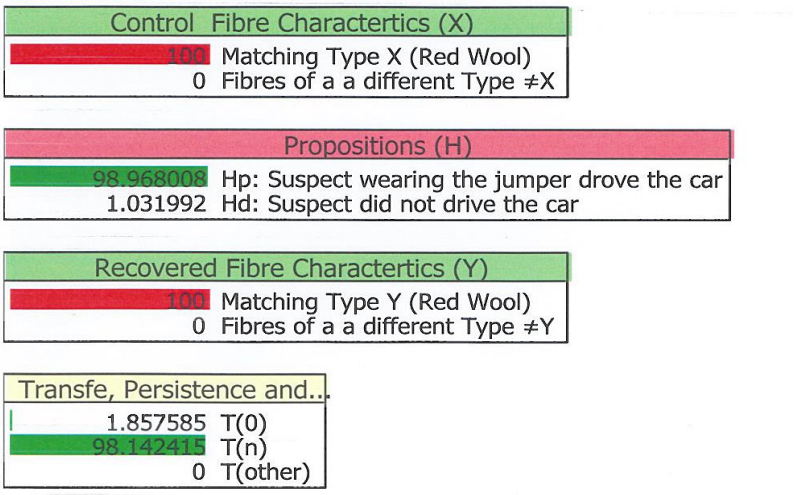


Figure 4.4: Bayesian network output where the presence of recovered fibres matching those of suspect item and the presence of unassigned fibres collectives are considered and provide a significant impact on the likelihood ratio *(i.e. by assigning* b_0 **as 0.1 and b_1 **as 0.9). LR = 95.9.**

When considering the effect of the finding other non-matching populations $\frac{(b_1\gamma_b t_0)}{(b_1\gamma_b t_0')}$ and following the above probability amendments for $\mathbf{b_0}$ and $\mathbf{b_1}$, the network calculates the likelihood ratio shown in *Figure 4.4*;

If (as in Scenario 1A) the contribution of any foreign fibre groups is ignored, then despite the changes to b_0 and b_1, the network calculates the likelihood ratio shown in *Figure 4.5*;

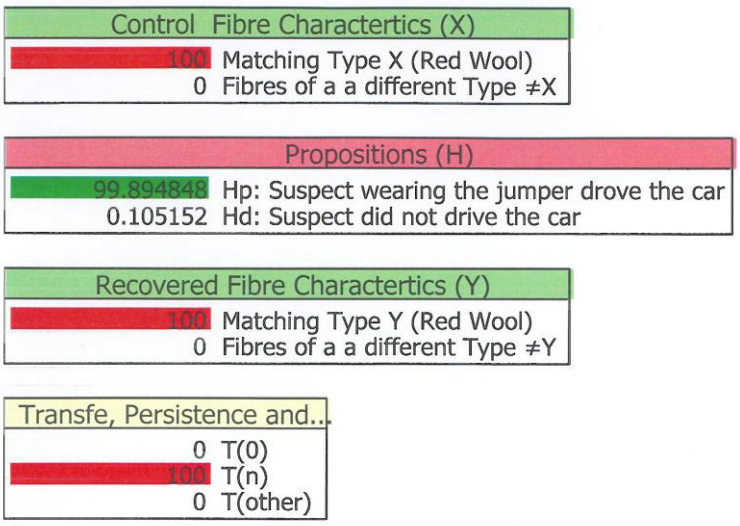


Figure 4.5 :Bayesian network likelihood ratio calculation where 100% of recovered fibres match those of suspect item and the presence of any unassigned fibre collectives are not considered. LR = 950

The effect of considering the presence or absence of foreign fibre groups is therefore in accordance with the directly calculated values.

4.3.3 Scenario 2A (two- way transfer)

We can now expand the case scenario of 1A to a two way fibre transfer situation (i.e. transfer of a given number (*n*) fibres from the offenders pullover to the car seat *with* a reciprocal transfer of a given number (*m*) fibres from the car seat to the offenders pullover). Whilst the scenario presented involves a reciprocal transfer of fibres from clothing and cars seats, it is important to state that other similar scenarios are possible e.g. reciprocal transfer between the clothing of two individuals.

Due to differences in donor sheddability/ retention, the relative rarity of the fibre type/ colour combination (i.e. the probability of obtaining an adventitious match) etc., the probability assignments for each donor item in this scenario will differ. In this scenario B1 is the probability data relating to a transfer of (*n*) fibres from the offender's pullover to the car seat, whilst B2 relates to a transfer of (*m)* fibres from the car seat to the offenders pullover. The probability assignments for each variable are summarised in *Table 4.3.*

	B1			B2
$\mathbf{t_n^{B1}}$	0.5		$\mathbf{t_m^{B2}}$	0.05
$\mathbf{t_0^{B1}}$	0.5		$\mathbf{t_0^{B2}}$	0.05
-	-		$\mathbf{t_{other}^{B2}}$	0.9
$\mathbf{t_n^{B1\prime}}$	0.5		$\mathbf{t_m^{B2\prime}}$	0.05
$\mathbf{t_0^{B1\prime}}$	0.5		$\mathbf{t_0^{B2\prime}}$	0.05
-	-		$\mathbf{t_{other}^{B2\prime}}$	0.9
$\mathbf{b_0^{B1}}$	0.9		$\mathbf{b_0^{B2}}$	0.1
$\mathbf{b_1^{B1}}$	0.1		$\mathbf{b_1^{B2}}$	0.9
$\boldsymbol{\gamma}^{\mathbf{B1}}$ & $\boldsymbol{\gamma}^{\mathbf{B1\prime}}$	0.002		$\boldsymbol{\theta}^{\mathbf{B2}}$ & $\boldsymbol{\theta}^{\mathbf{B2\prime}}$	0.02

Table 4.3: Probability assignments for variables under B1 and B2. For ease of distinguishing under B2, n has been replaced by m, and γ by θ , but remain analogous

It can be seen that for B1 (i.e. fibre transfer from pullover to seat), b_0 & b_1 have been assigned the probabilities of 0.9 and 0.1 respectively – to mimic a similar scenario to 1A where the foreign fibre backgrounds can be ignored. For B2 (i.e. transfer from the car seat to the pullover), b_0 & b_1 have been assigned the probabilities of 0.1 and 0.9 respectively. This is because it is likely that any pullover worn by an individual will (due to numerous contacts during its daily wear) will have fibre collectives present on its surfaces whose provenance is unknown.

Again, these and the other probability values assigned in this fibre cross-transfer case are employed purely for convenience.

The assumptions in this scenario are;

- The chances of the donor garment shedding large numbers of its constituent fibres are high, all the recovered red wool fibres are indistinguishable from the suspects garment

and that the chances of encountering other fibres not attributable to the owner are very low.

- The fabric of the car seat does not shed well, hence an equal probability that no fibres or a given number (n) will be shed and transferred.
- All of the fibres removed from the tapings of the pullover are indistinguishable from those comprising the car seat.
- The chances of encountering extraneous non matching fibres on the tapings from the pullover ($\mathrm{B2}$) are high.
- The chances of encountering extraneous non matching fibres on the tapings from the car seat ($\mathrm{B1}$) are low.

Since a demonstrable transfer of a large number of fibres from an offender's garment to a car seat $\mathrm{B1}$ may (when its 'shedding' potential is known) infer a prolonged duration of direct contact with the seat, the degree of reciprocal transfer (i.e. from the seat to the offender) $\mathrm{B2}$, is often conditioned by the number of fibres present and attributable to $\mathrm{B1}$.

In calculating the likelihood ratio where a reciprocal transfer of fibres has been demonstrated the product rule can be employed where the findings relating to $\mathrm{B2}$ are dependent on the findings relating to $\mathrm{B1}$, i.e.;

$$\mathbf{LR = LR_{B1}\ x\ LR_{B2|B1}}$$

As in scenario 1A the probability of encountering foreign fibre collectives on the tapings from the car seat is low, however the probability of encountering these on the tapings from the pullover are high.

The calculations for $\mathbf{LR_{B1\ \&\ B2|B1}}$ therefore become;

$$\mathbf{LR_{B1} = \frac{(b_0^{B1} t_n^{B1})}{(b_0^{B1} \gamma^{B1} t_n^{B1\prime})}} \qquad \mathbf{LR_{B2|B1}{}^{*} = \frac{(b_0^{B2} t_m^{B2}) + (b_1^{B2} \theta^{B2} t_0^{B2})}{(b_0^{B2} \theta^{B2} t_m^{B2\prime}) + (b_1^{B2} \theta^{B2} t_0^{B2\prime})}}$$

$$\text{For B2 } (b_1 \theta^{B2} t_0) \ \&\ (b_1 \theta^{B2} t_0') = (0.9 \times 0.02 \times 0.05) = 0.0009$$

$$LR_{B1} = \frac{(0.9 \times 0.5)}{(0.9 \times 0.002 \times 0.5)} \qquad LR_{B2|B1} = \frac{(0.1 \times 0.05) + 0.0009}{(0.1 \times 0.02 \times 0.05) + 0.0009}$$

$$\mathrm{LR_{B1}} = \frac{(0.45)}{(0.0009)} = 500 \qquad \mathrm{LR_{\ B2|B1}} = \frac{(0.0059)}{(0.001)} = 5.9$$

$$\mathbf{LR_{B1\ x}\, LR_{B2|B1} = 2950}$$

If we also wish to consider the contribution from the low background transfer probability relating to the tapings from the car seat, then the calculation for

$\mathbf{LR_{B1\ \&\ B2|B1}}$ becomes;

$$\mathbf{LR_{B1}} = \frac{\left(\mathbf{b_0^{B1} t_n^{B1}}\right) + \left(\mathbf{b_1^{B1} \gamma^{B1} t_0^{B1}}\right)}{\left(\mathbf{b_0^{B1} \gamma^{B1} t_n^{B1\prime}}\right) + \left(\mathbf{b_1^{B1} \gamma^{B1\prime} t_0^{B1\prime}}\right)}$$

$$\text{For B1 } \left(\mathbf{b_1^{B1} \gamma^{B1} t_0^{B1}}\right) \text{ \& } \left(\mathbf{b_1^{B1} \gamma^{B1\prime} t_0^{B1\prime}}\right) = (0.1 \times 0.002 \times 0.5) = 0.0001$$

$$\text{For B2 } \left(\mathbf{b_1^{B2} \theta^{B2} t_0^{B2}}\right) \text{ \& } \left(\mathbf{b_1^{B2} \theta^{B1\prime} t_0^{B2\prime}}\right) = (0.9 \times 0.02 \times 0.05) = 0.0009$$

$$\mathrm{LR_{B1}} = \frac{(0.9{\times}0.5){+}0.0001}{(0.9{\times}0.002{\times}0.5){+}0.0001} \qquad \mathrm{LR_{\ B2|B1}} = \frac{(0.9{\times}0.05){+}\ 0.0009}{(0.9{\times}0.02{\times}0.05){+}\ 0.0009}$$

$$\mathrm{LR_{B1}} = \frac{(0.4501)}{(0.001)} = 450.1 \qquad \mathrm{LR_{\ B2|B1}} = \frac{(0.0059)}{(0.001)} = 5.9$$

$$\mathbf{LR_{B1\ x}\, LR_{B2|B1} = 2655.6}$$

*Note that the probability assignments have been allocated for each variable assuming conditioning of B2 by B1.

In a situation where the provenance of any background fibres populations relating to B1 & B2 is established, the contribution of the respective background transfer probabilities can effectively be ignored (as in scenario 1A). In this situation both

$\mathbf{LR_{B1}}$ & $\mathbf{LR_{B2|B1}}$ can be calculated using;

$$\frac{(\mathbf{b_0 t_n})}{(\mathbf{b_0 \gamma t_n'})} \approx \frac{\mathbf{t_n}}{\boldsymbol{\gamma} \mathbf{t_n'}} \ ;$$

Where, $\frac{\mathbf{t_n}}{\boldsymbol{\gamma} \mathbf{t_n'}}$ becomes $\frac{\mathbf{1}}{\boldsymbol{\gamma}}$ if no difference between the transfer characteristics of the suspect and offenders garments is assumed. When we ignore the contribution of any possible

foreign fibre groups and assume that all transfers in $B1$ and $B2$ are attributable to the respective donor items, $\mathbf{t_n} = 1$.

$$LR_{B1} = \frac{(0.9 \times 0.5)}{(0.9 \times 0.002 \times 0.5)} \qquad LR_{B2|B1} = \frac{(0.1 \times 0.05)}{(0.1 \times 0.02 \times 0.05)}$$

$$LR_{B1} = \frac{(0.45)}{(0.0009)} = \frac{1}{0.002} \qquad LR_{B2|B1} = \frac{(0.005)}{(0.0001)} = \frac{1}{0.02}$$

$$= 500 \qquad = 50$$

$$\mathbf{LR_{B1} \times LR_{B2|B1} = 25000}$$

Figure 4.6 shows the network structure, again described by *Champod and Taroni (pending),* employed in this extended scenario;

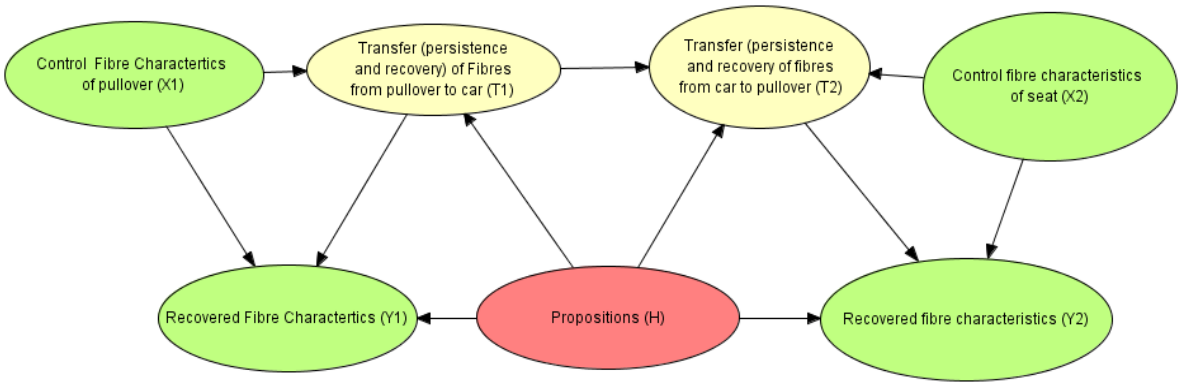


Figure 4.6: Bayesian network structure for 2-way transfer of fibres (pullover to car seat & car seat to pullover)

The probability assignments for each node of the network have been calculated according to *Champod and Taroni (pending)* using the data shown in *Table 4.3.* The resulting node assignments are shown in *Tables 4.4, 4.5 & 4.6;*

onditional Probability Table for Node T1				
	Hp		Hd	
State	**X**	**≠ X**	**X**	**≠ X**
$\mathbf{t_0^{B1}}$	t_0^{B1} **0.5**	**0.333**	$t_0^{B1'}$ **0.5**	$t_0^{B1'}$ **0.5**
$\mathbf{t_n^{B1}}$	t_n^{B1} **0.5**	**0.333**	$t_n^{B1'}$ **0.5**	$t_n^{B1'}$ **0.5**
$\mathbf{t_{other}^{B1}}$	$1 - t_0^{B1} - t_0^{B1}$ **0**	**0.333**	$1 - t_0^{B1'} - t_n^{B1'}$ **0**	$1 - t_0^{B1'} - t_n^{B1'}$ **0**

Conditional Probability Table for Node Y1 under Hp						
	$\mathbf{t_0^{B1}}$		$\mathbf{t_n^{B1}}$		$\mathbf{t_{other}^{B1}}$	
State	**X**	**≠ X**	**X**	**≠ X**	**X**	**≠ X**
y	$b_1\gamma_b$ **0.0002**	**0.5**	$\mathbf{b_0}$ **0.9**	**0.5**	**0**	**0**
≠ y	$1 - b_1\gamma_b$ **0.9998**	**0.5**	$\mathbf{1 - b_0}$ **0.1**	**0.5**	**1**	**1**

Conditional Probability Table for Node Y1 under Hd						
	$\mathbf{t_0^{B1}}$		$\mathbf{t_n^{B1}}$		$\mathbf{t_{other}^{B1}}$	
State	**X**	**≠ X**	**X**	**≠ X**	**X**	**≠ X**
y	$\mathbf{b_1\gamma_b}$ **0.0002**	$\mathbf{b_1\gamma_b}$ **0.0002**	$\mathbf{b_0\gamma}$ **0.0018**	$\mathbf{b_0\gamma}$ **0.0018**	**0**	**0**
≠ y	$\mathbf{1 - b_1\gamma_b}$ **0.9998**	$\mathbf{1 - b_1\gamma_b}$ **0.9998**	$\mathbf{1 - b_0\gamma}$ **0.9982**	$\mathbf{1 - b_0\gamma}$ **0.9982**	**1**	**1**

Table 4.4: Calculation and probability assignments for nodes T1 and Y1 under B1 of the Bayesian network structure, according to *Champod and Taroni (pending).*

Conditional Probability Table for Node T2				
	Hp		Hd	
State	$\mathbf{X}$	$\neq \mathbf{X}$	$\mathbf{X}$	$\neq \mathbf{X}$
$\mathbf{t_0^{B2}}$	t_0^{B2} **0.05**	**0.333**	$t_0^{B2\prime}$ **0.05**	$t_0^{B2\prime}$ **0.05**
$\mathbf{t_m^{B2}}$	t_m^{B2} **0.05**	**0.333**	$t_m^{B2\prime}$ **0.05**	$t_m^{B2\prime}$ **0.05**
$\mathbf{t_{other}^{B2}}$	$1 - t_0^{B2} - t_0^{B2}$ **0.9**	**0.333**	$1 - t_0^{B2\prime} - t_m^{B2\prime}$ **0.9**	$1 - t_0^{B2\prime} - t_m^{B2\prime}$ **0.9**

Conditional Probability Table for Node Y2 under Hp						
	$\mathbf{t_0^{E2}}$		$\mathbf{t_n^{E2}}$		$\mathbf{t_{other}^{E2}}$	
State	$\mathbf{X}$	$\neq \mathbf{X}$	$\mathbf{X}$	$\neq \mathbf{X}$	$\mathbf{X}$	$\neq \mathbf{X}$
$\mathbf{y}$	$\mathbf{b_1^{B2}\theta_b^{B2}}$ **0.018**	**0.5**	$\mathbf{b_0^{B2}}$ **0.1**	**0.5**	**0**	**0**
$\neq \mathbf{y}$	$\mathbf{1 - b_1^{B2}\theta_b^{B2}}$ **0.982**	**0.5**	$\mathbf{1 - b_0^{B2}}$ **0.9**	**0.5**	**1**	**1**

Conditional Probability Table for Node Y2 under Hd						
	$\mathbf{t_0^{E2}}$		$\mathbf{t_n^{E2}}$		$\mathbf{t_{other}^{E2}}$	
State	$\mathbf{X}$	$\neq \mathbf{X}$	$\mathbf{X}$	$\neq \mathbf{X}$	$\mathbf{X}$	$\neq \mathbf{X}$
$\mathbf{y}$	$\mathbf{b_1^{B2}\theta_b^{B2}}$ **0.018**	$\mathbf{b_1^{B2}\theta_b^{B2}}$ **0.018**	$\mathbf{b_0^{B2}\theta^{B2}}$ **0.002**	$\mathbf{b_0^{B2}\theta^{B2}}$ **0.002**	**0**	**0**
$\neq \mathbf{y}$	$\mathbf{1 - b_1^{B2}\theta_b^{B2}}$ **0.982**	$\mathbf{1 - b_1^{B2}\theta_b^{B2}}$ **0.982**	$\mathbf{1 - b_0^{B2}\theta^{B2}}$ **0.998**	$\mathbf{1 - b_0^{B2}\theta^{B2}}$ **0.998**	**1**	**1**

Table 4.5 Calculation and probability assignments for nodes T2 and Y2 under B2 of the Bayesian network structure, according to *Champod and Taroni (2014).*

Conditional Probability Table for Node H	
STATE	**PROBABILITY**
Hp (The suspect wearing the pullover drove the car)	0.5
Hd (The suspect did not drive the car)	0.5

Conditional Probability Table for Node X	
STATE	**PROBABILITY**
X	0.5
≠ **X**	0.5

Table 4.6: Calculation and probability assignments for nodes H and X under both B1 and B2 of the Bayesian network structure shown in *Figure 4.6*, according to *Champod and Taroni (2014).*

If the effect of the background fibre transfer probabilities for B2 is considered and that for B1 is ignored, the network calculates the likelihood ratio shown in *Figure 4.7*;

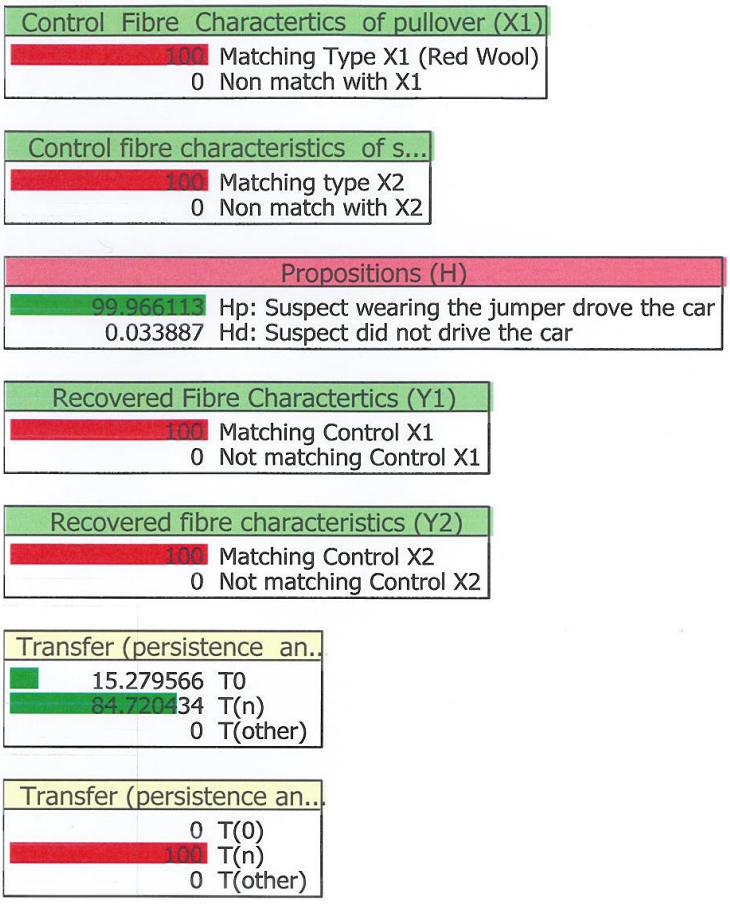


Figure 4.7: Bayesian network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with a high probability of encountering unassigned fibre collectives in B2 and the effect of any unassigned collectives present in B1 are low and ignored. LRB1 X LRB2|B1 = 2950.

If the effect of the background fibre transfer probabilities for both B1 & B2 is now considered, the network calculates the likelihood ratio shown in *Figure 4.8*;

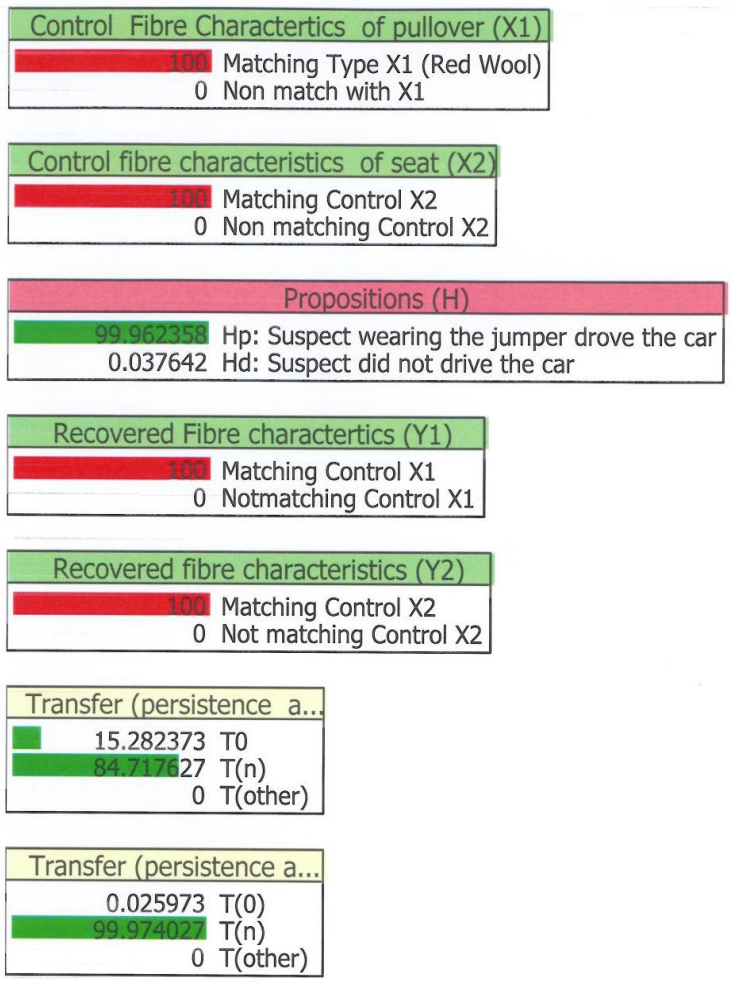


Figure 4.8: Bayesian Network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with a high probability of encountering unassigned fibre collectives in B2 and a low probability of encountering any unassigned collectives present in B1 considered. LR=2655.

Where the provenance of any background fibre collectives allows the contribution of the respective background transfer probabilities relating to B1 & B2 to be effectively ignored (as in scenario 1A), the network calculates the likelihood ratio shown in *Figure 4.9*;

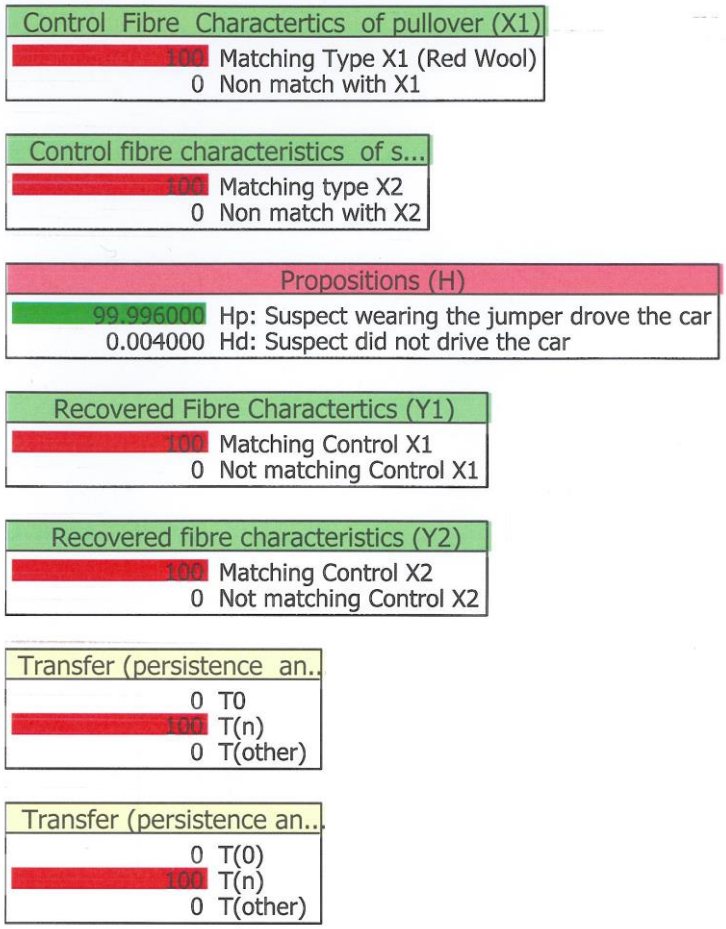


Figure 4.9: Bayesian Network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with the probabilities of encountering unassigned fibre collectives in B1 and B2 ignored (e.g. where the provenance of any unassigned collectives is known). LR= 25000.

It can be seen that network likelihood ratio calculated by the Bayesian networks are congruent with those obtained by direct calculation.

4.3.4 Scenario 2B (two- way transfer)

As in the one way transfer scenario 1B, let us again consider a situation where the car in question has been bought second or third hand and/ or is regularly occupied by friends and relatives of the owner. As previously stated, it is likely in such a situation that any tapings taken from the seats are likely to contain a number of fibre collectives that cannot be attributed to the current owner and whose provenance cannot be ascertained.

In such a situation, for the findings relating to the car seat (B1), we can now assign the background transfer probabilities (i.e. the probability of recovering no foreign fibre group (FFG) distinguishable from the garments of the owner, 'by chance', on the driver's seat) b_0 as 0.1 and the probability of recovering at least one foreign fibre group (FFG) distinguishable from the garments of the owner, 'by chance', on the driver's seat b_1 as 0.9.

The probabilities assigned to the other variables in B1 are exactly the same as the previous scenario.

The probabilities assigned to B2 remain unchanged.

The probability assignments for node Y1 (B1) was re-populated to take account of the new values for b_0 & b_1.

4.4 Background Fibre Population Transfer Probabilities

In this scenario if we ignore the effect of the high background transfer probability for B1 (e.g. if the provenance of any foreign fibre groups can be identified), then as in scenario 2A, the calculations for $\mathbf{LR_{B1}}$ & $\mathbf{LR_{B2|B1}}$ become;

$$\mathbf{LR_{B1}} = \frac{\left(\mathbf{b_1^{B1} t_n^{B1}}\right)}{\left(\mathbf{b_1^{B1} \gamma^{B1} t_n^{B1\prime}}\right)} \qquad \mathbf{LR_{B2|B1}} = \frac{\left(\mathbf{b_1^{B2} t_m^{B2}}\right)+\left(\mathbf{b_1^{B2} \theta^{B2} t_0^{B2}}\right)}{\left(\mathbf{b_1^{B2} \theta^{B2} t_m^{B2\prime}}\right)+\left(\mathbf{b_1^{B2} \theta^{B1\prime} t_0^{B2\prime}}\right)}$$

$$\text{For B2 } \left(b_1^{B2}\theta^{B2}t_0^{B2}\right) \text{ \& } \left(b_1^{B2}\theta^{B1\prime}t_0^{B2\prime}\right) = (0.9 \times 0.02 \times 0.05) = 0.0009$$

$$LR_{B1} = \frac{(0.1\times0.5)}{(0.1\times0.002\times0.5)} \qquad LR_{B2|B1} = \frac{(0.9\times0.05)+ 0.0009}{(0.9\times0.02\times0.05)+ 0.0009}$$

$$LR_{B1} = \frac{(0.05)}{(0.0001)} = 500 \qquad LR_{B2|B1} = \frac{(0.0059)}{(0.001)} = 5.9$$

$$\mathbf{LR_{B1} \times LR_{B2|B1} = 2950}$$

Despite the change in the background transfer probability values for B1, the LR is in accordance with scenario 2A.

If the effect of the high background transfer probability for B1 is now considered, then then the calculations for $\mathbf{LR_{B1\,\&\,B2|B1}}$, as in scenario 2A, become;

$$\mathbf{LR} = \frac{(\mathbf{b_1 t_n}) + (\mathbf{b_1 \gamma_b t_0})}{(\mathbf{b_1 \gamma t_n'}) + (\mathbf{b_1 \gamma_b t_0'})}$$

$$\text{For B1 } (b_1^{B2}\gamma^{B1}t_0^{B1}) \;\&\; (b_1^{B2}\gamma^{B1}t_0^{B1\prime}) = (0.9 \times 0.002 \times 0.5) = 0.0009$$

$$\text{For B2 } (b_1^{B2}\theta^{B2}t_0^{B2}) \;\&\; (b_1^{B2}\theta^{B1\prime}t_0^{B2\prime}) = (0.9 \times 0.02 \times 0.05) = 0.0009$$

$$LR_{B1} = \frac{(0.1\times0.5)+0.0009}{(0.1\times0.002\times0.5)+0.0009} \qquad LR_{B2|B1} = \frac{(0.9\times0.05)+0.0009}{(0.9\times0.02\times0.05)+0.0009}$$

$$LR_{B1} = \frac{(0.0509)}{(0.001)} = 50.9 \qquad LR_{B2|B1} = \frac{(0.0059)}{(0.001)} = 5.9$$

$$\mathbf{LR_{B1}\,x\,LR_{B2|B1} = 300}$$

As in scenario 2A, where the provenance of any background fibres populations relating to B1 & B2 can be established, both $\mathbf{LR_{B1}}$ & $\mathbf{LR_{B2|B1}}$ can be calculated using;

$$\frac{(\mathbf{b_0 t_n})}{(\mathbf{b_0 \gamma t_n'})} \approx \frac{\mathbf{t_n}}{\boldsymbol{\gamma}\mathbf{t_n'}} \;;$$

$$LR_{B1} = \frac{(0.1\times0.5)}{(0.1\times0.002\times0.5)} \qquad LR_{B2|B1} = \frac{(0.9\times0.05)}{(0.9\times0.02\times0.05)}$$

$$LR_{B1} = \frac{(0.05)}{(0.0001)} = \frac{\mathbf{t_n}}{\boldsymbol{\gamma}} = \frac{1}{0.002} \qquad LR_{B2|B1} = \frac{(0.005)}{(0.0001)} = \frac{\mathbf{t_m}}{\boldsymbol{\theta}} = \frac{1}{0.02}$$

$$= 500 \qquad = 50$$

$$\mathbf{LR_{B1}\,x\,LR_{B2|B1} = 25000}$$

Despite the change in the background transfer probability values for B1, the likelihood ratio is again, in accordance with scenario 2A.

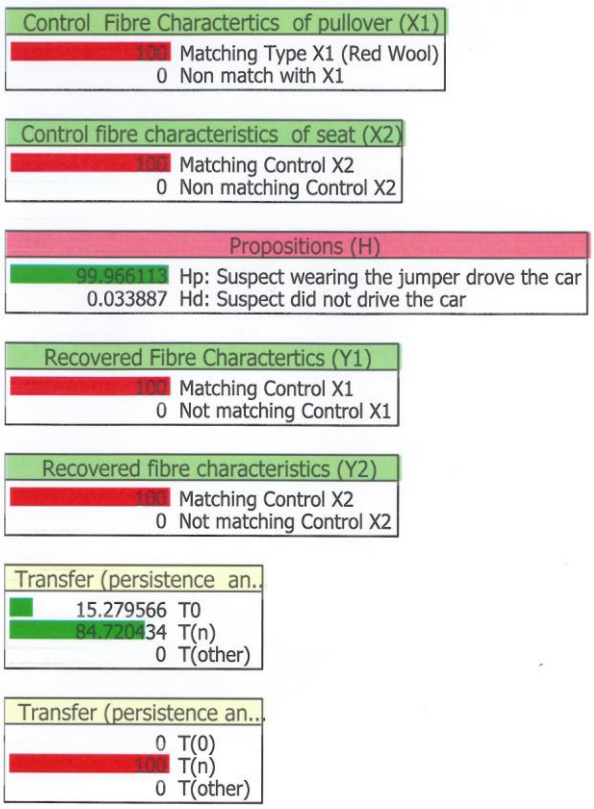


Figure 4.10: Bayesian Network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with a high probability of encountering unassigned fibre collectives but only the background probability for B2 is considered. LR=2950.

If the effect of the background fibre collectives on $B2$ is considered, the network calculates the likelihood ratio shown in *Figure 4.10*.

This value is in accordance with both the directly calculated value and that of the network employed in Scenario 2A.

If the effect of the background fibre collectives for both transfers ($B1$ & $B2$) is considered, the network calculates the likelihood ratio (taking into account the amended node Y1 ($B1$)) shown in *Figure 4.11*;

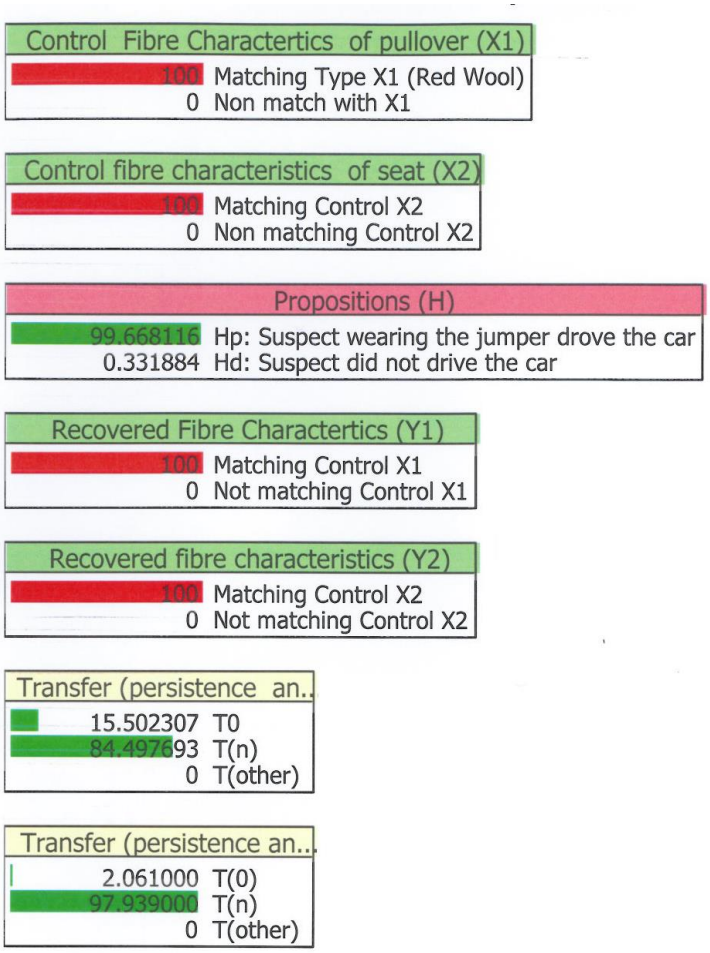


Figure 4.11: Bayesian Network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with a high probability of encountering unassigned fibre collectives but only the background probability for B2 is considered. LR= 300.

As in scenarios 1A & 2A, where the provenance of any background fibres allows the contribution of the respective background fibre collectives relating to both transfers (B1 & B2) to be effectively ignored, the network calculates the likelihood ratio shown in *Figure 4.12*;

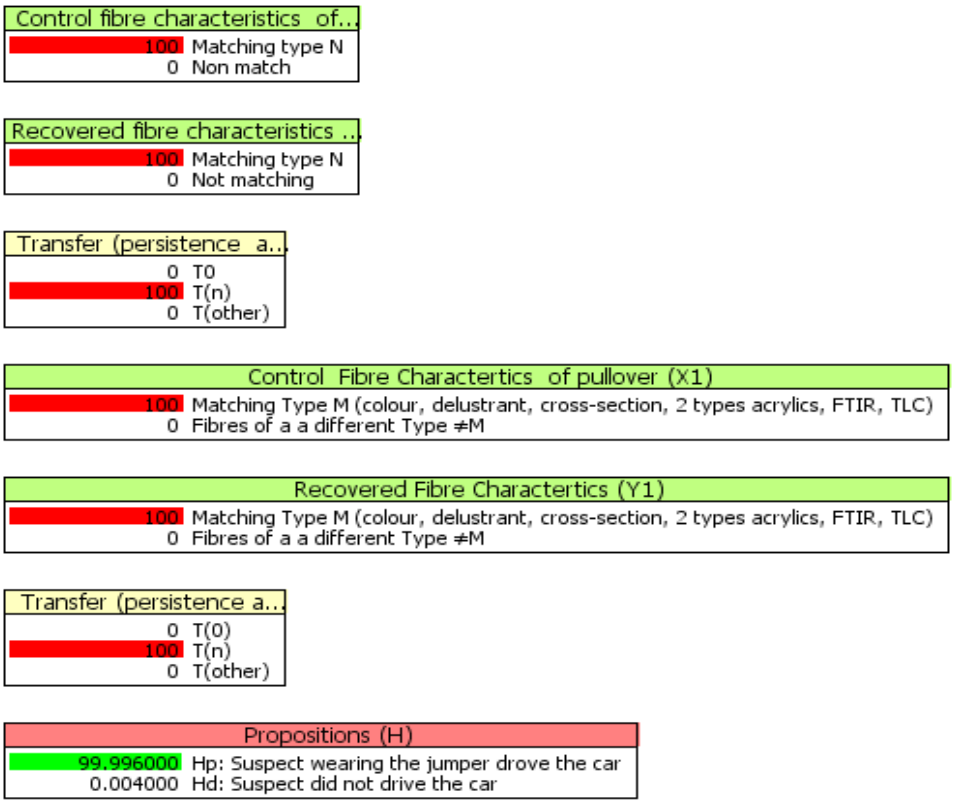


Figure 4.12: Bayesian Network likelihood ratio calculation where there is a reciprocal transfer of fibres matching those of the respective target items with the probabilities of encountering unassigned fibre collectives ignored (e.g. where the provenance of any unassigned collectives is known). LR= 25000.

Again, this value is in accordance with both the directly calculated value and that of the networks employed in Scenarios 1A & 2A.

4.5 The use of 'block' architecture for subsequent casework models.

The basic Bayesian network structures used in the previous exercises are relatively simple and the probability assignments relating to background fibre collectives are integrated into the node structure with those relating to the 'results'. Whilst this network architecture is useful for the purpose of testing the validity of the underlying calculations, this integration is somewhat restrictive in terms of modelling more complex casework scenarios.

A more flexible architecture involving a 'block' structure, where the probabilities relating to the fibre transfer results and the background fibre collectives reflecting a one-way fibre transfer scenario, are in a separate node structure, is shown in *Figure 4.13*.

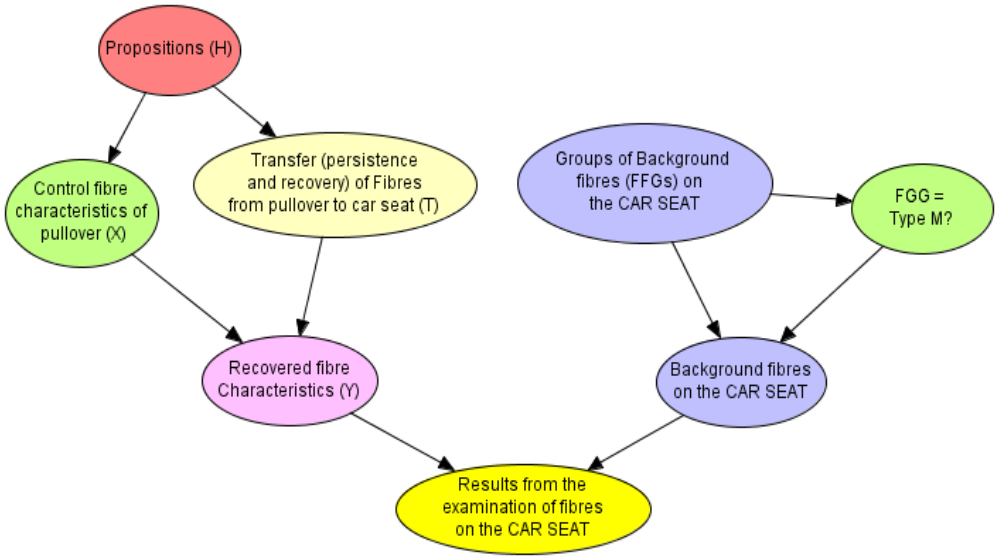


Figure 4.13: Extended Bayesian network for 1-way fibre transfer structure (pullover to car seat) separating nodes relating to unassigned collectives.

It should be noted that the main assumption in the Bayesian networks presented, is that the link between the pullover and the suspect is not disputed. In a real casework situation where such a link is subject to challenge, then further examinations (e.g. looking for fibre transfers from the pullover to other garments worn by the suspect) can be carried out to resolve this. To encompass this in the BN however, would make the architecture very complex.

It can be seen that the 'block' structure on the left hand side of the network is very similar to network structures shown in *Figures 4.1 and 4.6* (employed in the validation scenarios), however, in this structure it deals exclusively with the fibre transfer results. The 'block' on the right side of the network relates to the background fibre collectives. These two 'blocks' condition a separate 'results' node – effectively combining their effect on the observed outcome of the forensic examinations.

The 'integrated' network architectures used in the validation exercise do not allow us to easily encompass the possibility that recovered 'matching' fibres contain a contribution, in whole or

in part, from adventitious matches in the background populations. Since in real casework it would never be possible to 'distinguish' such an event, it is important for us to consider this possibility in the structure of the Bayesian network. The increased flexibility afforded by the separated 'block' structure in *Figure 4.13*, allows us to factor in this possibility by easily populating the 'results' node appropriately.

The probability assignment in the 'results' node (shown in *Figure 4.13)* reflecting the effect of background fibre collectives is highlighted in *Table 4.7*;

Results from theexamination of fibreson the CAR SEAT(Results_FIBRES)

C2	MATCHING fibres			NON_MATCHING fibres			NO fibres		
Background_(	NO FIBRE	MATCHIN	NON-MAT	NO FIBRE	MATCHIN	NON-MAT	NO FIBRE	MATCHIN	NON-MAT
MATCHING fit	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
MATCHING ar	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0
NON-MATCHI	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0
NO fibres at all	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0

Table 4.7: Results node probability assignment without inclusion of potential contribution of adventitious matches.

The arrow in *Table 4.7* indicates the probability assignment for no adventitiously matching background fibre collectives to be present. This effectively replicates the probability assignments used in the previous 'integrated' network structures.

In order to reflect the possible contribution (in part or in whole) of adventitious matches, all that is required in each of the scenario models in the simple change of probability assignment in the results node, as highlighted in *Table 4.8*. All other probability assignments in each node remain unchanged in both scenarios.

Results from theexamination of fibreson the CAR SEAT(Results_FIBRES)

C2	MATCHING fibres			NON_MATCHING fibres			NO fibres		
Background_(	NO FIBRE	MATCHIN	NON-MAT	NO FIBRE	MATCHIN	NON-MAT	NO FIBRE	MATCHIN	NON-MAT
MATCHING fit	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
MATCHING ar	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0
NON-MATCHI	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	1.0
NO fibres at all	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0

Table 4.8: Results node probability assignment for inclusion of potential contribution of adventitious matches in background populations.

In order to test the validity of the ‘block’ architecture, the network shown in *Figure 4.13* has been populated according to the variable assignments for scenarios 1A and 1B. The ‘results’ node has been populated according to *Table 4.7,* thus negating the potential contribution of adventitious matches in background populations.

The likelihood ratio calculation from this ‘block’ network reflecting scenario 1A (i.e. where the contribution of background fibre collectives is ignored) is shown in *Figure 4.14* .

The likelihood ratio calculation from the ‘block’ network reflecting scenario 1B (i.e. where the contribution of background fibre collectives is considered) is shown in *Figure 4.15.*

It can be seen that the likelihood ratio calculations obtained from the ‘block’ network architecture are congruent with the ‘integrated’ architecture of the networks used in this scenario.

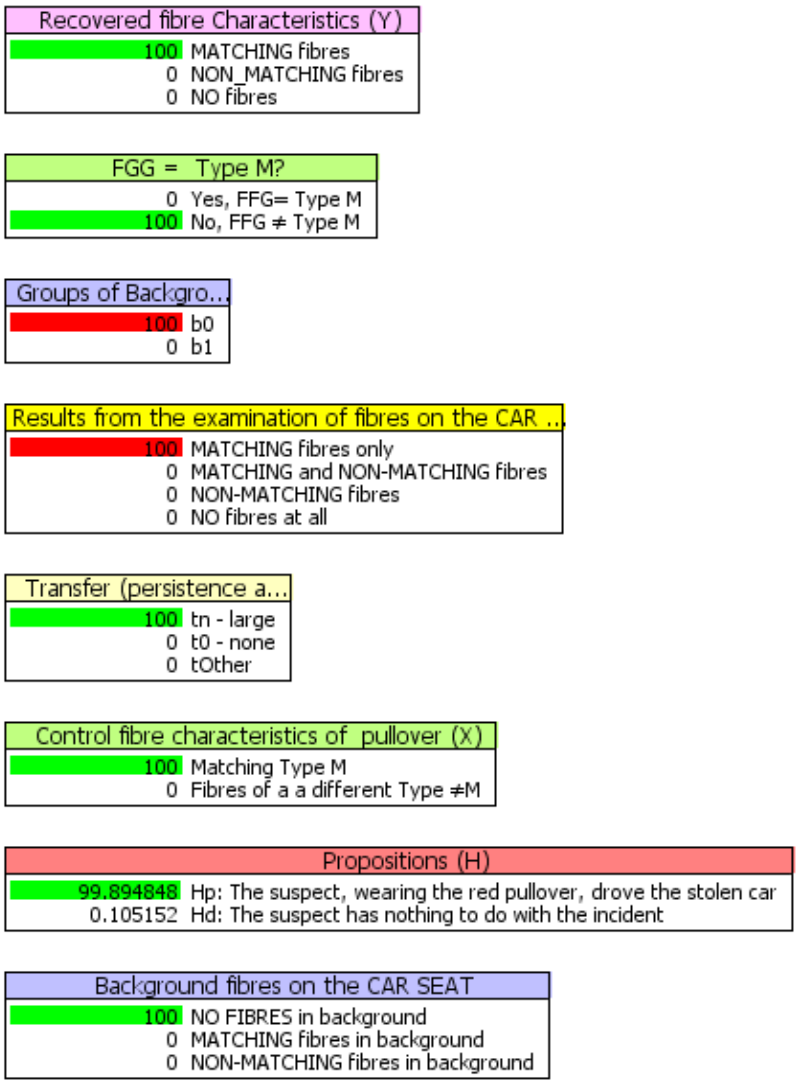


Figure 4.14: Scenario 1A Bayesian network likelihood ratio using separated structure with no contribution from any potential unassigned background collectives. LR= 950.

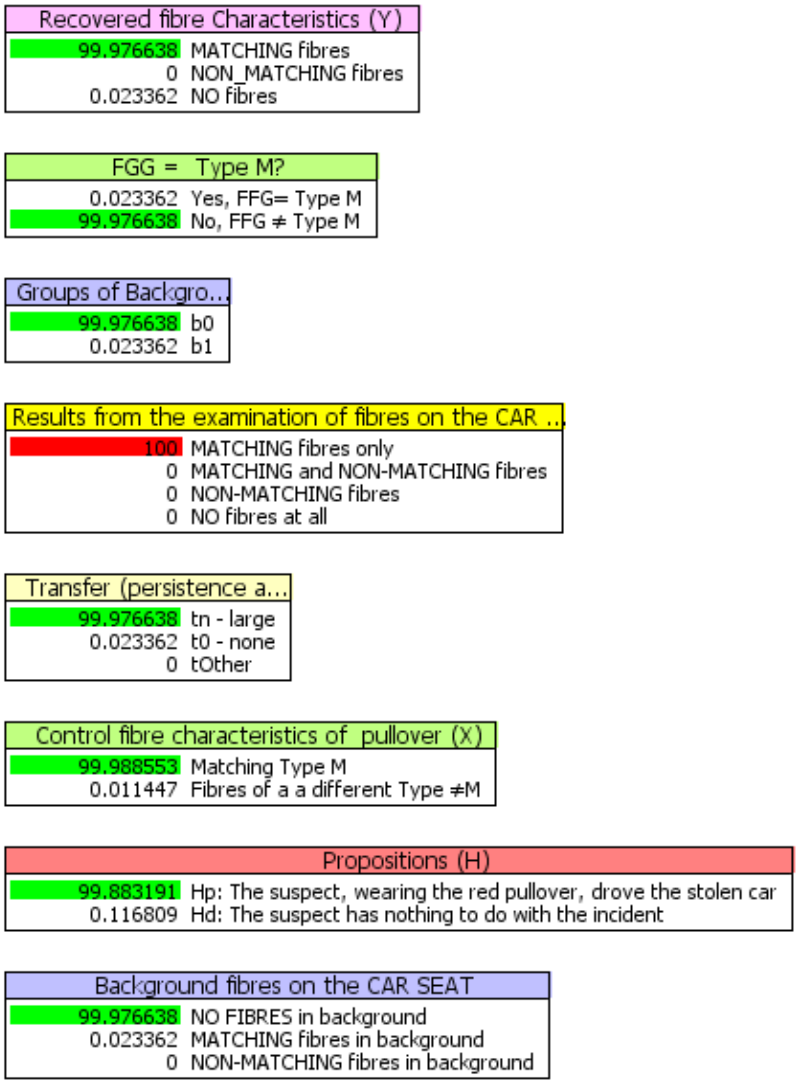


Figure 4.15: Scenario 1B Bayesian network likelihood ratio using separated structure with contribution from unassigned background collectives. LR = 855.

By using the 'block' network structure shown in *Figure 4.13* as a building block, it is therefore possible to construct a network structure to encompass a two-way fibre transfer scenario shown in *Figure 4.16*.

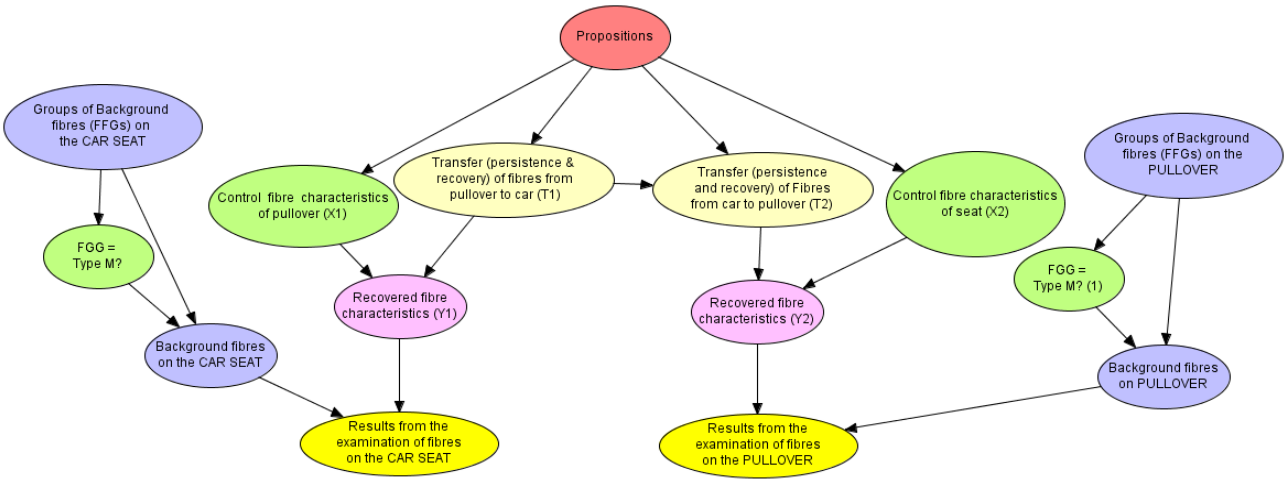


Figure 4.16: Expanded Bayesian network for 2 way fibre transfer structure (pullover to car seat & car seat to pullover) separating nodes relating to unassigned collectives on each recipient surface.

In order to test the validity of the 'block' architecture, the network shown in *Figure 4.16* has been populated according to the probability assignments for scenarios 2A and 2B shown in *Tables 4.4, 4.5 and 4.6*. Each of the 'results' node of this network has been populated according to *Table 4.7,* thus negating the potential contribution of adventitious matches in background populations in the likelihood ratio calculation.

The likelihood ratio calculation from this 'block' network reflecting scenario 2A (i.e. where the contribution of background fibre collectives under B1 and B2 is ignored) is shown in *Figure 4.17*. The likelihood ratio calculations from the 'block' network reflecting scenario 2B i.e. where the contribution of background fibre collectives is considered under B2 only, as well under both B1 & B2, are shown in *Figures 4.18 and 4.19* respectively.

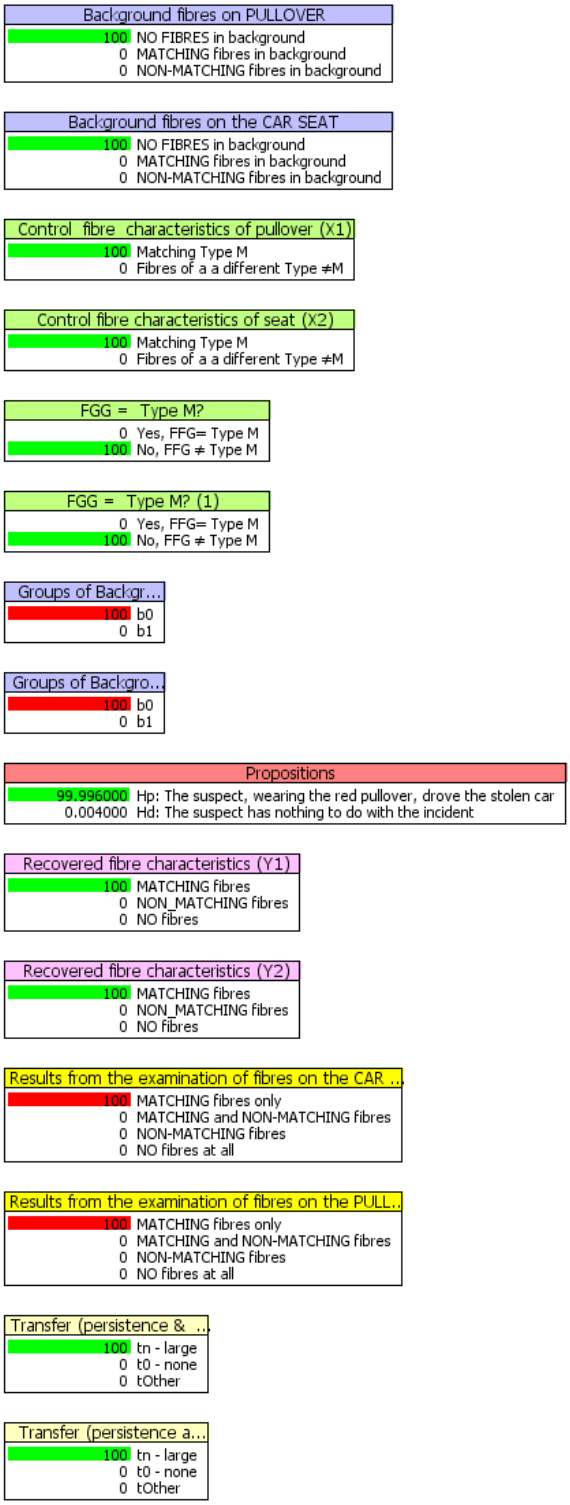


Figure 4.17: Likelihood ratio calculation using the 'block' network structure for 2 way transfer with no contribution from any unassigned background collectives under B1 or B2 (Scenario 2A) LR = 25000

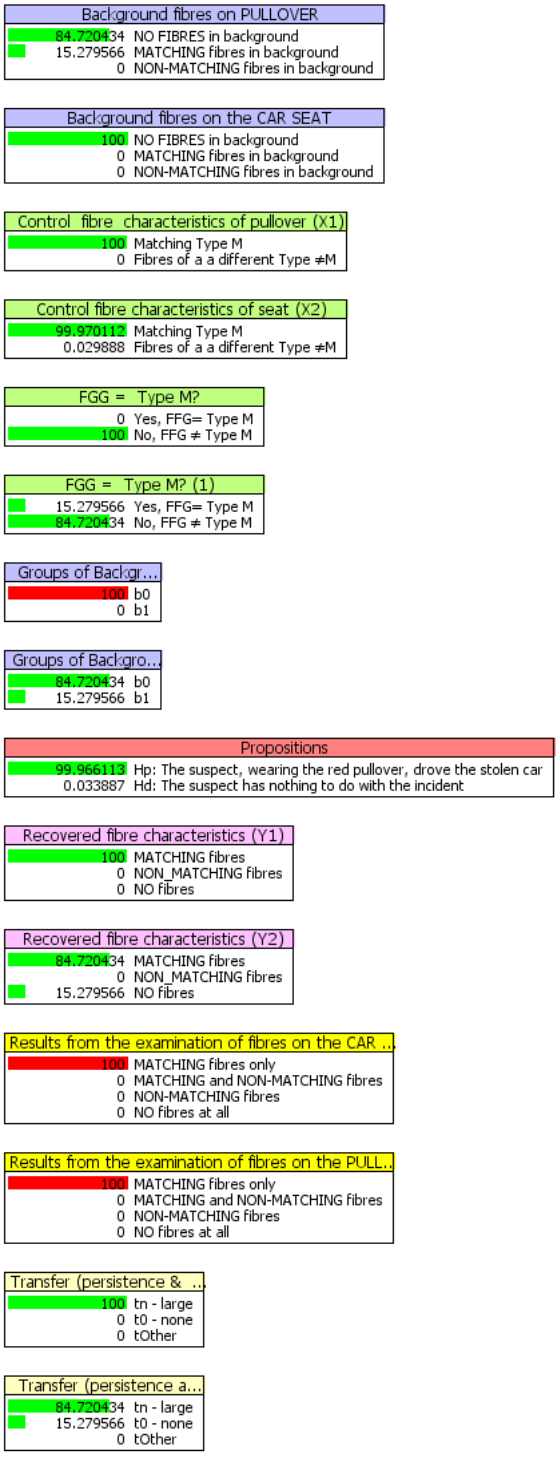


Figure 4.18: Likelihood ratio calculation using the 'block' network structure for 2 way transfer with contribution from unassigned background collectives under B2 only (scenario 2B). LR = 2950.

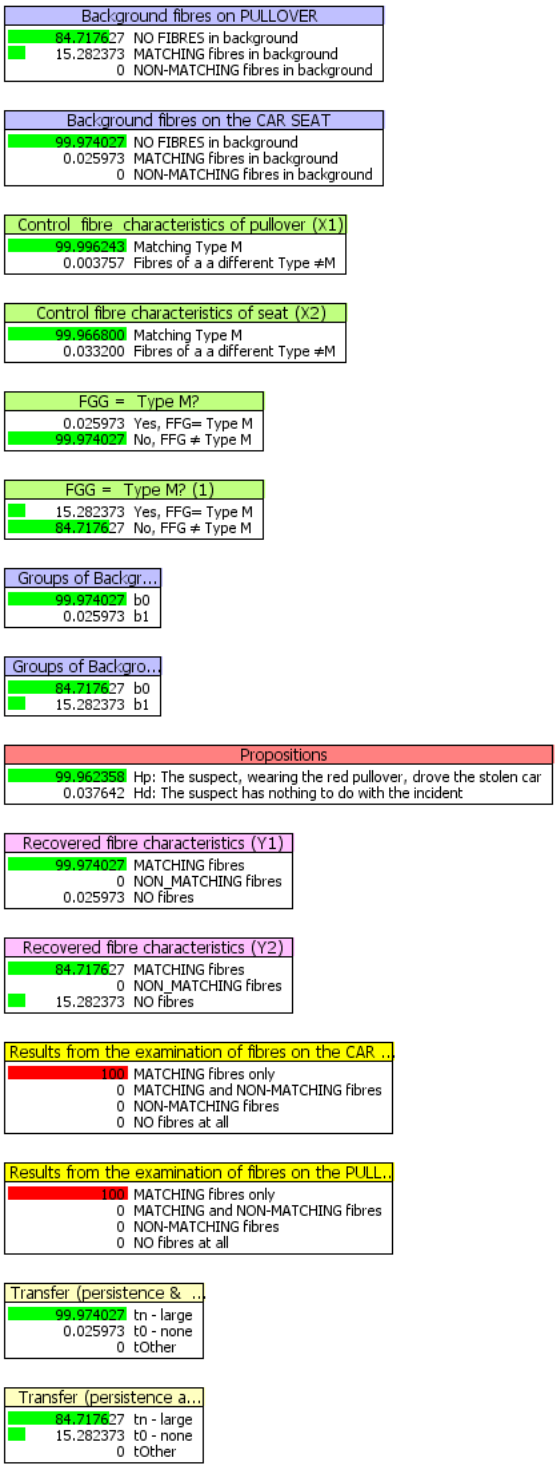


Figure 4.19: Likelihood ratio calculation using the 'block' network structure for 2 way transfer with contribution from unassigned background collectives under B1 & B2 (scenario 2B). LR = 2655.

Again, it can be seen that the likelihood ratio calculations obtained from the 'block' network architecture are congruent with the 'integrated' architecture of the networks used in the two-way fibre transfer (Scenario 2) case.

4.6 The effect of adventitious matches on likelihood ratios

Having demonstrated that the output from the 'block' network architectures is congruent with the validated 'integrated' networks, it is now necessary to determine the effect of the potential presence of adventitious matches in the background fibre collectives.

In order to demonstrate this, the outputs obtained using the networks shown in *Figures 4.18 and 4.19,* have been re-run after changing the probability assignment in the results nodes in B1 & B2 as shown in *Table 4.8*. All other node probability assignments in the network remain unchanged.

The re-calculated likelihood ratios are shown in *Figures 4.20 and 4.21.*

Whilst the actual effect of this change on the calculation of the likelihood ratio is minimal, (i.e. the values displayed in *Figures 4.18 and 4.19 (2950 & 2655)* become 3339 and 3006 respectively), the potential for a 'mix' of true transfer matches and adventitious background matches will be employed in subsequent casework modelling, as in practice, one would never truly be able discount that the demonstration of a transfer of fibres was either partly or wholly due to chance.

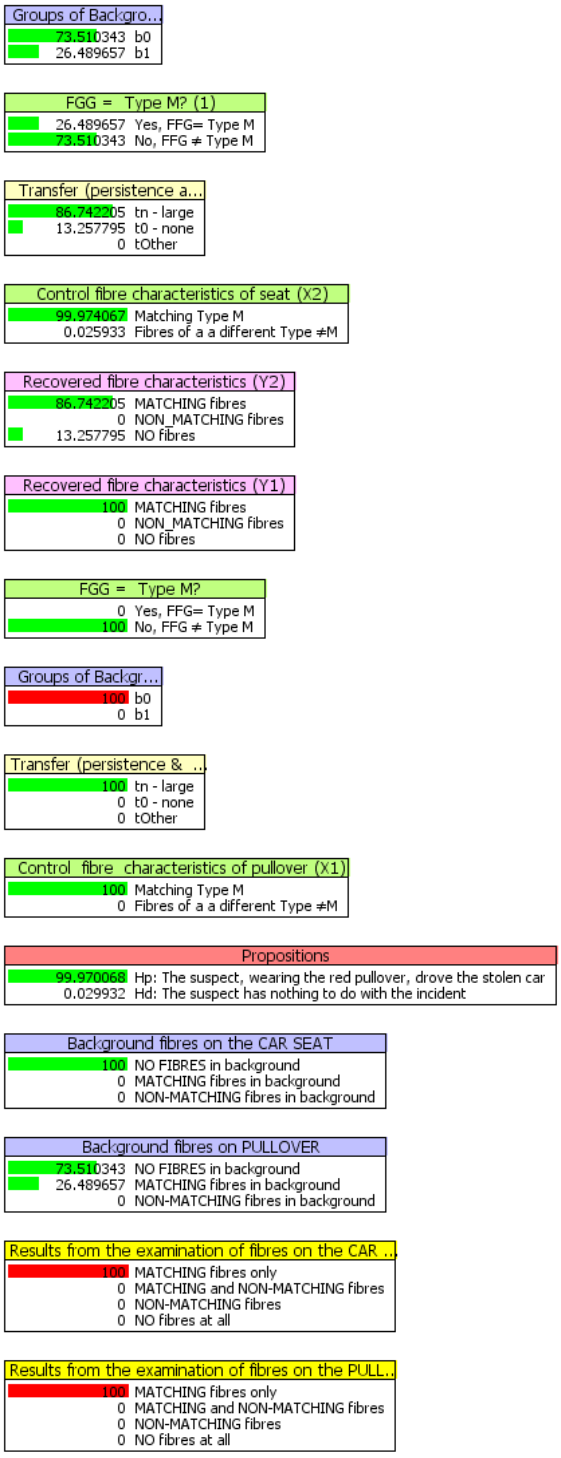


Figure 4.20: Likelihood ratio calculation using the 'block' network structure for 2 way transfer with contributions from unassigned background collectives under B2 only (scenario 2B) and potential adventitious matches in background collectives. LR = 3339.

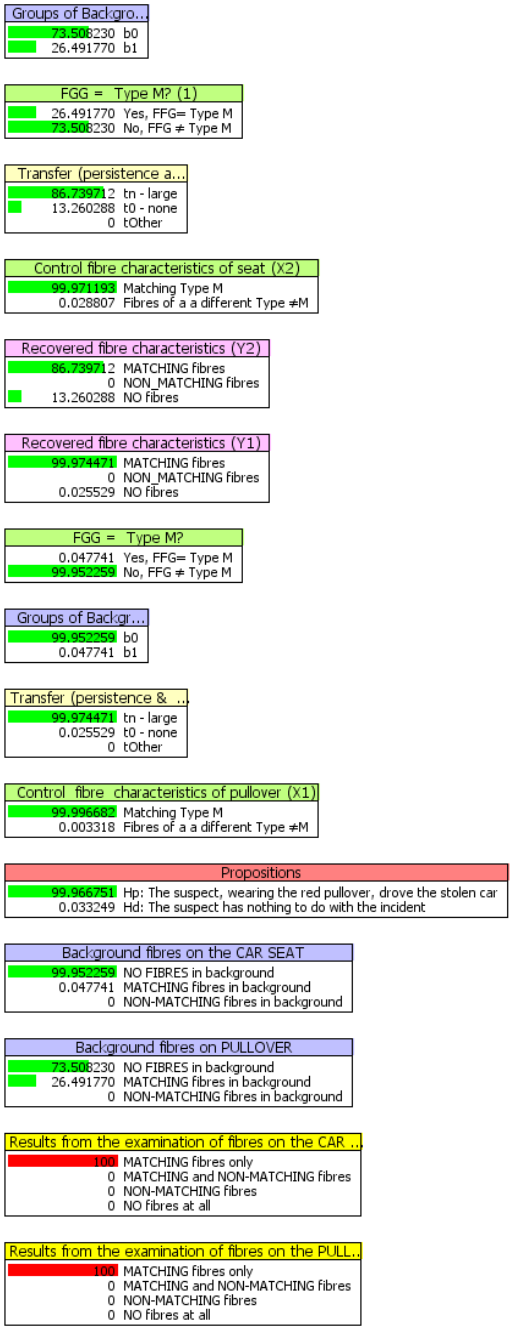


Figure 4.21: Likelihood ratio calculation using the 'block' network structure for 2 way transfer with contributions from unassigned background collectives under B1 & B2 (scenario 2B) and potential adventitious matches in background collectives. LR = 3006.

4.7 Summary

- The work described in this chapter has demonstrated that the underlying network construction in 'Hugin Researcher™' is sound and fit for purpose.
- A 'blocked' rather than an 'integrated' network architecture which encompasses the potential for adventitious fibre matches to contribute to the calculation of the likelihood ratio, will be used to model subsequent casework scenarios in this thesis.

5 ANALYSIS OF A CASE INVOLVING FIBRE TRANSFER TO SKIN

This chapter considers the significance of fibre evidence on skin and the paucity of published data useful in the assessment and evaluation of such evidence. In order to assess the contribution of the author's studies, their results are evaluated in the context of a real case scenario (in which the author provided testimony), involving the serial killings of five women around the town of Ipswich, in the county of Suffolk, England in 2006. This chapter will detail the circumstances of the case and the aspects of fibre transfer and persistence which were to prove of crucial interest for the court. An evaluation of the data from the author's studies (which were carried out subsequent to the case and its trial) with that which was available at the time, is performed using a Bayesian network conditioned by the framework of circumstances.

5.1 Case circumstances: The Ipswich serial killings

Over a period of 2 weeks in 2006, the naked bodies of 5 women were found in various depositions sites around the town of Ipswich in England. Two of these women had been deposited in a fast flowing river prior to their discovery whilst the remaining three had been deposited naked in woodland. All of the women were active prostitutes and habitual drug users.

Pathological and entomological data indicated that each of these women had been killed and deposited around the time of their disappearance. It estimated that the two women deposited in the river had been immersed for 2 and 5 weeks respectively, whilst those deposited on land had lain there exposed to extreme rainfall and high winds for 7, 4 and 2 days respectively. DNA profiles obtained from three women deposited on land led to the arrest of a suspect, Steve Wright.

Upon his arrest, the suspect refused to answer any questions regarding the evidence linking him to each of these women.

Since it was known that each of the women were active prostitutes, the investigative team felt that the DNA evidence in itself would not be enough to implicate the suspect with the murders and consequently fibre analysis was requested.

Despite being subjected to conditions not favourable to fibre persistence, analysis of surface debris recovered from each of the women's bodies revealed a number of fibre collectives common to each of the 5 women which were indistinguishable from the constituent fibres of various items relating to the suspect and/ or his environment.

Figure 5.1 shows the fibre transfers from demonstrable sources from the accused to the victims, as well as the number of foreign fibre collectives common to each of the women and items relating to the suspect, for which no demonstrable sources were found.

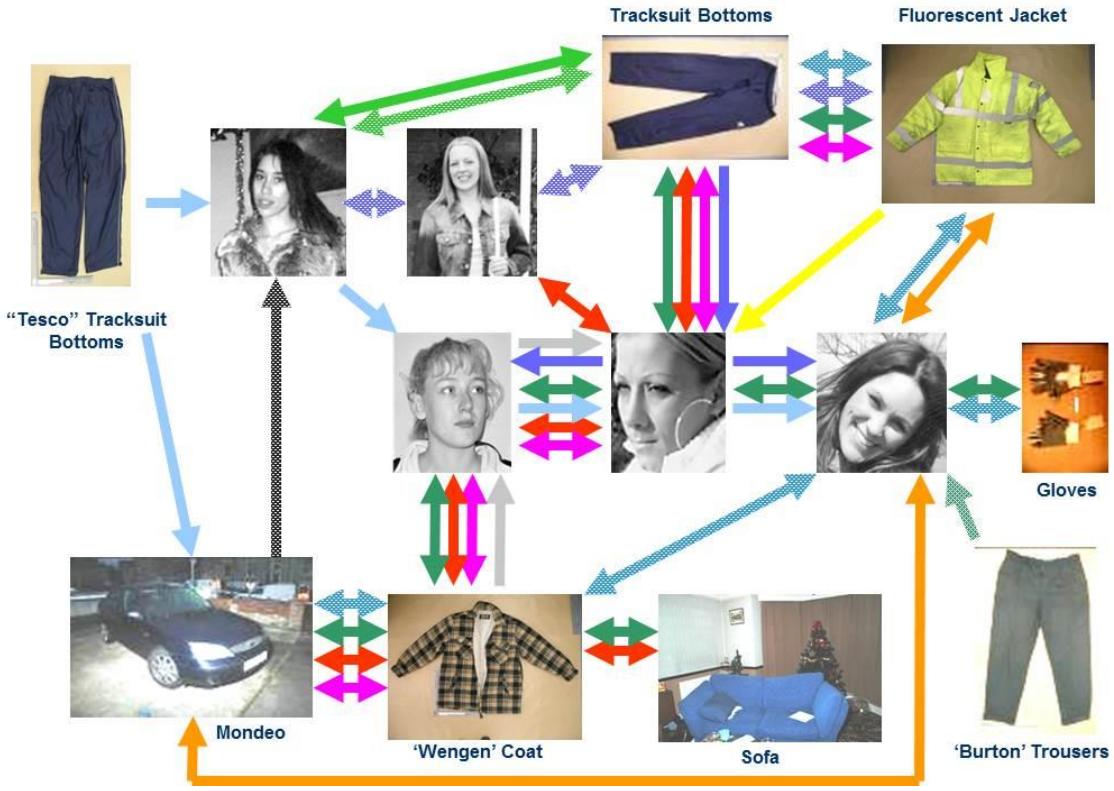


Figure 5.1: Schematic summary of the fibre evidence in the Ipswich serial killings. The single pointed arrows represent a transfer from a known garment relating to the accused. The double pointed arrows represent foreign fibre collectives common to each individual or item for which no demonstrable source was found.

For the purpose of this chapter, only the blue polyester microfibres relating to suspect's 'Tesco' tracksuits trousers are considered, these being the largest and (arguably) the most significant transferred collective. In addition, land deposited victims are only considered as no crime relevant fibres were found on the skin (but were in their hair) of those deposited in the river (see Figure 5.2).

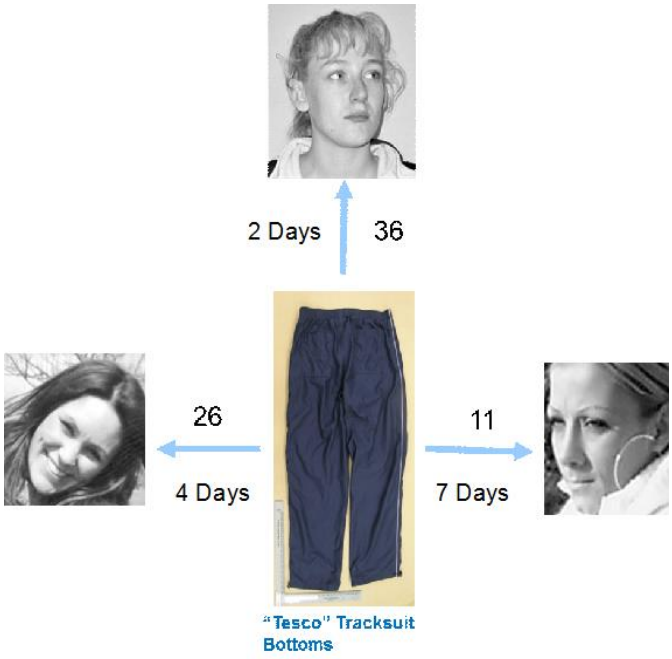


Figure 5.2: Schematic summary of the polyester microfibre evidence relating to the victims deposited on land. The numbers represent the fibres found on each woman which were indistinguishable from the tracksuit bottoms relating to the suspect and the time of deposition.

5.2 Issues in question and proposition setting

When presented with this evidence, the suspect moved from 'no comment' to maintaining that he had sex with each of the women "two days or so" before their disappearances. Importantly then, *the provenance of the fibres was not disputed.*

The question posed by the court was therefore, 'are the fibre collectives common to the women present as a consequence of contact with the accused two days before their disappearance, or as a consequence with contact around the time of their deaths and deposition?'. The propositions in this case were therefore;

Hp: The suspect was in contact with the victims during deposition

Hd: The suspect had contact two days before the victims death.

Since it was known from witness accounts that each of the women had showered or bathed on the day of the disappearance, the persistence of fibres on skin of the living, as well as the dead deposited outdoors, became an important interpretative issue.

This framework of circumstances forms the basic structure of the Bayesian Network model used in evaluating transfer and persistence data applied in the assessment and evaluation of the findings in this case.

However, at the time of the investigation and subsequent trial, very limited (if any) peer reviewed published data was available to assist in addressing the cogent issues relating to the evaluation of the evidence in this case. Consequently it is felt by the author that the evaluation of the evidence at the trial was somewhat understated.

The issues raised in this case highlighted the need to address the lack of empirical data relating to skin, namely;

1. What are the transfer and persistence characteristics ('t' values) of fibres on the skin of living individuals?
2. What are the transfer and persistence characteristics ('t' values) of fibres on the skin of a cadaver exposed to weather?
3. Is skin a truly non-retentive surface?
4. What predominant populations of fibres would be expected to be found on skin?
5. To what extent do each of these factors contribute to the evaluation of the evidence in such a homicide scenario?

These issues subsequently became drivers for research carried out by the author and others to address the lack of data relating to this specific aspect of fibre transfer and persistence in this particular homicide scenario.

The first, third and fourth of these questions were addressed through the novel study of fibre transfer and persistence characteristics of skin in living individuals, which also obtained fibre population data, again, on a substrate not previously studied *(Palmer and Burch, 2009)*.

As stated, one of the important issues in the assessment of the evidence in this case was the fact that each of the victims had bathed shortly before their disappearance (and it is inferred) their deaths and deposition.

Since there was no published literature on which to base an expectation of whether fibres transferred prior to washing or bathing would persist for any period of time following that activity, the assumption made at that time (based on intuitive reasoning) was that the expectation of finding fibres persisting of skin following washing, would be low. The data from this study showed that fibres on skin are exponentially lost over a 24 hour period - in much the same manner as that observed for clothing. The study also showed that following bathing or showering after 24 hours, no fibres would be expected to persist.

In terms of assessing the significance of the presence of the fibre collectives on the land deposited women, the work of *Krauss and Hildebrand, (1996)* was considered at the time of the investigation, since it was the only study available which was relevant to this particular issue. Using squares of pig skin which were seeded with fibres, the effect of wind and rain on their persistence was determined by leaving these exposed outdoors for 14 days. The results of this study presented an expectation that wind alone would have minimal effect on persistence but that c. 60% loss may be expected following rain.

By contrast, subsequent work by *Palmer and Polwarth, (2011)* using pig carcasses subjected to a direct fibre transfer scenario, showed that fibre loss in such circumstances was exponential, however, rainfall was found to accentuate the rate of loss. This study suggested that c. 95% loss could be expected after 7 days, in the absence of rainfall.

5.3 Fibres on the Skin of Living Subjects

The *Palmer and Burch, (2009)* study employed the use of two target garments; a pink wool top and a blue cotton/ polyester top. The results are as follows;

5.3.1 Transfer and persistence on bare skin (0–5 h)

Initial transfer of the target fibres involved wrapping a garment around and drawing it down the forearms of living male and female subjects (prior to the transfer experiment, the forearm of the subjects were taped to remove any extraneous fibres – this facilitating easier subsequent identification of the target fibres during the persistence sampling phase). These transfer experiments were performed using a blue cotton hooded top and a pink wool jumper. The arms were sampled by taping after intervals of 0.5, 1, 2, 3, 4 and 5 h for each garment.

The decay curves for both garments are shown in *Figure 5.3*. Both decay curves show one standard deviation limits for each time interval.

The average number fibres initially transferred was 245±142 (range=106–730) from the blue garment and 133±50 (range=48–214) from the pink garment. The difference between the initial transfer values for blue and pink garments was significant at the 5% level using standard t-testing.

As the same type of contact was used in both sets of experiments, these results can be attributed to the fact that the wool garment transferred its constituent fibres less easily than the cotton/ polyester garment. There was also variation within transfer experiments using the same garment by gender, with apparently fewer blue fibres being transferred to women. The difference in the number of pink fibres transferred to men and women was however, not significant at the 5% level.

It is likely that the number of fibres transferred was mainly dependent on two variables; the arm surface area and the density of arm hair (the number of initially transferred fibres was consistently higher for hirsute subjects). The standard deviations are high for both garments, which is likely to occur as a result of several factors;

- Variations in persistence are due to individual differences in skin surface texture (with more hirsute subjects being more retentive)
- Variation in subject activity following the initial fibre transfer.
- The inherent variability of initial primary transfer (influenced by factors such as variation in force and duration of contact).
- Natural variations in the force applied during contact with the garment.
- The shedding/ transfer potential of garments decreasing with repeated use.

The standard deviations are higher at the earlier time intervals because they reflect the larger experimental error when the rate of fibre loss is greatest. When the rate of fibre loss is high, small timing errors are magnified.

The overall shape of the decay curves shown in *Figure 5.3,* appear exponential after an initial rapid loss. The difference in persistence between male and female subjects was not significant

at the 5% level for either garment. After 5 h approximately 15% of the blue cotton and polyester fibres remained. The rate of loss of the pink wool fibres was higher however, with only 5% of fibres remaining after 5 h. The difference in rate of loss between blue and pink garments was significant at the 5% level.

In previous fibre persistence studies, no difference between the persistence of wool and other fibre types was reported by *Pounds and Smalldon, (1975a), Robertson, Kidd et al., (1982), Ashcroft, Evans et al., (1988) and Salter and Cook, (1996)*, however, the greater persistence of cotton fibres over wool fibres is not in agreement with results obtained for human head hair *Palmer and Banks, (2005)*. It has been suggested that woollen fibres might persist in human hair for longer than other fibre types, because of hair-to-hair interactions between both rough scaled surfaces (*Palmer and Banks, (2005)*, *Ashcroft, Evans et al., (1988)*). This however, does not appear to be the case for human skin and may be related to the difference in hair morphology, density and surface area from head hair.

Overall, these persistence results appear similar in nature to those reported for non-smooth garments *(Pounds and Smalldon, 1975a)* and therefore the treatment of skin as a non-retentive substrate is likely to be over-simplistic. Human skin also appears to differ from human hair, which retains fibres for longer than garments *(Salter and Cook, 1996)*.

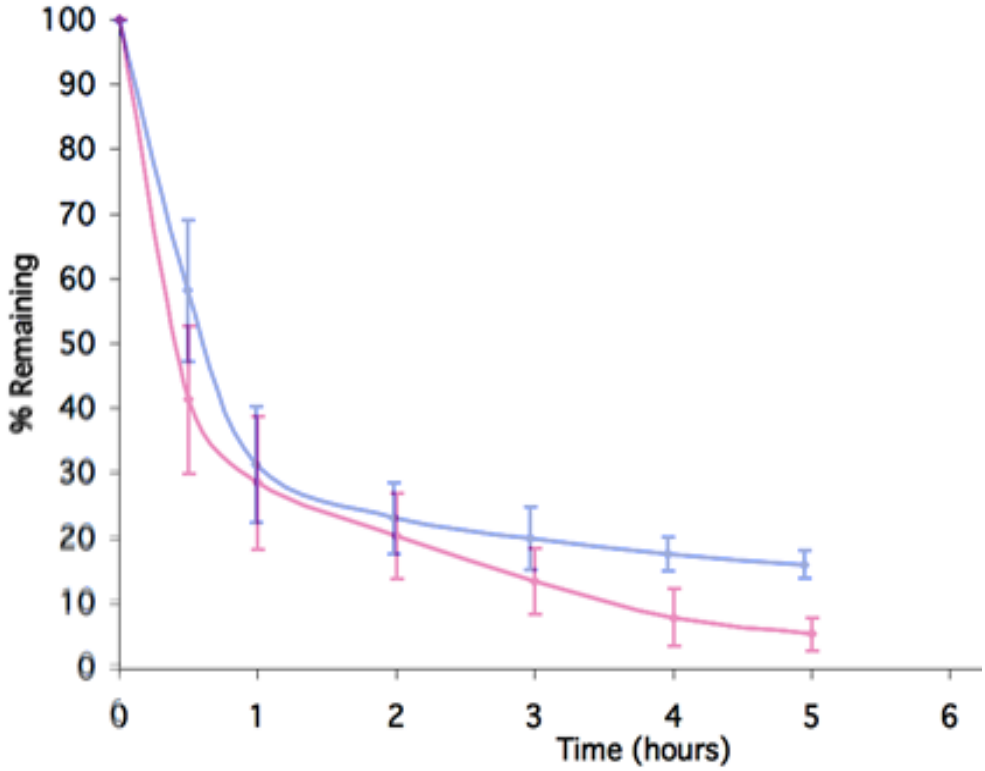


Figure 5.3: The persistence curves of wool (shown in pink) and polyester and cotton (shown in blue) on skin.

Fibre Persistence (24 hours)

After 24 hours during which time the subjects had showered or bathed, no target fibres were found on their skin. It is unknown to what extent bathing / showering influences the fibre loss (i.e. does the act of showering or bathing completely remove all fibres, or reduce the persisting numbers so that any remaining are lost through subsequent activity).

The results therefore show that where significant numbers of fibres are found on the naked body of a homicide victim, this would be incongruous with any assertion that contact took place with the source item over 24 hours earlier—particularly if the victim was known to have bathed or showered within that time period.

Fibre populations

The fibre tapings used to remove extraneous fibres from the subjects' arms prior to target fibre transfer, were used to provide a representative-sample of fibres which were classified according to both colour and generic class combination (*Figure 5.4*). Cotton occurred most

frequently in the observed population with the two most prevalent colour combinations being black/grey cotton and blue which accounted for over half of this fibre type (56%).

The fibre population studies of head hair *(Palmer and Oliver, 2004)*, cinema seats *(Cantrell, Roux et al., 2001)*, car seats *(Roux and Margot, 1997b)* and white t-shirts *(Massonnet, Schiesser et al., 1998)* support the finding that black/grey cotton is the most popular colour/ class combination followed by blue cotton. However, this study does not agree with a population study of Polish bus seats which found both blue cotton and green cotton to be more frequent than black/grey cotton *(Was-Gubala, 2001)*. The third most common grouping in this study was black/ grey polyester, a position not supported by previous studies which have reported either red cotton *(Palmer and Oliver, 2004)* or black/grey wool *(Roux and Margot, 1997b)* in this position. The next most common fibre class/colour combinations were blue wool (6%) and red cotton (5%) followed by green cotton, blue polyester and brown cotton (4%), brown polyester (3%) and black wool (2%). The remaining 16 groups had populations of 1% or smaller and in total accounted for less than 10% of the population.

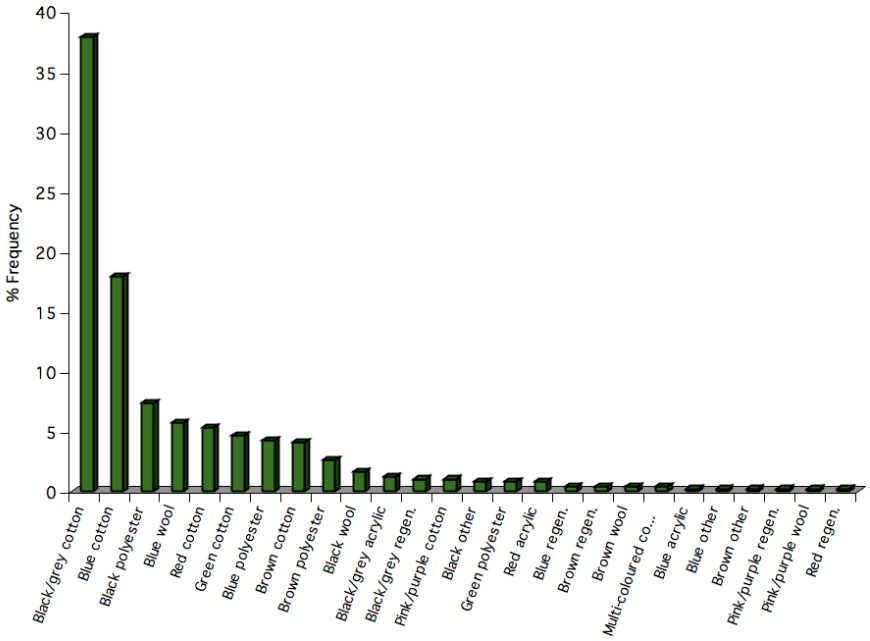


Figure 5.4: Relative frequencies of fibre type/ colour combinations on the skin of living subjects

The results of the fibre population aspect of this study were generally in accordance with those previously published for other substrates and can be used to complement the transfer and persistence data in evaluating the significance of fibres recovered from bare skin found to match a questioned item.

5.4 The persistence of fibres on skin deposited outdoors.

The study of *Palmer and Polwarth, (2011)* sought to directly address the issue of the transfer and persistence characteristics of fibres on the skin of a cadaver deposited outdoors.

The only other study relevant to this issue was that by using small sections of pig skin seeded with fibres *(Krauss and Hildebrand, 1996)*. The results of this work suggested fibre loss from skin exposed to wind was minimal and linear in nature and that rainfall was the most important factor in the persistence of fibres on skin in open air conditions.

The findings of this study relating to the nature of the persistence seemed counter intuitive and it was felt that the experimental design employing seeded fibres onto a 2 dimensional skin surface may be responsible for the findings.

In order to test the conclusions of the *Krauss and Hildebrand, (1996)* study, the *Palmer and Polwarth, (2011)* study employed the use of pig carcasses as a more realistic human simulant which were subjected to a fibre contact- transfer scenario.

Transfer and persistence

Transfer to pig carcass ‘A’ was carried out by the assailant wearing a woollen garment dyed with a fluorescent dye (to aid subsequent counting of transferred fibres) over a white paper ‘scene suit’. The ‘assailant’ then carried the pig carcass over his shoulder for a period of two minutes before depositing the carcass on a grassed area. This process was repeated for carcass ’B’ using a fluorescently dyed acrylic garment as the primary transfer source.

The number of transferred fibres recorded immediately post contact (T^0) was 619 for wool and 374 for acrylic. By day 10, the number of fibres remaining was 5 for wool and 3 for acrylic (each representing a 99.2% loss) which in each case, persisted until day 12.

On day one of the experiment, the reduction in the numbers of wool fibres and acrylic fibres was from 47% to 67% respectively. By day two the loss was 67% of the wool fibres and 74% of acrylic fibres.

By day five, the loss had increased to 93% for wool fibres and 96% for acrylic fibres. In each case, after day 5 there followed a more gradual loss until day 10, when no further loss was observed (see *Figure 5.5)*.

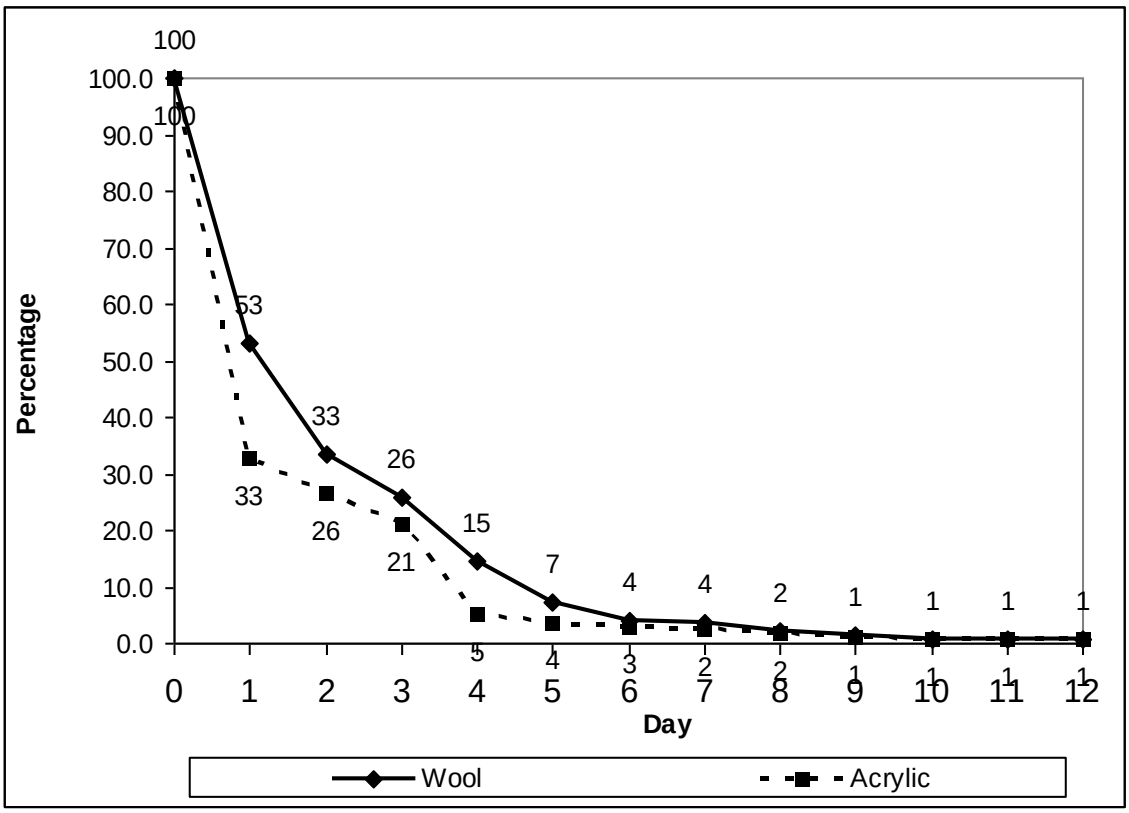


Figure 5.5: The persistence of wool and acrylic fibres on carcasses deposited outdoors

The high initial loss of fibres on day one of the experiment occurred in the absence of any precipitation and an average wind speed of 0.7 ms−1 with a maximum of 8.1 ms−1 (see *Figures 5.6 and 5.7*).

This loss is likely to be of the more loosely adhering fibres and is not in accordance with the results of *Krauss and Hildebrand, (1996)*. A smaller reduction in the number of fibres was observed for days two and three. No precipitation was observed on either of these days and

average wind speeds varied between 0.2 and 0.4 ms−1 with a maximum wind speed of 4.4 ms−1.

Day four saw 10.3 mm of rain fall (3.6 mm in 1 h), associated with average wind speeds similar to previous days, which resulted in a large decrease in the number of fibres (more marked for acrylic fibres) suggesting that rain may contribute to fibre loss to a greater extent than wind (*Figure 5.7*).

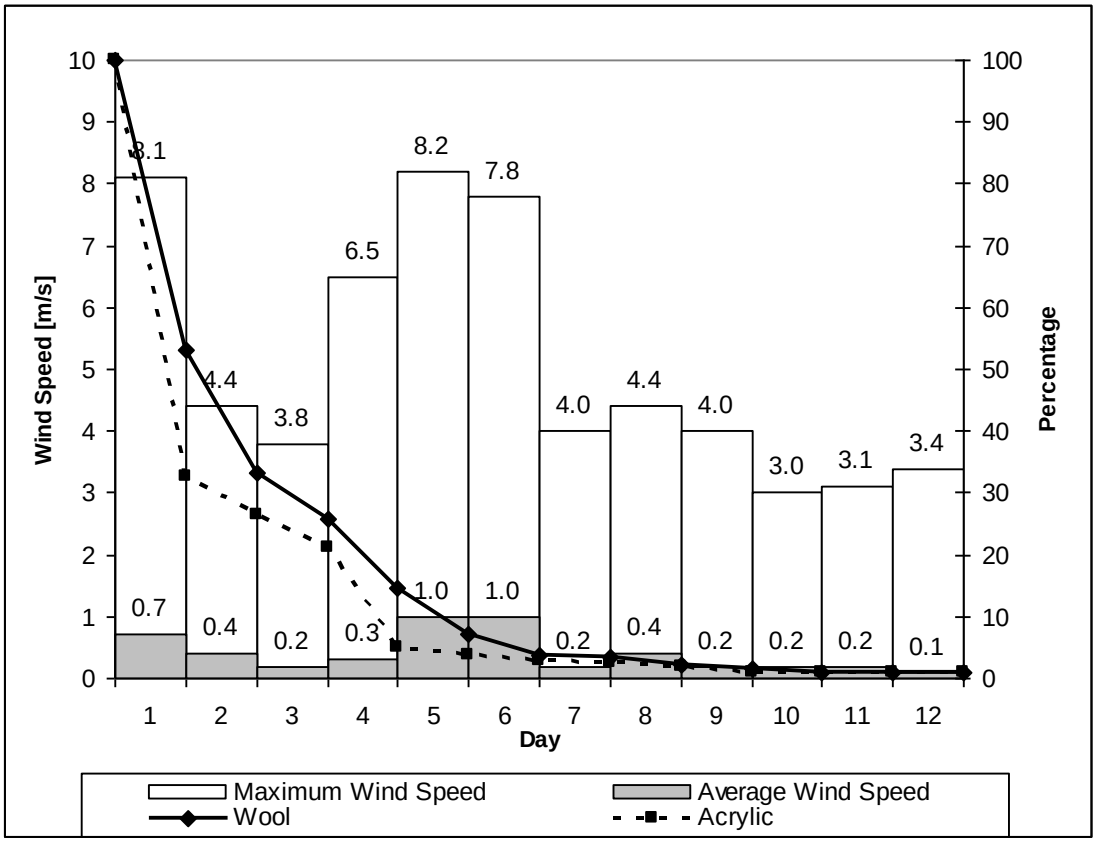


Figure 5.6: The effect of wind on the persistence of fibres transferred to carcasses

This finding is in accordance with *Krauss and Hildebrand, (1996)* and also supports that of the study of fibre persistence on living subjects *(Palmer and Burch, 2009)* where washing/ bathing was postulated as the major factor in the loss of transferred fibres after 24 hours. Higher average wind speeds on days five and six with no rainfall associated did not result in significant fibre loss.

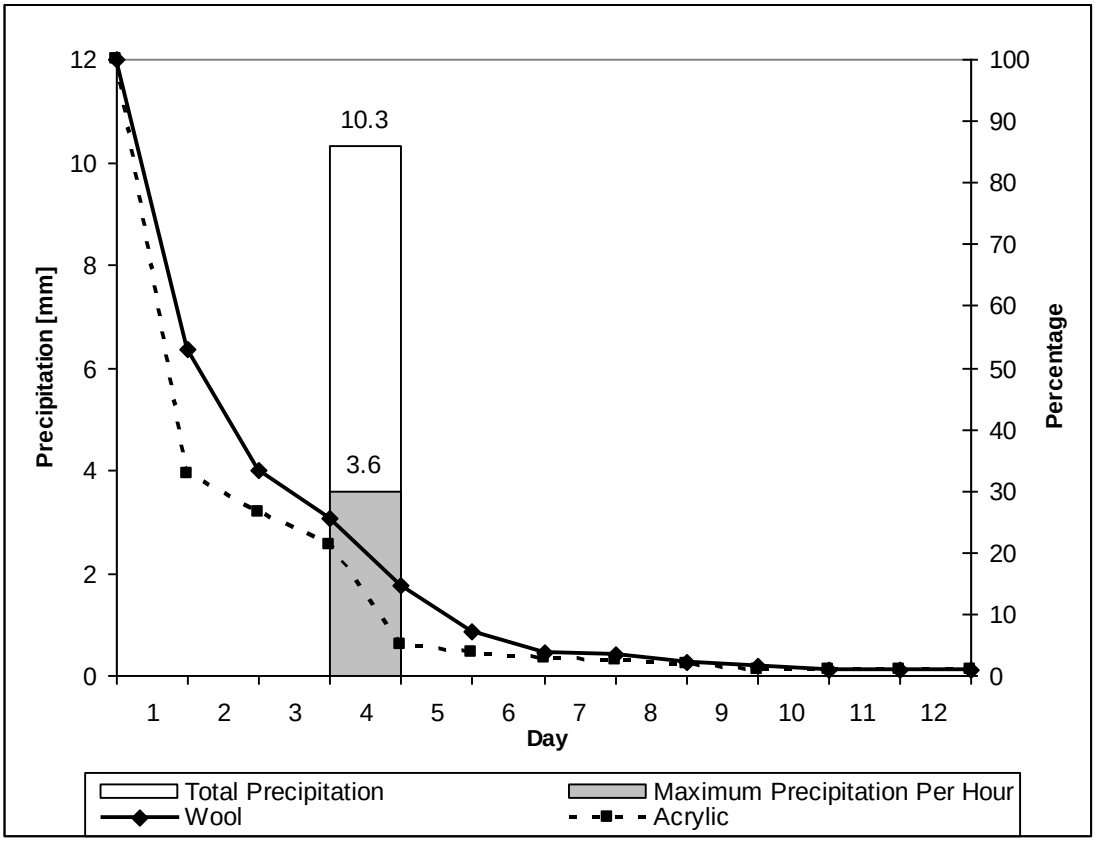


Figure 5.7: The effect of rain on the persistence of fibres transferred to carcasses

A gradual loss of fibres was observed for the remainder of the experiment where low average and maximum wind speeds were noted. It was of note that the longer wool fibres appeared to persist for a greater amount of time on the more hirsute areas of the carcass half. This was less obvious for the shorter acrylic fibres.

This observation is in keeping with that made during the study into the secondary transfer of fibres to pillowcases *(Palmer and Banks, 2005)* that wool tended to have a greater persistence in hair than other fibre types and proposed that this was due to scale to scale interactions.

The initial high loss of both fibre types is consistent with the results of a number of previous fibre persistence studies on a variety of surfaces, e.g.; garments *(Pounds and Smalldon, 1975a)*, head hair *(Salter and Cook, 1996)*, hands and gloves *(Marshall, 2005)* and on the skin of living subjects *(Palmer and Burch, 2009)*.

Whilst these previous persistence studies demonstrated an exponential loss of fibres from moving recipient surfaces, a similar exponential loss was observed in this study using the static pig skin recipient, however, the rate of loss was much lower. An exponential fibre loss, demonstrating a greater degree of fibre persistence over time, punctuated by larger losses dictated by the weather conditions, appears to be achieved by the static pig skin compared to garments which have been subjected to significant post contact activity.

The results of this study are not in accordance with the rate of fibre loss reported by *Krauss and Hildebrand, (1996)* who noted only a small reduction of 10–28% of the fibres (depending on generic fibre type over the first 10 days where no rain was measured and winds were of average speed (from 3.1 to 6.7 ms−1)). This loss appeared to be linear rather than exponential in nature. Little fibre loss was observed on the eleventh day where precipitation amounted to 2 mm, however, on the twelfth day alone where precipitation was 9 mm, a 58–70% loss of fibres was observed. The results of the *Palmer and Polwarth, (2011)* study agree with that of *Krauss and Hildebrand, (1996)* that useful fibre evidence can be retrieved from a body which has been deposited in an outdoor environment for a number of days.

The discrepancy is most likely due to the different experimental designs; the present study used more realistic human stimulant surface (involving a larger and more 3 dimensional surface area) with a more realistic contact situation, rather than small recipient two-dimensional surfaces which were then seeded with fibres.

This point appears to be supported if we consider the persistence of the largest fibre collective recovered (blue polyester microfibers) common to the three land based depositions which matched the constituent fibres of tracksuit bottoms belonging to the suspect.

Table 5.1 shows the number of blue polyester microfibers recovered from the victims and the time since deposition.

	No of blue polyester microfibres	**Time since Deposition (days)**

	Recovered	
Paula Clennel	36	2
Annette Nichols	26	4
Anneli Alderton	11	7

Table 5.1 Number of microfbres recovered against time of deposition

It is likely that the relatively large numbers of these fibres persisting on the victims' skin in adverse conditions is due to their high degree of sheddability and transfer potential from donor garments *(Kolar, 1994, Clayson and Wiggins, 1997, Quattrini, 1997)* – the more initially transferred, the more likely to persist over time. In the case under consideration, over 1000 of these blue polyester microfibres, matching the constituent fibres of the suspect's microfibre tracksuit bottoms, were found on the driver's seat of his car, which support the expectations of transfer informed by the literature.

It can be seen that despite significant rainfall, there would appear to be a gradual loss in the number of fibres persisting over time, rather than dramatic losses associated with rainfall demonstrated in the *Krauss and Hildebrand, (1996)* dataset.

Whilst only two fibre types were considered in the *Palmer and Polwarth, (2011)* study, the congruence of results obtained, in terms of rate and nature of fibre loss, are in keeping with other persistence studies *(Pounds and Smalldon, 1975a, Robertson, Kidd et al., 1982, Salter and Cook, 1996)*. This suggests that while other fibre types may differ in terms of numbers persisting in such a scenario, they are likely to demonstrate the same characteristics in terms of the persistence dynamics.

It is therefore fair and reasonable to assume that in general, a large proportion of fibres transferred to a naked body deposited outdoors can be expected to be lost in the first 2 days of deposition. Therefore, where an estimate of a time of outdoor deposition of a body can be made (e.g. via pathological and entomological data) any significant fibre collectives recovered from such a body after 2 days from deposition, are very likely to represent only a proportion of those originally transferred – indicating a primary transfer from the donor source.

The results of these two studies relating to the transfer and persistence of fibres on the skin of living subjects *(Palmer and Burch, 2009)* and on cadavers deposited outdoors *(Palmer and Polwarth, 2011)* contribute to our understanding in that;

- The greatest rate of loss of fibres from the skin of living subjects occurs in the first 2 hours, the persistence dynamics being similar to a textile garment.
- Fibres transferred to the bare skin of a living subject would not be expected to persist after 24 hours, where the subject had bathed or showered
- The population of fibres on skin appears to be congruent with other studies in that synthetic fibres are present in low frequency.
- The majority of transferred fibres on a body deposited outdoors are lost in the first 2 days – irrespective of rain.
- The presence of fibre collectives after 2 days (especially synthetic fibres) is significant and likely to represent remnants of a primary contact with a donor source around the time of body deposition.
- The general belief that skin can be regarded as a non-retentive surface is an over simplification, in that when it is dry, it appears to behave as a textile garment, but becomes much less retentive when wet.

5.5 The Bayesian network model of the case relevant factors

In order to assess the impact/ contribution of the author's data set relating to fibre persistence on skin on the pre-assessment of the case scenario in question, as well as the effect on the weight of evidence of the examination outcomes, a Bayesian network (BN) has been constructed (see *Figure 5.8*) using a single block architecture described in *Chapter 4*. Since building a BN to encompass all of the relevant collectives and victims in this case would be extremely complicated, with little or no benefit conferred in comparing outcomes using the two transfer and persistence datasets, this network has been constructed to model the findings relating to a single victim, involving the largest collective (blue polyester microfibers) common

to all of the victims and the suspect. This allows a direct comparison of the impact of the dataset from either *Palmer and Polwarth, (2011)* or *Krauss and Hildebrand, (1996).*

As stated previously, one of the salient circumstances of this case was that the provenance of the source of the recovered fibre collectives was not in dispute, but the question of when the transfer of these fibres took place was - a similar situation to that cited by *Bennett, Roux et al., (2010)*. Consequently and as discussed in *Chapter 4,* the consideration of the presence of non- matching foreign fibres groups (FFG's) and their influence on the probability of adventitious fibre matches becomes irrelevant (in addition, it is likely that the majority of FFG's on the victims are related to their own clothing or other textile items in the environment). The block structure relating to FFG's has therefore not been applied to the architecture of this particular BN case model.

The fibres were transferred by the accused at the time of deposition of the victim (Hp) as opposed to the fibres were transferred by the accused two days before the victim went missing (Hd).

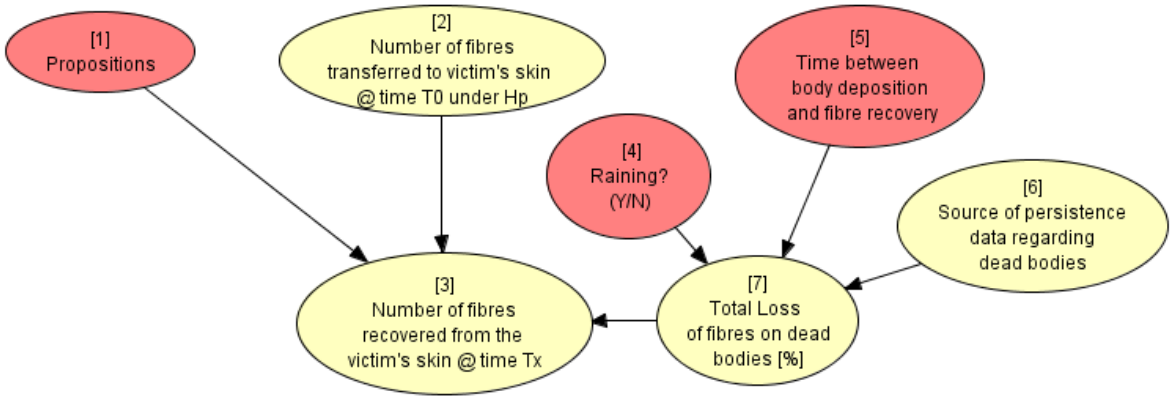


Figure 5.8 Structure of Bayesian network model the case circumstances

Table 5.2 summarises the node functions used in this architecture.

In this architecture, it should be noted that there is no conditioning between nodes 1 and 2. This is because the MLE's used in node 2 (shown in *Table 5.6*.) relate to the expectation of the number of fibres present on the victim at the time of deposition – if Hp is true. This is

crucial in that they condition directly upon node [3] (the number of fibres persisting after a given time interval). Under Hd, the number of fibres expected on the victim's body is very low and does not depends on the specific circumstances (timing, weather) used to model the loss of fibres under Hp. If transfer of fibres were back to 2 days before the deposition (as alleged), we expect the number of fibres recovered (instantiated in node [3]) to be very low: zero fibre with a probability of 0.99994, the rest of probabilities being evenly distributed on the other quantities (t>0).

Nodes	States	Definition of states
1	Hp Hd	The suspect was in contact with the victim at time of deposition The suspect had contact with the victim two days before their death.
2	t=0 t1-10 t11-20 t21-30 t31-40 t41-50 t51-100	States define the expectation of the number of fibres transferred from suspect to victim at the time of deposition (given the nature of the alleged activities and the shedding properties of the item in question) under Hp.
3	t=0 t1-10 t11-20 t21-30 t31-40 t41-50 t51-100	These states relate to the probability of finding a given number of matching fibres taking into account the number of total expected transferred fibres at deposition (i.e. conditioned by node [7] but only under Hp) and the number of fibres expected under Hd.
4	Raining or Not Raining	This node alters the conditioning of Node[3] by Node[7], since the persistence data according to Krauss and Hildebrand, (1996)is very different for wet or dry condition.
5	Time of Recovery 1 day after deposition 2 days after deposition 4 days after deposition 7 days after deposition	These states relate to the time of fibre recovery relative to the time of deposition. This conditions upon node [7] (the expected total loss of fibres)
6	Palmer and Polwarth (2011) Krauss and Hildebrand (1996)	Allows switching between the data set of the two different studies investigating the persistence of fibres in an outdoor deposition scenario. This conditions upon node [7] (the expected rate of loss of fibres)
7	0-25% 25-35% 35-45% 45-55% 55-65% 65-75% 85-95% >95%	These states relate to the probability of a particular discrete range of fibre loss over the observed time period. This is conditioned by Nodes [4], [5] and [6].

Table 5.2: Node states and definitions used within the Bayesian network model

Palmer and Powarth (2011) n=2				
Day	**. Range**	**Fibres Remaining (Mean)**	**% Fibre Loss (Mean)**	**Estimated Variance (Max-Min)/100**
1	10	43	57	0.2
2	7	30	70	0.07
3	5	24	76	0.05
4	11	10	90	0.11
5	3	6	94	0.03
6	1	4	96	0.01
7	2	3	97	0.02
8	0	2	98	0
9	0	1	99	0
10	0	1	99	0
11	0	1	99	0
12	0	1	99	0
Krauss and Hidebrand (1996) n=3				
Day	**Range**	**Fibres Remaining (Mean)**	**% Fibre Loss (Mean)**	**Estimated Variance (Dist Density)**
1	0	50	0	0.013
2	1	49	0	0.013
3	1	49	1	0.013
4	1	49	1	0.013
5	1	49	1	0.013
6	1	49	1	0.013
7	2	49	2	0.040
8	2	49	2	0.040
9	3	47	5	0.093
10	2	47	5	0.053
11	0	45	10	0.053
12	11	10	80	1.480
13	10	8	84	1.480
14	8	5	90	0.76

Table 5.3 :Fibre persistence data obtained from pig carcasses (Palmer and Polwarth, 2011) and sections of pig skin (Krauss and Hildebrand, 1996)

Data from the studies of *Krauss and Hildebrand, (1996)* and *Palmer and Polwarth (2011)* are used to inform the conditional probability tables for nodes [4], [6] and [7]. The transfer and persistence data from the *Palmer and Polwarth, (2011) and Krauss and Hildebrand, (1996)* studies are summarised in *Table 5.3*.

Given that in the Ipswich serial killings all of the victims deposited in land were subjected to sustained rainfall during and after their deposition, this has been factored in when populating the conditional transfer tables for the relevant nodes, as have the actual timescales of fibre recovery.

The respective mean values and variance estimations have been used to calculate a distribution of probabilities for the range of losses over the time periods defined in each study, using an R script in collaboration with *Champod, (2015).* This is shown in Appendix 2 of this thesis.

The calculated probability distributions have subsequently been used as maximum likelihood estimates (MLE) for the expected loss of fibres from the bodies of the victims during their deposition (node [7]) and are shown in *Tables 5.4* and *5.5*.

Given that over the twelve days of the *Palmer and Polwarth, (2011)* experiment there was only one day of significant rainfall, the persistence of the fibres may have been greater than would be expected if persistent periods of rainfall were encountered. The highlighted rows refer to the timescales encountered in the Ipswich serial killings.

Data from the *Krauss and Hildebrand, (1996)* study showed a very ‘flat’ persistence until rainfall was encountered, which resulted in an 80-90% loss of fibres followed by another period of ‘flat’ persistence. This is shown in *Figure 5.9* which relates to polyester fibres.

	Krauss and Hildebrand (1996)					Palmer and Polwarth (2011)				
% Loss	**T^0**	**Day 1**	**Day 2**	**Day 4**	**Day 7**	**T^0**	**Day 1**	**Day 2**	**Day 4**	**Day 7**
0-25	0.999	1.223E-4	0.002	1.3E-6	1.3E-6	0.999	0.376	0.082	0.043	0.017
25-35	1.098E-4	0.001	0.001	3.88E-5	3.88E-5	1.098E-4	0.022	0.054	0.014	0.003
35-45	1.2E-5	0.008	0.00623	4.586E-4	4.586E-4	1.2E-5	0.019	0.064	0.015	0.003
45-55	9.0E-7	0.030	0.020	0.003	0.003	9.0E-7	0.019	0.075	0.017	0.003
55-65	0.0	0.083	0.055	0.014	0.014	0.0	0.020	0.089	0.020	0.004
65-75	0.0	0.178	0.123	0.052	0.052	0.0	0.022	0.106	0.025	0.005
75-85	0.0	0.296	0.235	0.159	0.159	0.0	0.029	0.132	0.036	0.0077
85-95	0.0	0.329	0.371	0.415	0.415	0.0	0.053	0.187	0.071	0.014
>95	0.0	0.073	0.185	0.355	0.355	0.0	0.435	0.207	0.753	0.938

Table 5.4: Maximum likelihood estimates for fibre loss during deposition (Raining on Day 1)

	Krauss and Hildebrand (1996)					Palmer and Polwarth (2011)				
% Loss	**T^0**	**Day 1**	**Day 2**	**Day 4**	**Day7**	**T^0**	**Day 1**	**Day 2**	**Day 4**	**Day7**
0-25	0.999	0.999	0.994	0.994	0.999	0.999	0.376	0.082	0.0437	0.017
25-35	1.098E-4	1.098E-4	0.003	0.003	1.2E-6	1.098E-4	0.022	0.054	0.014	0.003
35-45	1.2E-5	1.2E-5	0.001	0.001	0.0	1.2E-5	0.019	0.064	0.015	0.003
45-55	9.0E-7	9.0E-7	6.447E-4	6.447E-4	0.0	9.0E-7	0.019	0.075	0.017	0.003
55-65	0.0	0.0	2.634E-4	2.634E-4	0.0	0.0	0.020	0.089	0.020	0.004
65-75	0.0	0.0	8.73E-5	8.73E-5	0.0	0.0	0.022	0.106	0.025	0.005
75-85	0.0	0.0	2.05E-4	2.05E-4	0.0	0.0	0.029	0.132	0.036	0.007
85-95	0.0	0.0	0.0	0.0	0.0	0.0	0.053	0.187	0.071	0.014
>95	0.0	0.0	0.0	0.0	0.0	0.0	0.435	0.207	0.753	0.938

Table 5.5: Maximum likelihood estimates for fibre loss during deposition (Not Raining)

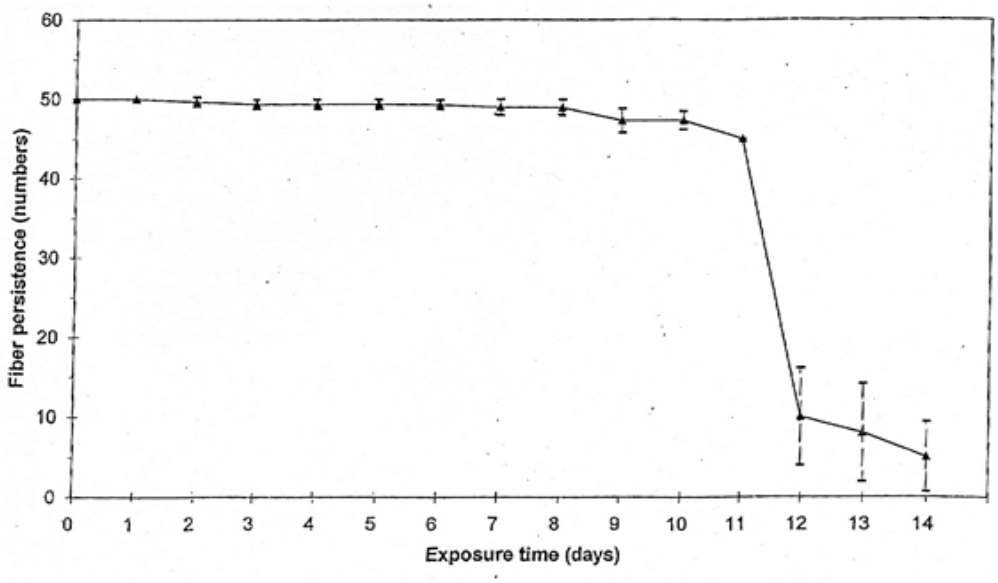


Figure 5.9: Mean number of polyester fibres seeded on pig skin sections persisting over time (*Krauss and Hildebrand, 1996).* The effect of rainfall on day 11 can be seen.

Node [6] allows each study's data set to be used in node [4] for subsequent conditioning of node [7].

The MLE's have been provided for scenarios involving wet and dry conditions, as (discussed later in the chapter) this has implications for each dataset. *Figures 5.10 and 5.11,* show representations of the persistence characteristics of both studies under wet and dry conditions respectively. In the Ipswich serial killings, rain was encountered throughout the recovery periods, hence persistence data relating to days 12-14 from the *Krauss and Hildebrand, (1996)* study for day 1 of the BN model (*Figure 5.11*).

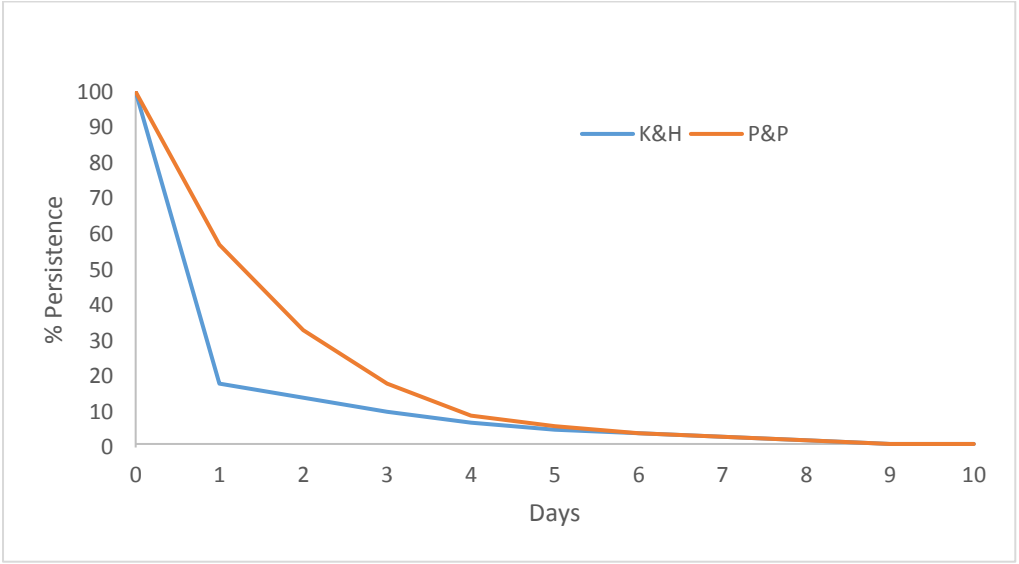


Figure 5.10: comparison of persistence characteristics of *Krauss and Hildebrand (1996)* and *Palmer and Polwarth (2011)* data applied to Ipswich serial killings circumstances (i.e. raining)

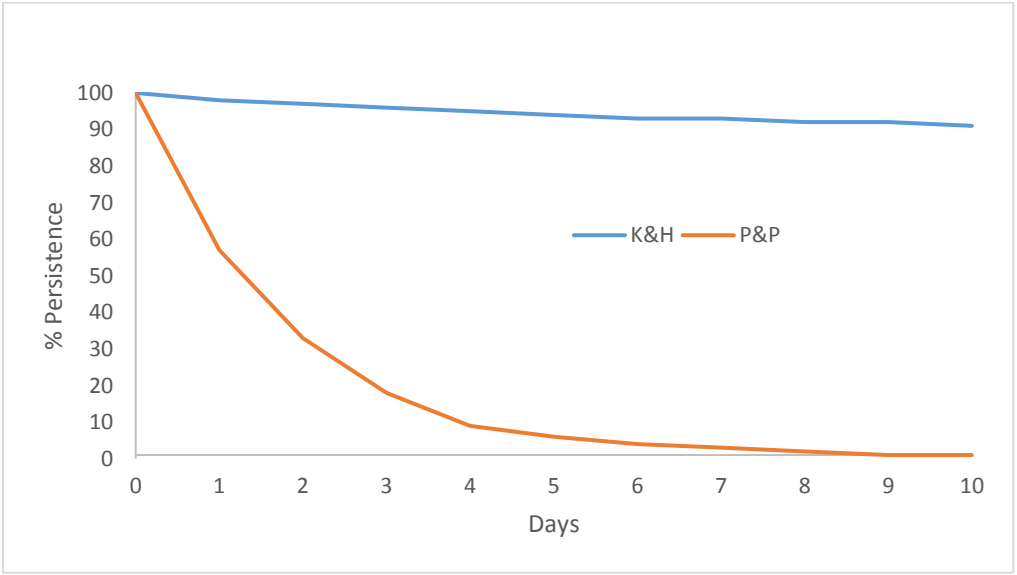


Figure 5.11: comparison of persistence characteristics of *Krauss and Hildebrand (1996)* and *Palmer and Polwarth (2011)* data applied to a deposition scenario with dry conditions.

When a deposition scenario involving dry conditions is considered however, days 1-11 from the *Krauss and Hildebrand, (1996)* are applied for the whole period (*Figure 5.12*) within the BN model.

Since rain was not found to be the main factor governing fibre persistence in the *Palmer and Polwarth, (2011)* study, the same data is applied in both the 'wet' and 'dry' scenarios. This is discussed further in *section 5.7*.

The largest size of the fibre collective common to the three victims and the suspect was that of blue polyester microfibers. As previously discussed, garments composed of this fibre type are well known to shed copiously and consequently it is likely that higher numbers of these would be encountered at the key time frames compared to the fibre types used in the two studies *(Kolar, 1994, Clayson and Wiggins, 1997, Quattrini, 1997)*. Where the *Figure 5.12* shows the number of fibres found on each women against the persistent curve of *Palmer and Polwarth (2011).*

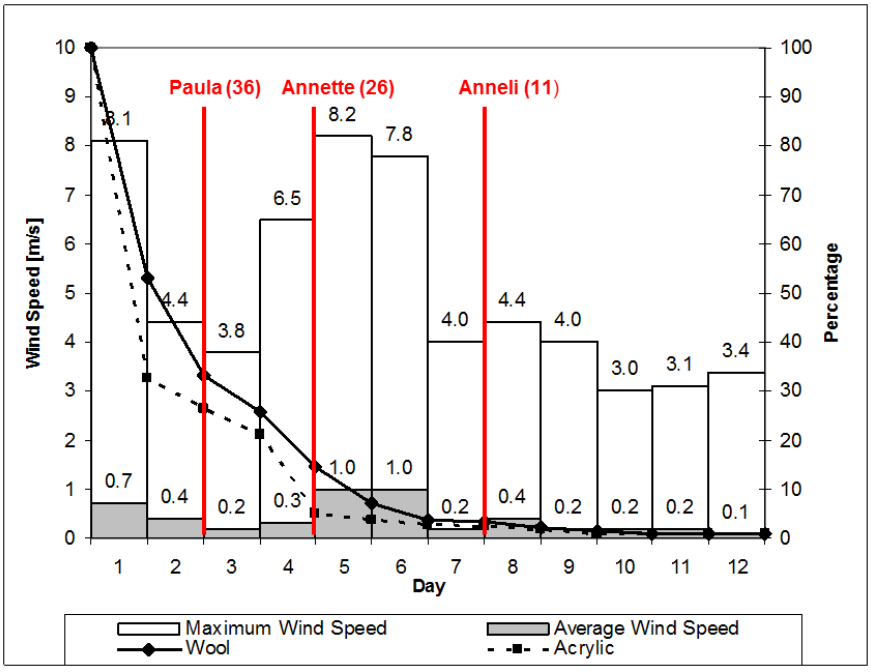


Figure 5.12: Numbers of blue polyester microfibres recovered for each of the three victims against the relevant percentage loss from the *Palmer and Polwarth (2011)* study.

By using the percentage loss observed at the relevant timescale it therefore appears possible to provide an estimate of the number of fibres transferred at the time of deposition (T^0). Using the *Palmer and Polwarth (2011)* data*,* the following estimates are obtained;

Anneli Alderton (11/3 x 100) = 360 fibres (T^0)

Annette Nichols (26/10 x 100) = 260 fibres (T^0)

Paula Clennel (36/30 x 100) = 120 fibres (T^0)

It must be emphasised that these figures are estimates and assume that; the nature and duration of contact between the suspect and the victims was similar and that the efficiency of recovery by each person taping the bodies was identical. In addition, it should be noted that all of the bodies were wet and therefore the use of tape lifts in such circumstances does not result in optimum recovery efficiency. As cited by *Lowrie and Jackson, (1991)*, the effectiveness of a given method of fibre recovery in particular case circumstances, must be taken into account when interpreting the significance of the number of fibres found.

Nevertheless, bearing in mind the shedding characteristics of microfibres, these estimates do not in the experience of the author, appear unreasonable.

This data, and that *of Krauss and Hildebrand, (1996)* are therefore used in the BN to compare the ability of each dataset to 'back calculate' probability estimates for the number of fibres transferred at the time of deposition, based upon observed outcomes at a particular time since deposition interval. The difference between the assigned probabilities obtained from each dataset, are then assessed.

Given the limitations of the quoted results, fair and reasonable estimates based on T^0 data from *Palmer and Polwarth, (2011)* are used to inform the conditional probability table (CPT) for the initial transfer parameters under Hp for node [2] *for microfibres.* These are shown in *Table 5.6.*

Where target fibres other than *microfibers* are encountered, simple 'garment sheddability tests' such as those described by *Coxon, Grieve et al., (1992)* and *De Wael, Lepot et al., (2010)* can be employed to inform the CPT probability table.

No. Fibres	Hp

t=0	0.005
t1-10	0.05
t11-21	0.05
t21-30	0.1
t31-40	0.1
t41-50	0.2
t51-100	0.495

Table 5.6: Assignments for the conditional probability table of Node 2 concerning the expectations of the number of fibres deposited at (T^0) under Hp.

The MLE's used in node 2 are crucial in that they condition directly upon node [3] (the number of fibres persisting after a given time interval), to 'drive' the calculation of likelihood ratio of the BN. Changes to the MLE's of node [2] will therefore hugely influence the evaluation of the evidence. The robustness of the data used to inform the MLE's is therefore extremely important and this will be discussed further in Chapter 7.

5.6 Results

The Bayesian network (BN) can be used in either 'pre-assessment' or 'evaluative' mode. The former allows a 'prediction' of observed outcomes according to particular casework scenarios given Hp or Hd, the latter evaluating the significance of a particular observed outcome in terms of a likelihood ratio, to inform our prior belief on Hp and Hd.

Figure 5.13 shows the BN in pre-assessment mode, where Hp is considered to be true, the *Palmer and Polwarth,* (2011) dataset is considered, the victim (Paula Clennel) has been subjected to rainfall during deposition and fibre recovery has taken place 2 days after deposition. It can be seen that the BN has calculated that the most likely observation given these conditions is that 1-10 matching fibres would be recovered, with the next most likely observation being 11-20 fibres.

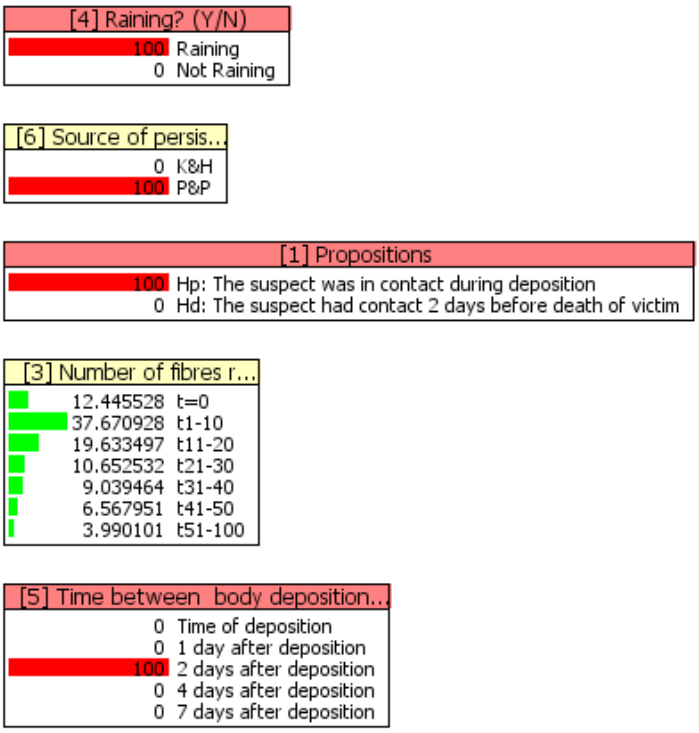


Figure 5.13: Output of BN in pre-assessment mode.

Likewise *Figure 5.14* shows the BN in evaluative mode. Again, the *Palmer and Polwarth, (2011)* dataset is considered, the victim has been subjected to rainfall during deposition, and fibre recovery has taken place 2 days after deposition. This time a given observation (36 recovered matching fibres) is defined in node [3] and the likelihood ratio is calculated. In this example, the time of fibre recovery and the number of microfibres found on Paula Clennel has been used. It can be seen in *Figure 5.14* that this observation is actually the fifth likely outcome predicted by the BN in pre-assessment mode.

Taking the predicted outcomes produced by the BN in assessment mode, allows us to subsequently use these in evaluative mode in order to produce likelihood ratios for different case circumstances and compare those produced by each data set. The same exercise is also carried out using the actual data from the case in question. The results of this are shown in *Table 5.7*. (*N.B. The probability values in this and subsequent tables in this section, are expressed between 0 and 100. This is to simplify the calculations from the BN output*.)

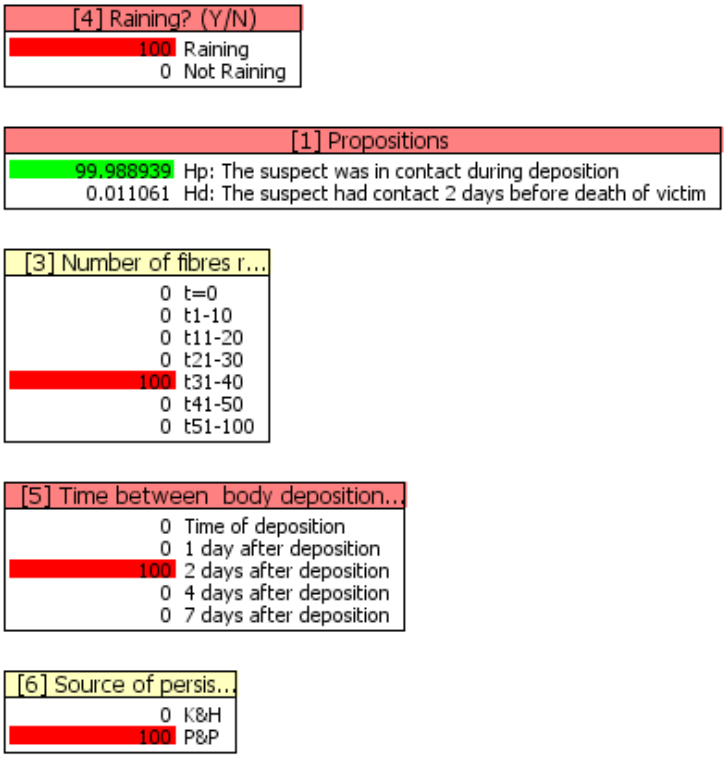


Figure 5.14: Output of BN in evaluative mode

When the actual data relating to the victims is used the *Krauss and Hildebrand (1996)* data evaluates the findings for Anneli Alderton (11 fibres at day 7) in wet conditions, as '*very strong'* support for Hp. The *Palmer and Polwarth, (2011)* data evaluates the same outcome as '*strong*' support for Hp *(Association of Forensic Science Providers, 2009)*. It can be seen that when the *Krauss and Hildebrand, (1996)* data is employed by the BN, larger likelihood ratios are obtained from outcomes involving smaller amounts of fibres found over time, compared to the *Palmer and Polwarth, (2011)* data. The converse is true when the *Palmer and Polwarth, (2011)* data is employed by the BN.

The disparity in evaluation can be accounted for in the experimental design of both studies, which is discussed in more detail later in this chapter.

Raining						
	Deposition Time (Days)	**Actual Fibres Found**	**p(E|Hp)/ p(E|Hd) (K&H)**	**LR (K&H)**	**p(E|Hp)/ p(E|Hd) (P&P)**	**LR (P&P)**
Paula Clennel	2	36	99.968/ 0.031	3178	99.988/ 0.011	9040
Annette Nichols	4	26	99.973/ 0.026	3805	99.965/ 0.034	2890
Anneli Alderton	7	11	99.993/ 0.006	16050	99.920/ 0.079	1262

Not Raining						
	Deposition Time (Days)	**Actual Fibres Found**	**p(E|Hp)/ p(E|Hd) (K&H)**	**LR (K&H)**	**p(E|Hp)/ p(E|Hd) (K&H)**	**LR (P&P)**
Paula Clennel	2	36	99.996/ 0.003	31435	99.988/ 0.011	9040
Annette Nichols	4	26	99.990/ 0.009	10001	99.965/ 0.034	2890
Anneli Alderton	7	11	99.986/ 0.013	7500	99.920/ 0.079	1262

Table 5.7: Likelihood ratios for actual case data and predicted outcomes (raining and not raining).

Day Since Deposition	Outcome Probabilities (K&H)	p(E|Hp)/ p(E|Hd) (K&H)	LR (K&H)	Outcome Probabilities (P&P)	p(E|Hp)/ p(E|Hd) (P&P)	LR (P&P)
2	t0 (12.03)	10.738/ 89.261	0.120	t0 (12.44)	11.068/ 88.931	0.124
	t1-10 (54.15)	99.998/ 0.002	54170	t1-10 (37.67)	99.997/ 0.002	37678
	t11-20 (21.64)	99.995/ 0.004	21644	t11-20 (19.63)	99.994/ 0.005	19634
	t21-30 (7.51)	99.986/ 0.013	7512	t21-30 (10.65)	99.990/ 0.009	10653
	t31-40 (3.17)	99.968/ 0.031	3178	t31-40 (9.03)	99.988/ 0.011	9003
	t41-50 (1.09)	99.909/ 0.091	1099	t41-50 (6.56)	99.984/ 0.015	6568
	t51-100 (0.38)	99.739/ 0.260	382	t51-100 (3.99)	99.974/ 0.025	3990
4	t0 (19.26)	16.151/ 83.848	0.192	t t0 (35.24)	26.161/ 73.838	0.354
	t1-10 (59.54)	99.998/ 0.002	59558	t1-10 (49.48)	99.997/ 0.002	49479
	t11-20 (16.04)	99.993/ 0.006	16050	t11-20 (5.61)	99.982/ 0.017	15048
	t21-30 (3.8)	99.973/ 0.026	3804	t21-30 (2.89)	99.965/ 0.034	2890
	t31-40 (1.08)	99.907/ 0.092	1089	t31-40 (2.95)	99.966/ 0.033	2959
	t41-50 (0.21)	99.545/ 0.454	219	t41-50 (2.24)	99.955/ 0.044	2248
	t51-100 (0.04)	99.771/ 2.228	43	t51-100 (1.37)	99.927/ 0.072	1378
7	t0 (19.26)	16.151/ 83.848	0.192	t t0 (43.16)	30.149/ 69.850	0.461
	t1-10 (59.54)	99.998/ 0.002	59558	t1-10 (52.78)	99.998/ 0.002	52769
	t11-20 (16.04)	99.993/ 0.006	16050	t11-20 (1.26)	99.920/ 0.079	1254
	t21-30 (3.8)	99.973/ 0.026	3804	t21-30 (0.71)	99.860/ 0.139	717
	t31-40 (1.08)	99.907/ 0.092	1089	t31-40 (0.92)	99.891/ 0.108	923
	t41-50 (0.21)	99.545/ 0.454	219	t41-50 (0.72)	99.863/ 0.136	729
	t51-100 (0.04)	99.771/ 2.228	43	t51-100 (0.45)	99.778/ 0.221	450

Table 5.8: BN probabilities for observed outcomes at the time relevant times of deposition using both data sets (raining during this period). The numbers in brackets represent the probability of outcome given by the BN.

Table 5.8 shows that when the BN is employed in 'pre-assessment' mode for wet conditions, larger likelihood ratios are obtained for outcomes involving higher numbers of fibres (21-100 fibres) at day using the *Palmer and Polwarth, (2011)* data, the converse being apparent when the *Krauss and Hildebrand, (1996)* is employed. It can be seen that as the time since deposition increases, the likelihood ratios obtained from the two data sets becomes more congruent.

Whilst the land deposited victims of the Ipswich serial killings had all been subjected to significant rainfall after their deposition, it is important to consider a situation where the weather conditions are dry and how this impacts upon each of the two data sets.

Whilst the *Krauss and Hildebrand, (1996)* data predicts an immediate and dramatic loss of fibres in the presence of rainfall, it can be seen (in *Figure 5.11)* that in its absence, the persistence of fibres is somewhat 'flat', undergoing a very small and gradual loss over time.

Table 5.9 shows the results of this exercise for a scenario where the weather conditions are dry during and after deposition.

As might be expected, the situation is opposite to that observed when rain is present. In dry conditions, the *Krauss and Hildebrand, (1996)* data predicts a high number of fibres to be present at all timeframes, with very little difference across the case specific timeframes (days 4 and 7 being identical). In terms of the verbal scale *(Association of Forensic Science*

Providers, 2009), the finding of 21-100 fibres is evaluated as '*very strong*' support for Hp, whilst finding between 1-20 fibres is evaluated as '*strong*' support for Hp.

The evaluation of case findings for both 4 and 7 days recovery using the *Krauss and Hildebrand, (1996)* data produces a likelihood ratio of 16501 in dry conditions for an outcome of 51-100 fibres compared to 43 when rain is encountered (*Table 5.8*). This translates as a drop on the verbal scale from 'very strong' to 'moderate' support for Hp.

Day Since Deposition	Outcome Probabilities (K&H)	p(E|Hp)/ p(E|Hd) (K&H)	LR (K&H)	Outcome Probabilities (P&P)	p(E|Hp)/ p(E|Hd) (P&P)	LR (P&P)
2	t0 (3.00)	2.913/ 97.086	0.030	t0 (12.44)	11.068/ 8.931	0.124
	t1-10 (5.01)	99.980/ 0.019	5017	t1-10 (37.67)	99.997/ 0.002	37678
	t11-20 (7.54)	99.986/ 0.013	7546	t11-20 (19.63)	99.994/ 0.005	19634
	t21-30 (10.05)	99.990/ 0.009	10054	t21-30 (10.65)	99.990/ 0.009	10653
	t31-40 (31.43)	99.996/ 0.003	31436	t31-40 (9.03)	99.988/ 0.011	9003
	t41-50 (26.46)	99.996/ 0.003	26468	t41-50 (6.56)	99.984/ 0.015	6568
	t51-100 (16.48)	99.993/ 0.006	16484	t51-100 (3.99)	99.974/ 0.025	3990

4	t0 (3.00)	2.912/ 97.087	0.030	t t0 (35.24)	26.161/ 73.838	0.354
	t1-10 (5.00)	99.980/ 0.019	5000	t1-10 (49.48)	99.997/ 0.002	49479
	t11-20 (7.50)	99.986/ 0.013	7500	t11-20 (5.61)	99.982/ 0.017	15048
	t21-30 (10.00)	99.990/ 0.009	10001	t21-30 (2.89)	99.965/ 0.034	2890
	t31-40 (31.50)	99.996/ 0.003	31505	t31-40 (2.95)	99.966/ 0.033	2959
	t41-50 (26.50)	99.996/ 0.003	26503	t41-50 (2.24)	99.955/ 0.044	2248
	t51-100 (16.50)	99.993/ 0.006	16501	t51-100 (1.37)	99.927/ 0.072	1378
7	t t0 (3.00)	2.912/ 97.087	0.030	t t0 (43.16)	30.149/ 69.850	0.461
	t1-10 (5.00)	99.980/ 0.019	5000	t1-10 (52.78)	99.998/ 0.001	52769
	t11-20 (7.50)	99.986/ 0.013	7500	t11-20 (1.26)	99.920/ 0.079	1254
	t21-30 (10.00)	99.990/ 0.009	10001	t21-30 (0.71)	99.860/ 0.139	717
	t31-40 (31.50)	99.996/ 0.003	31505	t31-40 (0.92)	99.891/ 0.108	923
	t41-50 (26.50)	99.996/ 0.003	26503	t41-50 (0.72)	99.863/ 0.136	729
	t51-100 (16.50)	99.993/ 0.006	16501	t51-100 (0.45)	99.778/ 0.221	450

Table 5.9: BN probabilities for observed outcomes at the relevant times of deposition using both data sets (in a scenario where no rain during this period). The numbers in brackets represent the probability of outcome given by the BN.

By contrast, the *Palmer and Polwarth, (2011)* data as in the 'wet' scenario, produces a more progressive increase in likelihood ratio between outcomes involving high numbers of recovered fibres to those involving small numbers within and between the time periods in question. Again, the disparity in evaluation can undoubtedly be accounted for in the experimental design of both studies.

One of the features of any transfer and persistence study is that as well as providing information regarding the likelihood of finding fibres over time, they can potentially provide time frames for when a given activity or contact took place and potentially give indications of how many fibres were likely have been transferred initially (T^0). Such estimates can be used to assist in determining whether finding a relatively small number of fibres after a given length of time (T^x) could be explained by a secondary or primary contact.

Both the *Krauss and Hildebrand, (1996)* and the *Palmer and Polwarth (2011)* data have very definite (but different) characteristics which can potentially provide information regarding initial levels of fibre transfers resulting from an alleged activity.

Again, using the BN in assessment mode (where Hp=1), expectations of initial fibre transfer numbers (T^0) can be obtained at node [2], through conditioning by the observed recovery of fibres (T^x) at node [3], the post-deposition recovery time at node [5], the source of persistence data at node [6] and the presence of rain at node [4].

This is illustrated in *Figure 5.15.*

This exercise has been carried out for each post-deposition interval, each potential observed outcome, using each persistence data set in a dry and raining deposition scenario.

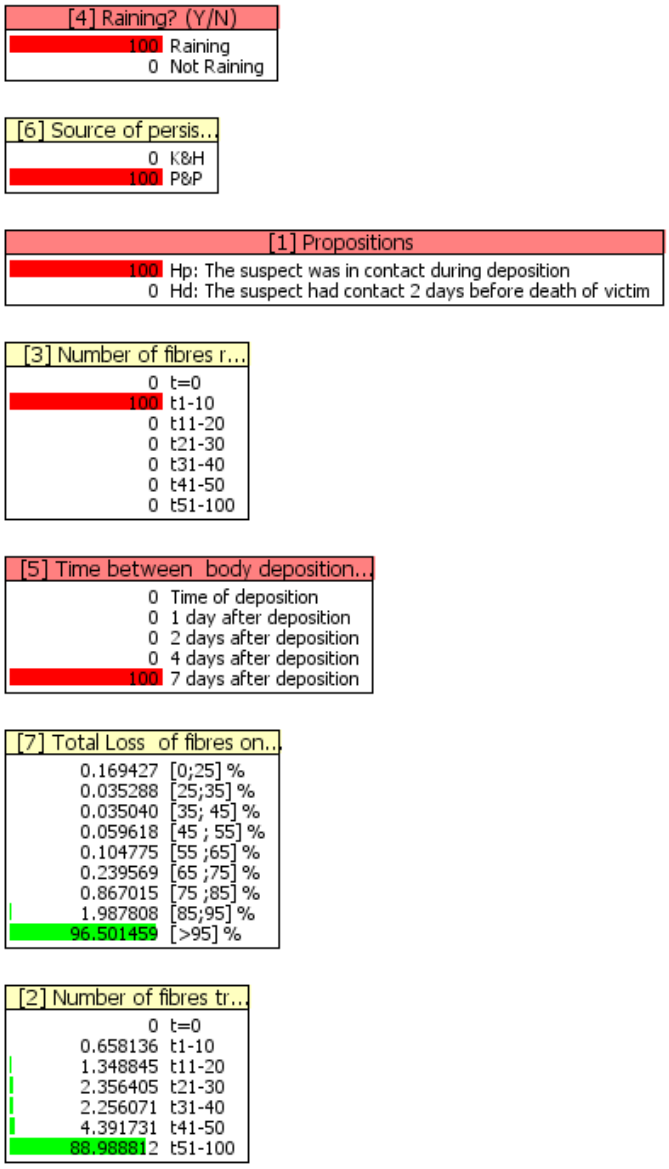


Figure 5.15: BN assessment mode for prediction of fibres transferred at T^0

The results are shown in *Tables 5.10 – 5.12*.

1 day post deposition fibre recovery				
	Raining		Dry	
Observed Outcome T^x	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**
t1-10	t0 (0) t1-10 (2.43) t11-20 (9.15) t21-30 (16.92) t31-40 (14.27) t41-50 (24.21) t 50-100 (32.99)	t0 (0) t1-10 (4.24) t11-20 (6.15) t21-30 (5.01) t31-40 (4.28) t41-50 (7.73) t 50-100 (72.57)	t0 (0) t1-10 (49.99) t11-20 (50) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (4.24) t11-20 (6.15) t21-30 (5.01) t31-40 (4.28) t41-50 (7.73) t 50-100 (72.57)
t11-20	t0 (0) t1-10 (0) t11-20 (0.15) t21-30 (3.05) t31-40 (7.98) t41-50 (22.03) t 50-100 (66.77)	t0 (0) t1-10 (0) t11-20 (13.93) t21-30 (32.85) t31-40 (7.77) t41-50 (13.33) t 50-100 (32.09)	t0 (0) t1-10 (0) t11-20 (33.33) t21-30 (66.66) t31-40 (0) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (0) t11-20 (13.93) t21-30 (32.85) t31-40 (7.77) t41-50 (13.33) t 50-100 (32.09)
t21-30	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0.06) t31-40 (0.84) t41-50 (7.2) t 50-100 (91.89)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (31.24) t31-40 (35.24) t41-50 (8.11) t 50-100 (25.31)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (49.99) t31-40 (50) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (31.24) t31-40 (35.24) t41-50 (8.11) t 50-100 (25.31)
t31-40	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0.01) t41-50 (1.69) t 50-100 (98.28)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (13.76) t41-50 (29.99) t 50-100 (56.24)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (15.87) t41-50 (31.74) t 50-100 (52.38)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (13.76) t41-50 (29.99) t 50-100 (56.24)
t41-50	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (1.18) t 50-100 (98.81)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (35.53) t 50-100 (64.46)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (37.73) t 50-100 (62.26)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (35.53) t 50-100 (64.46)
t51-100	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)

Table 5.10: Prediction of fibres present at T^0 for each potential observed outcome at Day 1. The numbers in brackets represent the probability of outcome given by the BN.

2 days post deposition fibre recovery				
	Raining		Dry	
Observed Outcome T^x	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**
t1-10	t0 (0) t1-10 (1.82) t11-20 (7.62) t21-30 (14.35) t31-40 (12.66) t41-50 (22.43) t 50-100 (41.09)	t0 (0) t1-10 (3.87) t11-20 (9.35) t21-30 (13.25) t31-40 (10.45) t41-50 (17.66) t 50-100 (45.38)	t0 (0) t1-10 (49.82) t11-20 (49.88) t21-30 (0.09) t31-40 (0.04) t41-50 (0.07) t 50-100 (0.06)	t0 (0) t1-10 (3.87) t11-20 (9.35) t21-30 (13.25) t31-40 (10.45) t41-50 (17.66) t 50-100 (45.38)
t11-20	t0 (0) t1-10 (0) t11-20 (0.15) t21-30 (2.5) t31-40 (6.41) t41-50 (18.01) t 50-100 (72.91)	t0 (0) t1-10 (0) t11-20 (2.75) t21-30 (12.77) t31-40 (12.36) t41-50 (22.78) t 50-100 (49.32)	t0 (0) t1-10 (0) t11-20 (33.09) t21-30 (66.41) t31-40 (0.21) t41-50 (0.16) t 50-100 (0.1)	t0 (0) t1-10 (0) t11-20 (2.75) t21-30 (12.77) t31-40 (12.36) t41-50 (22.78) t 50-100 (49.32)
t21-30	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0.17) t31-40 (0.96) t41-50 (6.72) t 50-100 (92.13)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (5.91) t31-40 (12.68) t41-50 (17.7) t 50-100 (63.69)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (49.56) t31-40 (49.84) t41-50 (0.24 t 50-100 (0.33)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (5.91) t31-40 (12.68) t41-50 (17.7) t 50-100 (63.69)
t31-40	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0.24) t41-50 (2.37) t 50-100 (97.38)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (4.57) t41-50 (19.63) t 50-100 (75.79)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (15.81) t41-50 (31.74) t 50-100 (52.44)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (4.57) t41-50 (19.63) t 50-100 (75.79)
t41-50	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (2.8) t 50-100 (97.19)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (22.46) t 50-100 (77.53)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (37.7) t 50-100 (62.29)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (22.46) t 50-100 (77.53)
t51-100	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)

Table 5.11: Prediction of fibres present at T^0 for each potential observed outcome at Day 2. The numbers in brackets represent the probability of outcome given by the BN.

4 and 7 days post deposition fibre recovery				
	Raining		Dry	
Observed Outcome T^x	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**	**T^0 Outcome probabilities (K&H)**	**T^0 Outcome probabilities (P&P)**
t1-10	t0 (0) t1-10 (1.05) t11-20 (5.7) t21-30 (11.25) t31-40 (10.69) t41-50 (20.05) t 50-100 (51.23)	t0 (0) t1-10 (1.22) t11-20 (2.85) t21-30 (4.46) t31-40 (3.95) t41-50 (7.3) t 50-100 (80.19)	t0 (0) t1-10 (50) t11-20 (50) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (1.22) t11-20 (2.85) t21-30 (4.46) t31-40 (3.95) t41-50 (7.3) t 50-100 (80.19)
t11-20	t0 (0) t1-10 (0) t11-20 (0.01) t21-30 (0.63) t31-40 (2.68) t41-50 (9.7) t 50-100 (86.91)	t0 (0) t1-10 (0) t11-20 (3.46) t21-30 (12.97) t31-40 (10.23) t41-50 (19.09) t 50-100 (54.23)	t0 (0) t1-10 (0) t11-20 (33.33) t21-30 (66.66) t31-40 (0) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (0) t11-20 (3.46) t21-30 (12.97) t31-40 (10.23) t41-50 (19.09) t 50-100 (54.23)
t21-30	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0.15) t41-50 (2.42) t 50-100 (97.42)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (9.58) t31-40 (16.03) t41-50 (15.56) t 50-100 (58.8)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (50) t31-40 (50) t41-50 (0) t 50-100 (0)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (9.58) t31-40 (16.03) t41-50 (15.56) t 50-100 (58.8)
t31-40	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0.36) t 50-100 (99.63)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (7.34) t41-50 (23.01) t 50-100 (69.64)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (15.87) t41-50 (31.74) t 50-100 (52.8)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (7.34) t41-50 (23.01) t 50-100 (69.64)
t41-50	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0.21) t 50-100 (99.78)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (27.3) t 50-100 (72.69)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (37.73) t 50-100 (62.26)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (27.3) t 50-100 (72.69)
t51-100	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)	t0 (0) t1-10 (0) t11-20 (0) t21-30 (0) t31-40 (0) t41-50 (0) t 50-100 (100)

Table 5.12: Prediction of fibres present at T^0 for each potential observed outcome at Day 4, The numbers in brackets represent the probability of outcome given by the BN.

For, the data relating to 1 day post deposition fibre recovery (*Table 5.10*), in the presence of rainfall, the data set relating to *Krauss and Hildebrand (1996)* produces a higher probability of large fibre numbers at the initial T^0 transfer across all observable outcomes –

with the exception of outcome t51-100, where it is congruent with the *Palmer and Polwarth (2011)* data.

In the dry scenario, the situation is different, with the *Palmer and Polwarth, (2011)* producing greater probabilities for large fibre numbers at the initial T^0 transfer, involving outcomes involving 1-30 recovered fibres. Where the observable outcome involves the recovery of between 31-100 fibres, the probabilities regarding large fibre numbers at the initial T^0 transfer are very congruent between the two data sets.

At 2 days post-deposition recovery (*Table 5.11*), with rainfall, there is a large degree of congruence between the two datasets regarding levels of T^0 transfer at outcomes t1-10 and t51-100. Where the observed outcome falls between 11-50 recovered fibres, the *Krauss and Hildebrand, (1996)* dataset predicts greater values for T^0 transfer for these observations. Where greater than 20 recovered fibres are found, both datasets predict the same high T^0 transfer. As with the previous exercise, the situation is reversed in when rainfall is absent.

In the dry scenario, the situation is similar to day 1, with the *Palmer and Polwarth (2011)* producing greater probabilities for large fibre numbers at the initial T^0 transfer, this time involving outcomes involving 1-40 recovered fibres. Where the observable outcome involves the recovery of between 41-100 fibres, the probabilities regarding large fibre numbers at the initial T^0 transfer are very congruent between the two data sets.

At 4 days post-deposition recovery (*Table 5.12*), with rainfall, the two data sets produce very congruent predictions for levels of T^0 transfer across all observed outcomes.

In the dry scenario, the situation is similar to day 2, with the *Palmer and Polwarth (2011)* producing greater probabilities for large fibre numbers at the initial T^0 transfer involving outcomes involving 1-40 recovered fibres. Again, where the observable outcome involves the recovery of between 41-100 fibres, the probabilities regarding large fibre numbers at the initial T^0 transfer are very congruent between the two data sets.

The results regarding 7 days post-deposition recovery are identical to that of 4 days.

5.7 Discussion

The results obtained from the BN using the two datasets are not unexpected given the nature of the persistence data obtained from the two different experimental designs.

The *Krauss and Hildebrand, (1996)* study concluded that in the absence of rain, wind had negligible effect on the persistence of fibres. In the presence of rain their results showed an immediate and dramatic loss of fibres which then 'stabilised'. Since all of the land deposited victims of the serial killings were subjected to heavy rainfall during and after deposition, then according to this study, a dramatic loss in fibres would have been expected within the first 1-2 days.

By contrast, the *Palmer and Polwarth, (2011)* study concluded that wind and other factors (e.g. animal activity) resulted in an exponential loss of fibres akin to that observed in other similar studies *(Pounds and Smalldon, 1975a, Robertson, Kidd et al., 1982, Palmer and Burch, 2009).*

It can be seen that the greatest difference appears to be that of precision between days 2-5 after deposition. At 7 days the persistence characteristics of each study would be almost identical given the conditions encountered in the case.

It has to be borne in mind that in the *Palmer and Polwarth, (2011)* study, rain was found to accentuate the rate of loss of fibres. However, this study was carried out during the summer in the UK and only 1 day of rain was encountered during the study period. Had more periods of rain been encountered it is possible that the exponential loss observed would have been much greater than the data suggests. If this was the case, then clearly the differences between the datasets would be smaller.

In considering the circumstances of a case similar to the Ipswich serial killings, but where the conditions had been dry during and after the deposition of the bodies, the application of the two datasets would appear similar to that shown in *Figure 5.14*.

Since the results of the *Krauss and Hildebrand, (1996)* study concluded that in the absence of rain, fibre loss was very gradual and linear in nature, then compared to the *Palmer and Polwarth, (2011)* study this would be very 'flat' in nature and differ little over the timescales encountered.

These features explain the differences in the results of both the pre-assessment and evaluation modes of the BN.

It can also be seen from the results in *Table 5.1* that the observed outcomes relating to each of the victims deposited on land are higher than that predicted by the BN. However, they also show a progressive decrease over the successive time lines which intuitively one might expect in the circumstances.

This apparent disparity between the observed and expected outcome is not unexpected, since neither the *Krauss and Hildebrand, (1996)* nor the *Palmer and Polwarth, (2011)* studies used microfibres as a target source. As previously discussed, garments composed of microfibres shed their constituent fibres much more copiously than other 'normal' types and consequently initial transfers at T^0 are likely to be very high, resulting in concomitant high numbers persisting over time.

Whilst the experimental data used to inform the probability estimates is not strictly compatible with microfibres *per se,* it should be reiterated that in the case presented, crime relevant fibre collectives other than microfibres (e.g. polyester and acrylic fibres) were recovered and therefore the data sets employed will be relevant for these.

The author therefore believes that whilst the experimental designs of both studies can account for the apparent disparity in expectations concerning microfibres, the actual methodology employed using Bayesian networks, is nevertheless valid in terms of assessing datasets and evidence relating to this particular homicide scenario.

In terms of the BN assessment of the size of the initial transfer at T^0 , when rainfall is encountered, the difference between the two data sets during 2-4 days accounts for the disparity in estimates, in particular, the consistently higher estimates given by using the *Krauss and Hildebrand, (1996)* datasets. In the absence of rainfall however, the 'flat' nature of the *Krauss and Hildebrand, (1996)* datasets results in no difference in estimates for given observations at different time scales.

6 ANALYSIS OF A CASE INVOLVING FIBRE TRANSFER TO HAIR

In this chapter the Bayesian network architecture described in Chapter 4, is used to evaluate the contribution of data from the author's studies (population study and study into the secondary transfer of fibres from head hair to pillowcases) in cases involving fibres in head hair. The chapter begins with an overview of a real case involving a series of linked armed robberies where a red 'balaclava' was recovered from a getaway car involved in the crime. It then describes how evidence in the form of fibres present in the head hair and pillowcases of suspects, could have been potentially used to assist the investigation. Studies which provide data useful for informing the conditional probability tables of the Bayesian network used to model relevant crime scene scenarios are described and discussed. In addition to using the Bayesian network to evaluate fibre evidence and the strategic value of seizing bedding (as proposed by the author) relating to suspects in these scenarios, the 'sensitivity' (i.e. effect on the likelihood ratio due to 'degree of knowledge' concerning the available data) of the various parameters contributing to the global likelihood ratio, is assessed.

6.1 Case example: A series of armed robberies

The following real casework circumstances are typical of that in which fibre evidence can provide evidence on its own and/ or complement other evidence types; not only by informing regarding potential contact between a suspect and a questioned item, but also providing timeframes for such contacts.

In 2008 a series of linked armed robberies occurred in a number of counties of England. In one of these incidents an abandoned 'getaway' car was found to contain a number of items used in the commission of the robbery, including a red balaclava. The balaclava and other items in the car were examined for sources of DNA (i.e. saliva, hairs) and fingerprints. No evidence useful in identifying the perpetrators was obtained from this exercise.

Approximately 10 days later, a number of suspects were arrested in connection with these incidents. Head hair tapings or combings from these individuals were not considered, nor was the seizure of pillowcases or bedding. It was subsequently learned that none of the investigative team were aware of the potential evidence that could have been obtained had these items been recovered.

Whilst no fibre evidence was obtained in this particular case, its circumstances can be used as the basis for a 'global' model to evaluate the importance and interdependencies of key parameters and different scenarios in such cases.

6.2 Fibres in head hair: 'Operational' considerations

Masks or 'balaclavas' used in the commission of crimes such as that described above, are frequently fashioned from the sleeves of knitted sweaters, where the cuff region is tied in a knot and eye and mouth holes are cut in the fabric (see *Figure 6.1*). Due to the nature of knitted fabric and the fact it is invariable cut for such purposes, there is a high potential for primary fibre transfer from the item to head (or indeed facial) hair (see *Figure 6.1*). Because of the knitted nature of the original garment, the fibres encountered in such cases are often (but not exclusively) acrylic, cotton or (in the authors experience, less frequently) wool, found in a variety of colours.

Figure 6.1: Mask constructed from the arm of a knitted sweater – typical of that used by the perpetrators of armed robberies.

Commercially produced balaclavas or 'ski masks' are also encountered and (again, in the author's experience) are usually composed of knitted black or green acrylic fibres.

Consequently (see later in this chapter), global estimates for *'γ' values* (i.e. probability estimates for 'fibre 'rarity') are derived from data relating to cotton and acrylic fibres.

Despite the results of studies (*Ashcroft, Evans et al., 1988*, *Salter and Cook, 1996*) which show that there is a high potential for primary transfer of fibres from masks to hair and the possibility of estimating a time frame for wearing a questioned item such as a balaclava, there has been poor uptake for this type of examination in the UK and elsewhere. The reason for this does not solely appear to be a lack of awareness on the investigators part, but also due to the fact that in many instances, the suspect is apprehended outside the expected window of persistence as defined by the literature (typically over 7 days).

6.2.1 Questions concerning fibre evidence in head hair

In response to this '*operational demand*' the author sought to address four specific questions;

1. What is the expectation of finding significant numbers of a particular *generic* fibre type/colour combinations used in the construction of items such as balaclavas, in head hair, compared to other studied substrates (i.e. 'γ' and 'b' values)?

2. How likely are adventitious (coincidental) matches with a *specific* target fibre after instrumental analysis and comparison has been carried out on fibres from head hair (i.e. 'γ' values)?

3. Is it possible, through an understanding of the mechanisms of secondary transfer and persistence of fibres from head hair to pillowcases, to obtain evidence of a recent association between a questioned item such as a balaclava and a suspect apprehended outside the expected window of persistence of fibres in head hair (i.e. after 7 days post incident)? Data relating to *t parameters* being the important consideration here.

4. What are the important factors influencing this transfer and persistence ('t parameter') data?

5. How do these source and activity level questions influence the strength of evidence in a particular case?

The first and second questions are addressed by the author through the fibre population study in head hair *Palmer and Oliver, (2004*) and the target fibre study *(Palmer and Chinherende, 1996)* concerning red acrylic fibres and studies on the discrimination of blue cotton fibres

(*Biermann, 2007, Palmer, Hutchinson et al., 2009*, *Palmer and Luff, 2013*, *Palmer and Wagner, 2013, Buzzini and Massonnet, 2015).*

The third and fourth questions are addressed by the author through the investigation of the secondary transfer of fibres from head hair to pillowcases *(Palmer and Banks, 2005)* in order to determine if, and to what extent, data from this study complements that obtained from studies concerned with the *primary* transfer and persistence of fibres in head hair.

The fifth question is addressed using the Bayesian network model and sensitivity analysis referred to in *Section 6.3.*

If it is shown that provided the data obtained from these studies can complement and/ or augment fibre evidence in such cases, then this will justify the proposed investigative strategy (i.e. seizing pillowcases) in such cases.

6.2.2 The population of fibres in head hair.

The question relating to the relative frequency of a particular fibre type and colour combination in head hair has been addressed by the author in a fibre population study in head hair (*Palmer and Oliver, 2004)*. Whilst fibre population studies have been carried out on a number of different substrates (*Was-Gubala, 2001, Massonnet, Schiesser et al., 1998, Roux and Margot, 1997b)*, this was the first to consider the relative frequencies of specific fibre type/ colour combinations in head hair.

The results of the fibre type data obtained from this study showed that the fibre population consisted mainly of natural fibres (72.6%), with the largest generic grouping being cotton (69.2%). This finding is in agreement with all population studies previously mentioned. Wool was the other natural fibre type occurring at a frequency of 3%; however this appears to be under-represented in this study compared to those previously cited.

The reasons behind this apparent disparity with other similar studies are likely to be related to both the climatic and seasonal variation between this study and those done previously. The fibre population studies of car seats *(Roux and Margot, 1997b)* and cinema seats *(Cantrell, Roux et al., 2001)* were all conducted during the winter months of their respective climates whilst the sampling for this study was conducted in early summer (July) in the UK. It is

therefore likely that the low frequency of wool encountered in this study, is a reflection of the type of clothing generally worn during warmer weather.

Since the fibre content of hair is likely to be a direct reflection of the clothing worn by an individual, it is not unreasonable to assume that repeating this study in the winter months would see the relative frequency of wool rise as a consequence of the need for heavier winter clothing.

This result corroborates the findings of *Biermann and Grieve, (1996b)*, who investigated this aspect of seasonal variation, when they examined the content of a mail-order garment database as a means of estimating relative fibre frequencies within the population. Within the data they collected was a comparison of fibre composition of garments sold during the fall/ winter and spring/ summer seasons in Germany. Within this breakdown, we see the increased frequency of wool and acrylic during the winter season, with a reduced frequency of cotton.

In the head hair population study, man-made fibres accounted for 27% of the sampled population. Among these, polyester was most commonly seen, accounting for about 60% of the man-made fibres, or 16% of the overall fibre population.

This is a marked contrast to a number of studies (*Was-Gubala, 2001, Roux and Margot, 1997b)*, which found the most commonly encountered man-made fibres consisted of regenerated cellulosic fibres, which includes viscose (rayon), acetate and other cellulosic fibres such as modal and lyocell. Regenerated cellulosic fibres were the second largest group of man-made, accounting for 5.7%. These results are summarised in *Table 6.1*;

Fibre Type	Frequency (n=441)
Cotton	0.692
Polyester	0.163
Reg. Cellulosic	0.057
Acrylic	0.032
Polyamide	0.018
Other	0.05

Table 6.1: **The relative frequencies of generic fibre types in head hair (Palmer and Oliver 2004)**

Acrylic and polyamide confirmed the results of the previous studies as being relatively rare, accounting for 3.2% and 1.8% respectively. This study shows polyester to be the most prominent man-made fibre in head hair by a considerable margin. Consideration of the results of *Biermann and Grieve, (1996b),* show no seasonal variation that might account for this finding, in fact their data demonstrates that polyester content increases in winter clothing, while viscose tends to decrease. Although not investigated, this apparent disparity may be due to the increase in the use of artificial 'fleece' style clothing – which is prominently made of polyester fibres.

Figure 6.2 shows a summary of the 20 most common colour/ generic class combinations and their proportion of the sample. Of a possible 72 combinations, all but 12 comprised less than 1% of the sampled population. The high frequency of cottons is clearly illustrated, with black/ grey and blue cottons accounting for nearly half of the population.

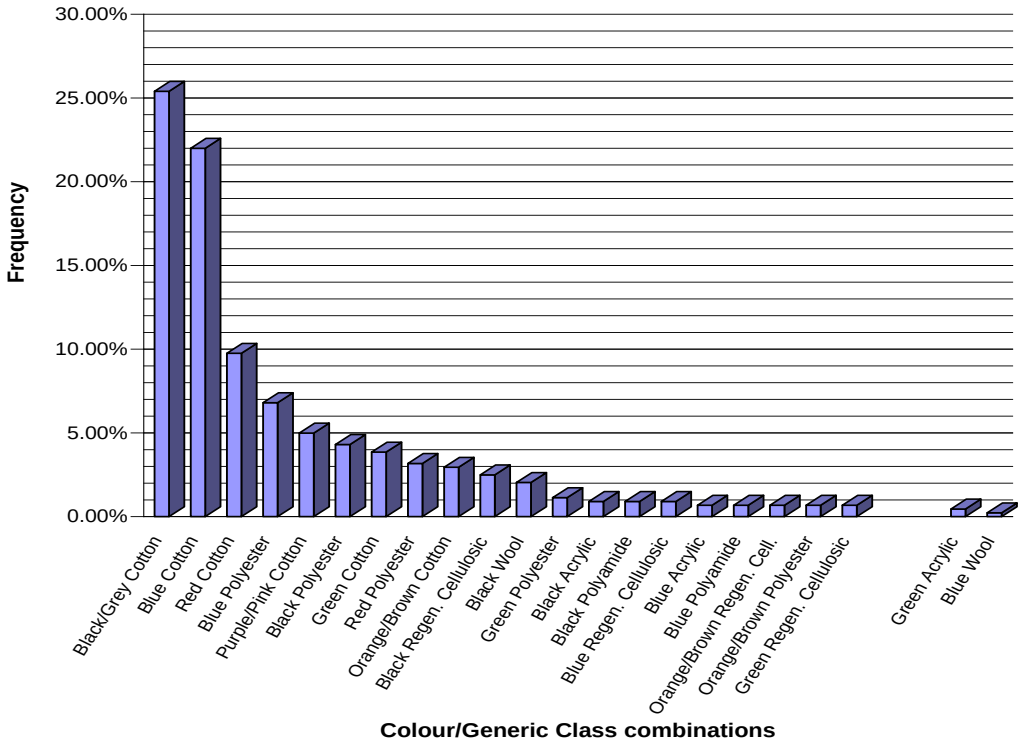


Figure 6.2: The relative frequencies of fibre colour/ generic class combinations in head hair (Palmer and Oliver 2004)

The studies of cinema seats *(Cantrell, Roux et al., 2001)*, outdoor surfaces (*Grieve and Biermann, 1997a*), car seats *(Roux and Margot, 1997b)* and white t-shirts *(Massonnet, Schiesser et al., 1998)* all support this finding, having found black/ grey and blue cottons to be most populous in each respective environment. However, in these studies the next most common colour/ generic class combination cited was coloured (usually black) wool, a finding not supported by this study. Black wool was the most common wool seen, at a frequency of 2.0%. Possible reasons for the under-representation of wool have been previously discussed.

Interestingly, blue wool is often selected for use in target studies. In a head hair study conducted by *Cook, Webb-Salter et al., (1997)*, blue wool was selected due both to its believed high frequency and its commonality in case work.

This fibre type/ colour combination was also used in a target study performed in 1996 on seats in public houses (*Kelly and Griffin, 1998)*. Blue wool was selected as a relatively common fibre, and typical of a high selling, mass-produced garment (in this case a Marks & Spencer

pullover). As is shown in *Figure 6.2*, the *Palmer and Oliver (2004)* study suggests that blue wool is rarely encountered in this substrate (only one blue wool was found out of the 441 fibres identified). Again, it is likely that many of these conflicting observations can be attributed to climatic differences or seasonal fluctuations.

The most frequent man-made fibre/colour combination was blue polyester at 6.8%, followed closely by black polyester at 4.3%. Of particular relevance to crimes involving masks and balaclavas was the relative low frequency of acrylic fibres (3.2%).

Acrylics are commonly seen in casework as components of manufactured balaclavas/ ski masks. Even the most common acrylic fibres, consisting of those being black or grey, accounted for less than 1% of the population (0.9%). Green acrylic fibres, another common component of black balaclavas, were seen at a level of 0.5%.

Since the sleeves of pullovers are often used as improvised masks, the low occurrence of wool (a relatively common component of pullovers) in the hair, even in common colours such as black and blue, has implications when considering the evidential value of finding large numbers of wool in a suspect's hair. The significance of this finding does however, appear to be influenced by the time of year/ climate relevant to the case.

Comparison of the fibre loads recovered from each hairstyle revealed that fewer fibres were consistently recovered from long hair than from medium or short hair. As shown in *Figure 6.3*, the mean number of fibres recovered from short and medium hair lengths are similar and considerably larger than the number of fibres recovered from long hair.

However, as expected there is a large degree of variation between individuals. The reason for this is possibly a combination of two factors. Firstly, the method of taping seems to be less efficient at retrieving fibres in long hair, simply because the greater volume of hair makes it more difficult for the collector to access the base and roots of the hair, making embedded small fragments that may be there inaccessible.

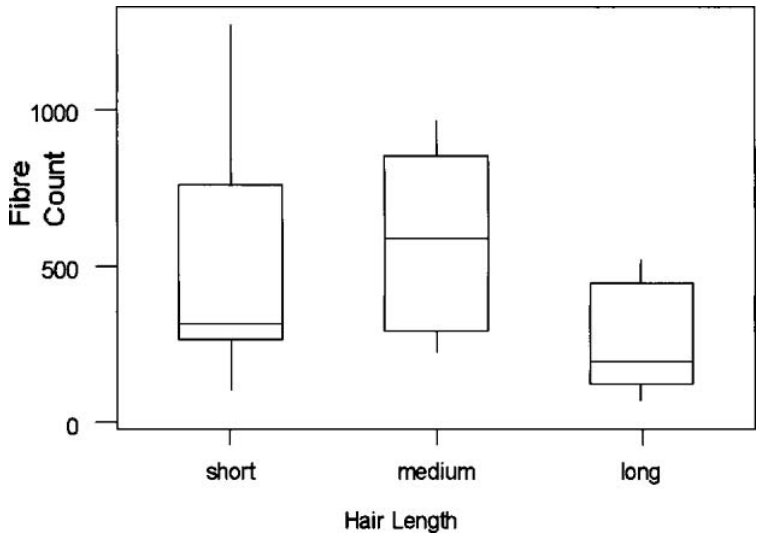


Figure 6.3: Comparative fibre loads in different hair lengths (Palmer and Oliver, 2004)

It is also more difficult to touch the tape to every plane and surface of those with long hair – compromising the efficiency of recovery.

It may be that fibre recovery using a 'seeded comb' may be more efficient, however, the time taken to construct these devices and ensure they are contaminant free, as well as a more prolonged search and recovery, made this method impractical for this study.

This finding also appears to indirectly support other studies on fibre persistence. *Salter and Cook, (1996)* reported that consistently more fibres from headgear were transferred to shorter, coarser hairstyles than to long hair. Their study also noted that the coarse, short hair on *one subject* exhibited greater persistence than the long hair of another subject.

This finding was also confirmed by the study of secondary fibre transfer from head hair to pillowcases (*Palmer and Banks, 2005*) and the proposed factors responsible, e.g. frequency of grooming, are likely to be equally applicable in this instance.

In summary, the results of the *Palmer and Oliver, (2004)* study are in general accordance with other similar studies in demonstrating the predominance of dark coloured cottons (black, grey and blue) and the relative rarity of most coloured man-made fibre types. In all but 12 combinations of colour and generic class, there was sufficient discrimination to obtain frequency rates of less than 1.0% (including acrylic fibres, which are commonly encountered in casework as components of masks used in crimes).

6.2.3 ‘Target’ fibre studies

Although fibre population studies provide fibre frequency data only at a *very generic level* (e.g. ‘blue’ and ‘nylon’) this is either ignored or misunderstood by many practitioners and members of the criminal justice system alike. Consequently this often results in the evidential value of a particular fibre type/ colour combination being woefully understated (*Grieve, 2000a*, *Grieve, 2000b*, *Palmer and Booth, 2010)*.

'Target fibre’ studies on the other hand, provide a greater illustration of the significance of fibre evidence, since these address the issue of how likely it is to encounter significant numbers of a particular fibre type/ colour combination on an unrelated, random surface, *which has been subjected to the full range of comparative tests employed in casework*. These are effectively an extension of ‘Colour Block Studies’ which investigate the degree of discrimination within a particular generic fibre type colour combination afforded by the comparative tests employed.

Early studies of this nature involved searching cars and clothing (*Cook and Wilson, 1986, Jackson and Cook, 1986*) for the presence of a particular fibre type (‘target’) whose morphology, colour, chemical and dye characteristics had been previously fully defined at the laboratory.

A target study conducted by *Cook, Webb-Salter et al., (1997)*, used data to calculate the likelihood of finding fibres from an innocent source matching blue wool, as well as green and grey acrylics found in head hair.

Similar calculations were also performed by *Roux and Margot, (1997a)* in order to obtain probability values for finding given numbers of particular fibre type/ colour combinations on car seats. None of these studies however, considered seasonal/ climatic factors as a conditioning factor.

Whilst these early studies provided useful data, the number and type of substrates examined were fairly limited in terms of encompassing potential contact with the huge number and variation of textiles in the population. The resources required to carry out studies using every type of surface likely to be encountered by an individual are very high.

For a more informative assessment to be obtained, a different approach involving the sampling of a substrate which had been subjected to *repeated* contacts from large cross section of textile items present in the environment, was required.

To address this issue, the author applied this type of study to a situation where a limited number of substrates had been subject of innumerable contacts from huge number of random textile items in the population. To this end, the author chose cinema seats as well as un-valeted vehicles from a used car lot, as substrates for this study (*Palmer and Chinherende, 1996)*.

It had been estimated that over 140,000 people had used the cinema auditorium with 12 months of the study (the seats of the auditorium were not subjected to a routine cleaning regime). 66 vehicles were sample in the used car lot. Two different target fibres were selected in this study; green cotton and red acrylic, and the numbers of the donor garments available for purchase in the UK obtained.

The results of this study relating to red acrylic fibres (which are relevant to informing global estimations for 'γ' values for the Bayesian network model in section 6.3) are summarised in *Table 6.2*.

Red Acrylic Target Fibre			
Seat	**Low Power Microscopy**	**High Power microscopy**	**MSP***
Car	712	3	3
Cinema	112	14	14
Total	824	17	17

Table 6.2: Number of red acrylic fibres matching target garment after each analytical comparison sequence (*Microspectrophotometry).

A similar study also using red acrylic as the 'target' was carried out by *Bruschweiler and Grieve, (1997),* provided similar results*.* Using tape lifts obtained from the member institutions of the European Fibre Group, these authors examined 435 fibres with only 2 of these fibres found to match the target when subjected to the full comparison including instrumental analysis.

The results of these studies show that finding red acrylic fibres of a specific colour and type, which are indistinguishable from a particular target garment, is a rare event.

Since the case circumstances considered in this chapter involve a red acrylic mask, the results of the target fibres relating to red acrylic fibres become important in that they serve to inform the 'γ' parameters for the Bayesian network model in this chapter.

6.2.4 The discrimination of cotton fibres

As previously discussed, in addition to acrylic fibres, 'home-made' masks fashioned from sweaters are often comprised of cotton fibres. Cotton fibres are the most

frequently encountered fibres in forensic casework with black/ grey and blue being the most common colours.

In order to provide global estimates for the 'γ' parameters for the Bayesian network model in this chapter (*Section 6.4.2*), we need to consider the discrimination of a commonly encountered colour class of this fibre type, i.e. blue cotton. In the absence of target fibre studies relating to this fibre colour combination, we need to consider the results of relevant colour block studies.

As previously discussed, the *generic* 'commonality' of these fibres often results in the perception of these fibres having little or no evidential value. However, over the past 20-30 years there have been a number of substantial technological advances which have resulted in improvements to analytical instrumentation in terms of increased discrimination, reliability and functionality. The main advantage from these developments is the ability to examine smaller analytes with an increased degree of discrimination.

The discrimination afforded by the current range of microspectrophotometers capable of operating into the UV range of the electromagnetic spectrum offer much better discrimination, particularly when used in combination with other techniques, yet this does not seem to have been factored into the evidence evaluation processes of many practitioners (*Grieve, 2000a*, *Grieve, 2000b*, *Palmer and Booth, 2010)*.

Grieve, Dunlop et al., (1990) carried out a study to assess the discrimination of coloured cotton fibres and concluded that microscopy alone offered very poor discrimination, but that this was considerably increased when visible range MSP was carried out in combination. In the years

following this study, more discriminating instrumentation capable of operating from the visible into the UV range has been introduced into many operational forensic laboratories. The results obtained by *Biermann, (2007)* who considered the discrimination afford by UV-Visual range MSP in combination with microscopy, provided further evidence that these fibre types can be reliably distinguished – contrary to popular belief. Since the discriminating power of microscopy alone in the comparison of blue cotton fibres has been shown to be 'virtually useless' *(Grieve, Dunlop et al., 1990)*, the dogma still held by many practitioners in applying microscopy as a 'first test' in comparing coloured cottons is questionable.

Further investigation of the discrimination of blue cotton fibres by UV-Vis MSP alone, by *Palmer, Hutchinson et al., (2009)* augmented the results of the previous studies and provided a sound scientific justification for modifying the scheme of analysis to use MSP as the 'first test' in these circumstances. A summary of the results are shown in *Table 6.3.*

	100 Blue Cotton Fibres		**Total Groups**
Perceived Colour	73 'dark blue' fibres	27 'light blue' fibres	2
Visible Range MSP	22 spectral types	9 spectral types	31
UV-Vis Range MSP	43 spectral types	17 spectral types	60
DP=0.96 for UV-Vis MSP			

Table 6.3: Summary of the results of the study into the discrimination of blue cotton fibres (*Palmer, Hutchinson et al, 2009*).

Recent unpublished colour block studies involving blue cotton fibres found on cinema seats *(Palmer and Luff, 2013)* and public bus seats *(Palmer and Wagner, 2013)* have provided very similar results with discrimination powers of 0.99 and 0.98 being obtained respectively. The frequency of the most common group was found to be 0.09 (n=102) and 0.12 (n=114) respectively.

6.2.5 The Secondary Transfer of Fibres from Head Hair to Pillowcases

The study of the mechanism involved in the secondary transfer of fibres from head hair to pillowcases, allows us to approach questions 3 and 4 as defined at the beginning of this chapter.

6.2.5.1 Transfer and persistence

The results of the study by *Palmer and Banks, (2005),* show that secondarily transferred fibres can persist on pillowcases for up to 14 days. The persistence of these secondarily transferred fibres does not appear to follow the classic exponential 'decay' curve associated with primary fibre transfer of fibres on garments, but appears to exhibit a much more ‘linear’ loss.

Since the pillowcases can be considered to exist in a closed environment, the majority of fibre loss is likely to occur as a consequence of 'back transfer' to the primary recipient who may return a proportion on subsequent contacts. The rate of loss in this situation is likely to be similar to that observed in the studies of fibre persistence on car seats (*Robertson and Lim, 1987, Roux, Chable et al., 1996*), with similar mechanisms involved.

A large variation in the numbers of secondarily transferred fibres from individual subjects was observed and this is undoubtedly due to individual differences in lifestyle, personal grooming, frequency of bathing/showering, etc. - as well as the inherent variability of the initial primary transfer itself. Since it is unlikely that information relating to all of these variables would be available in real casework situations, it was considered that there was no value in attempting to correlate such factors against the results obtained.

6.2.5.2 Differential transfer/ persistence

The results of the persistence experiment showed using an acrylic/ wool blended fabric (50:50), that the acrylic component was transferred to head hair to a greater extent than the wool component (approximately 60:30). This observation is in accordance with other published data (*Parybyk and Lokan, 1986, Salter, Cook et al., 1987*) relating to the differential shedding properties of items where fibres are transferred in proportions which differ from the stated proportion of fibre components on the label of clothing incorporating a blended fabric.

After 24 hours, the relative numbers of these persisting fibre types had altered to an average 50:50 ratio, with the absolute numbers of each fibre component of the blend having predictably decreased. The greatest percentage loss was however, with the acrylic fibre component.

This finding tends to suggest that wool fibres persist more tenaciously in head hair than acrylic and this may well be due to scale to scale interactions, which have been previously postulated *(Ashcroft, Evans et al., 1988)*. This could provide an explanation for the relatively low numbers of secondarily transferred wool fibres, as opposed to any view that the findings are a feature of poor primary transfer characteristics.

In summary, whilst the factors such as hair style/length and fibre type may have some effect on the degree of the secondary transfer of fibres from head hair and their subsequent persistence, the main issue is that fibres transferred in this manner persist on pillowcases well beyond the expected time frame reported (3-7 days) for the primary transfer to hair (*Ashcroft, Evans et al., 1988*, *Salter and Cook, 1996*) with the rate of loss being much more 'flat'.

The results of this study clearly demonstrate the potential value in seizing items such as pillowcases from the homes of those suspected to be involved in crimes where masks have been used to conceal identity - particularly when a suspect has been apprehended outside the expected 'window' of fibre persistence associated with head hair

The data from these studies outlined in this section of the chapter show that;

- There is a low expectation of finding significant numbers of synthetic fibres such as those used in the production of balaclavas (home-made and mass produced) in head hair.
- The expectation of finding significant numbers of a given fibre type/ colour combination matching those of a target fibre which has undergone the full battery of analytical testing is very low.
- The analytical tests/ comparison processes used are fit for purpose and capable of distinguishing between items which are ostensibly very similar.
- The results of colour block studies show that although blue cotton is a 'common' fibre type colour combination as defined by various population studies, the discriminating

power of instrumental analysis nonetheless allows significance to be attributed to its presence.

- Fibres are readily transferred to head hair from masks and that these transferred fibres have a high potential for secondary transfer.
- The potential for these secondary transfers appears to be greater in individuals with short hair as opposed to those with long hair since they tend to have higher fibre loads. However, given the inherent variability of this data it would be difficult to precisely quantify this.
- Fibres secondarily transferred from head hair to pillowcases appear to be highly persistent over time.
- Cotton appears to be more readily transferred secondarily than acrylic and wool, with wool showing the least potential. The results indicate that this may be due to a greater persistence of wool in head hair rather than poor primary transfer characteristics.

The data obtained from these studies are used to inform the conditional probability tables (CPT) for the various nodes in the Bayesian network, as outlined in *section 6.4.*

6.3 Bayesian network structure of relevant crime scenario model

In order to assess the impact/ contribution of the data generated from the studies described in this chapter on the strength of evidence, a Bayesian network (shown in *Figure 6.4*) has been constructed using the 'block structure' described in *Chapter 4*. In addition to the evaluation of the evidence, the Bayesian network is used as a pre-assessment tool to examine the usefulness of the data from these studies, in terms of predicting fibre recovery outcomes over various time scales.

Assumptions made in this model are;

- The mask is expected to shed its constituent fibres.
- The bedding (pillowcase) has not been washed over the defined timeframes.

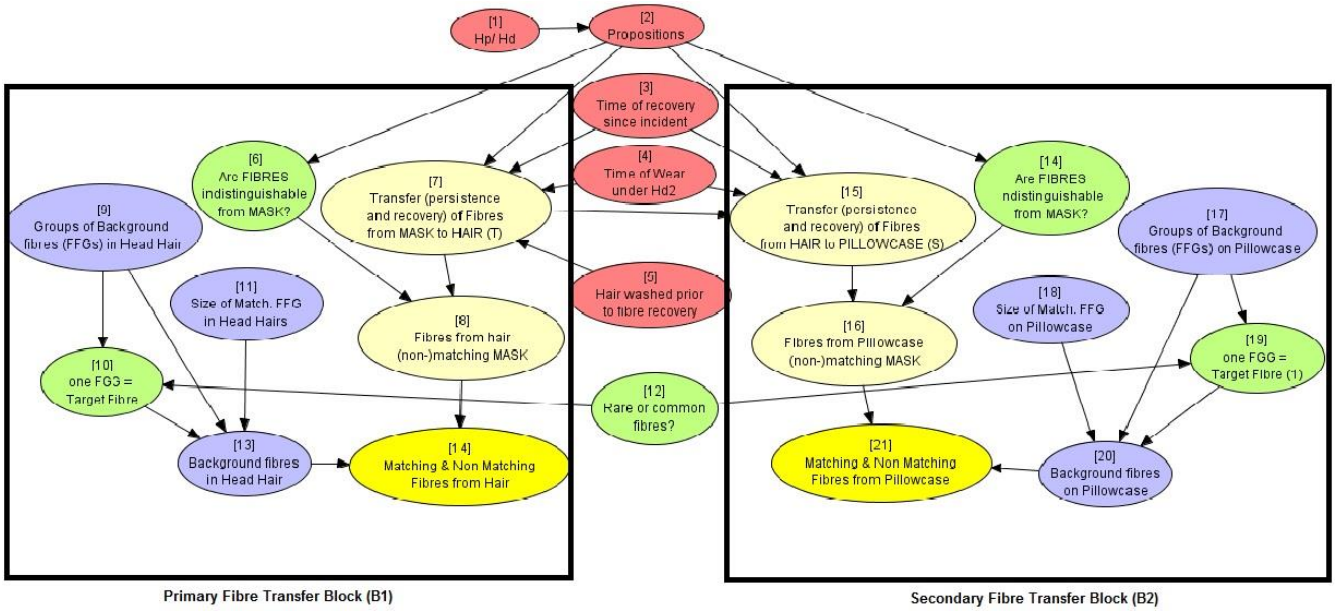


Figure 6.4: Structure of network modelling the relevant factors in the crime scenario model B1 & B2

The left side block (B1), deals with the primary transfer of fibres from the mask to the suspect's head hair, the right side block (B2) deals with the secondary transfer of fibres from the head of the suspect to their pillow case. *Table 6.4* summarises the key nodes conditioning upon those used in blocks B1 and B2 of this architecture.

It can be seen node [2] encompasses one Hp proposition and two different Hd propositions and allows switching between these two Hd propositions so that the likelihood ratio calculations involving Hp can be evaluated for each possible defence scenario, separately i.e.;

Hp: The suspect wore the mask at the time of the incident, as opposed to:

Hd1: The suspect has never worn the mask (or any mask)

Or

Hd2: The suspect wore the mask sometime before the incident (for the purposes of this chapter we consider 7 days and 14 days pre-incident wear).

Nodes	States	Definition of states
1	Hp/ Hd	Displays summary of Hp/ Hd as specified in node [2]
2	Hp Hd1 Hd2	Hp: The suspect wore the mask at the time of the incident Hd1: The suspect never wore the mask (or any mask) Hd2: The suspect wore the mask some time before the incident
3	1-3 days 7days	Fibres recovered 1- 3 days post-incident Fibres recovered 7 days post incident
4	7 days 14 day	Mask worn 7 days pre-incident (Hd2) Mask worn 14 days pre-incident (Hd2)
5	Washed Unwashed	Suspects hair has been washed post-incident Suspects hair has not been washed post incident
12	Rare Fibre Common Fibre	Match probability estimate for 'rare' target fibre type Match probability estimate for 'common' target fibre type

Table 6.4: Description of nodes common to primary transfer block (B1) and secondary transfer block (B2)

The node structure and function for primary transfer block B1 is summarised in *Table 6.5*. The functions of the nodes in block B1 have also previously been described in C*hapter 4*.

Nodes	States	Definition of states
6	Matching type M Fibres not type M	Recovered fibres indistinguishable from mask Recovered fibres distinguishable from mask
7	t>10 t6-10 t1-5 t0	Finding >10 fibres under Hp, Hd1, Hd2 Finding 6-10 fibres under Hp, Hd1, Hd2 Finding 1-5 fibres under Hp, Hd1, Hd2 Finding no fibres under Hp, Hd1, Hd2
8	t>10 t6-10 t1-5 t0 1nm Fibres No fibres	finding > 10 non matching fibre finding 6-10 non matching fibres finding 1-5 non matching fibres finding no matching fibres finding 1 non matching fibre groups finding no fibres
9	5-20 FFG 2-5 FFG 1 FFG 0 FFG	finding 5-20 foreign fibre groups finding 2-5 foreign fibre groups finding 1 foreign fibre group finding no foreign fibre groups
10	FFG matching type M FFG not type M	Finding an adventitious match with the fibres comprising the mask, given the number of FFG's recovered. Finding no adventitious matches with the fibres comprising the mask, given the number of FFG's recovered.
18	Small (<=10) Large (>10)	Sizes of FFG's under consideration
13	M(>10)/>1nG M(1-10)/>1nG M(>10)/ 1nG M(1-10)/ 1nG M(>10) M(1-10) >2nG 2nG 1nG No fibres	Considered outcomes for the combination of numbers matching fibres and non-matching fibre groups.
14	t>10/>1nG t6-10/>1nG t1-5/>1nG t>10/1nG t6-10/1nG t1-5/1nG t>10 t6-10 t1-5 No Match fibres No fibres	Considered outcomes for the combination of numbers matching fibres and non-matching fibre groups. conditioned by node [13]

Table 6.5: Description of nodes and related states in primary transfer block (B1)

6.4 Primary transfer block (B1) probability assignments

6.4.1 The Dirichlet distribution

The probability assignments used in the transfer blocks B1 and B2 have been expressed as both maximum likelihood estimates as well as Dirichlet parameter distributions, which are used in the sensitivity analysis described later in this chapter (see *Section 6.9.1*).

The Dirichlet distribution is a statistical function which describes the random distribution of multinomial variables. It is used in Bayesian statistics to inform prior and obtain posterior parameters based on acquired data. For example, if we consider the number of background foreign fibres groups (FFG) described in node 9 of the Bayesian network, we can see this has 4 possible states (0 FFG, 1 FFG, 2-5 FFGs and >5 FFG's.). We will consider this parameter as a multinomial variable with four possible states. The Dirichlet distribution will be used to model this multinomial. If through experimental (or casework) observation we had only observed each of these states once, this is described as a 'flat' Dirichlet distribution and denoted *Dir (1,1,1,1)* and that distribution will represent our "prior" state of affair. Where further observations revealed 10, 10, 20 and 30 instances of the respective states, then it is possible to update and describe the posterior distribution as *Dir (11,11,21,31).* This is because the posterior counts are added to the prior counts to specify the parameters of the updated Dirichlet distribution.

Where there is 'ignorance' concerning a particular set of four parameter values such as FFGs, we would therefore use the distribution *Dir (1,1,1,1)* as an uninformative prior.

The prior and posterior distributions therefore describe the information content of the data.

For example if we consider a flat prior of *Dir (1,1,1,1)*, this means for parameter state 0 FFG, we are uncertain whether this would always be 0, the possibility exists that values for this may actually (due to incomplete observation) vary between 0 and x and the Dirichlet distribution function allows us to capture this. The same principle applies to the other parameter values.

If we consider a posterior distribution for example; *Dir (11,11,21,31)* then the variance of the distribution for each parameter value is less than that of the flat prior.

6.4.2 Primary transfer and persistence (t values)

The probability assignments under Hp for the primary transfer (i.e. mask to head hair) in *node 7* of block component (B1) of the Bayesian network have been estimated from the data provided by the studies of *Ashcroft, Evans et al., (1988)* and *Salter and Cook, (1996) as summarised in Table 6.6.*The figures relating to the unwashed hair aspect of the *Ashcroft, Evans et al, (1988)* study are quoted directly from the published results.

	Time of recovery following contact with donor item (Hair not washed)		
Ashcroft et al (1988)	**1 Day**	**3 days**	**7 days**
Number of Acrylic fibres	*8-20 (mean=13)*	*4-9 (mean=6)*	*4-7(mean=6)*
Number of Wool fibres	*9-20 (mean=14)*	*6-10 (mean=8)*	*4-8 (mean=6)*
Salter & Cook (1996)	**1 Day**	**3 days**	**7 days**
Number of Acrylic fibres	*10-82*	*5-20*	*2*
Number of Wool fibres	*17-60*	*4-15*	*3*
	Time of recovery following contact with donor item (Hair washed)		
Ashcroft et al (1988)	**1 Day**	**3 days**	**7 days**
Number of Acrylic fibres	*10-16*	*5-8*	*No data*
Number of Wool fibres	*10-20*	*5-10*	*No data*
Salter & Cook (1996)	**1 Day**	**3 days**	**7 days**
Number of Acrylic fibres	*5*	*No data*	*No data*
Number of Wool fibres	*4*	*No data*	*No data*

Table 6.6: **Persistence data derived from the studies of Ashcroft, Evans et al (1988) and Salter and Cook (1996)**

The values relating to the washed hair recovery were calculated using quoted loss of 80% for day 1 and 90% for day 3 using the baseline transfer values of 51-80 (acrylic) and 48-98 (wool).

The *Ashcroft, Evans et al*, *(1988)* study involved 13 subjects in a total of 130 experiments. The *Salter and Cook, (1996)* study involved 5 subjects in a total of 54 experiments. The data provided by these studies is therefore based upon a total of 184 experiments. This information will be used to inform the parameters of the *Dirichlet distributions* used and discussed in *section 6.9.1*.

No information is provided regarding day 7, however, the authors do state that repeated washing would be required to remove all fibres.

The results published in the *Salter and Cook, (1996)* relating to unwashed hair during the above time periods are expressed as percentage loss, which according to the persistence curves they present, appears to be approximately 80% and 95% for 1 day and 3 days respectively – *although the method of data presentation in this paper makes it difficult to be precise.*

In addition, the persistence graphs presented *do not represent all subjects*. The number fibre ranges quoted for immediate post transfer are 49-408 for acrylic and 84-302 for wools. The figures quoted for days 1 and 3 in the above table are therefore estimates based upon the percentage loss. The fibre numbers for 7 days are quoted directly from the study.

Likewise, the method of data presentation relating to washed hair persistence is somewhat lacking with only data quoted during day 1, again only for 1 subject. However, the authors concur with *Ashcroft, Evans et al, (1988),* that a single hair washing would not be expected to remove all transferred fibres They also conclude that there is little expectation of finding fibres after 7 days if hair is washed during that time.

Whilst both of these studies present expectations regarding fibre persistence following hair washing during a 7 day period, they do not provide any empirical data to illustrate/ support this. This will be discussed in greater depth in *Chapter 7* of this thesis. Therefore, given the inherent variability in the quoted results, fair and reasonable *generic* transfer probability assignments based upon the data from these studies *under Hp* are shown in *Table 6.7*;

B1	**Mask to head Hp (hair not washed)**	
	1-3 days^{+}	**7days^{+}**

	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$t_{>10}$	0.6	113	0.005	1
$t_{5\text{-}10}$	0.3	56	0.015	3
$t_{1\text{-}5}$	0.09	17	0.68	128
t_0	0.01	2	0.3	56
B1	**Mask to head Hp (hair washed)**			
	1-3 days$^+$		**7days***	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$t_{>10}$	0.2	38	0.002	2
$t_{5\text{-}10}$	0.35	66	0.002	2
$t_{1\text{-}5}$	0.35	66	0.004	4
t_0	0.1	18	0.992	996

Table 6.7: Transfer probability assignments for primary transfer (B1) based on Ashcroft, Evans et al (1988), Cook & Salter (1996). **$^+$ The Dirichlet parameters are based upon a total of 184 observations (after adding prior counts). *No data available, Dirichlet parameters based upon expectations from 1000 hypothetical observations (after adding prior counts).**

The transfer values for 7 days relating to washed hair have been assigned through consideration of the available data from the above studies.

In considering the 't' values for Hd1 (i.e. that the suspect had never worn the mask or any mask), again these have been assigned based upon the existing studies and are shown in *Table 6.8*. Where no data is available from these studies, values have been assigned, based on expectations obtained from casework, involving the outcome (in terms of counts) obtained from 1000 theoretical observations. In other words, the MLE's have been assigned according to the authors expectations (from casework experience) of observations from a thousand such cases.

The process goes as follows. The variable (T) is described by four possible states (t>10; t5-10, t1-5 and t0) that are considered as the outcomes of a multinomial variable. The parameters of that distribution are initially informed by a non-informative prior distribution with the parameters *Dir* (1,1,1,1). It is as if we are considering one observation for each state. We will update the Dirichlet distribution based on casework experience (recalled back from memory). Based on a hypothetical corpus of a 1000 cases, it has been considered that in 1 case we could obtain more than 10 fibres or between 5 and 10 fibres, in two cases, we would obtain between 1 and 5 fibres. In the remaining 996 case we will have 0 transferred fibres. The parameters of the Dirichlet distribution are simply updated as follows: *Dir* (2, 2 ,3, 997). From these counts, we can derive the MLE estimates (0.001, 0.001, 0.002 and 0.996) for each state of the variable.

	Mask to head Hd1			
	1-3 days*		**7days***	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$t_{>10}$	0.001	2	0.001	2
t_{5-10}	0.001	2	0.001	2
t_{1-5}	0.002	3	0.002	3
t_0	0.996	997	0.996	997

Table 6.8: Transfer probabilities for 't' values under Hd1. *No data available, Dirichlet parameters based upon expectations from 1000 hypothetical observations (after adding prior counts).

Under Hd2 (i.e. where the defence proposition is that the suspect has worn the mask but at some time previous to the offence) two time scales will be considered; item worn within 7 days or 14 days *prior to the offence.*

In order to assign transfer probability values for Hd2 under B1, it is necessary to consider and modify transfer probability data for B1 under Hp, which in turn is modified by the time period of fibre recovery *post offence* i.e. 1-3 days or 7 days.

For B1, this gives us 4 potential periods of persistence to consider;

For example:

1. If the Hd2 scenario is true that the suspect wore the mask 7 days before the offence and that fibres were recovered from the hair 1-3 days after the offence, then effectively we need to consider persistence data for up to 10 days (i.e. 7 days as used in Hp).

2. If the Hd2 scenario is true that the suspect wore the mask 7 days before the offence and that fibres were recovered from the hair 7 days after the offence, then effectively we need to consider persistence data for up to 14 days (i.e. 7 days as used in Hp).

3. If the Hd2 scenario is true that the suspect wore the mask 14 days before the offence and that fibres were recovered from the hair 1-3 days after the offence, then effectively we need to consider persistence data for up to 17 days (i.e. 7 days as used in Hp).

4. If the Hd2 scenario is true that the suspect wore the mask 14 days before the offence and that fibres were recovered from the hair 7 days after the offence, then effectively we need to consider persistence data for up to 21 days (i.e. 7 days as used in Hp).

This is summarised in *Table 6.9:*

	Time of alleged pre-incident wear (Hd2)	**Effective time of persistence to consider (Hd2)**
1-3 days	7 days	10 days
7 days	7 days	14 days
1-3 days	14 days	17 days
7 days	14 days	21 days

Table 6.9: Times of fibre persistence considered under Hd2

The maximum likelihood estimates (MLE's) used for informing the conditional probability tables of node [7] under Hd2 are summarised in *Table 6.10*.

Head hair washed*					
Hd2 worn 7 days before			**Hd2 worn 14 days before**		
	Mask to head Hd2			**Mask to head Hd2**	
	1-3 days	**7 days**		**1-3 days**	**7 days**

	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution		Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$t_{>10}$	0.001	1	0.001	1	$t_{>10}$	0.001	1	0.001	1
$t_{5\text{-}10}$	0.005	5	0.001	1	$t_{5\text{-}10}$	0.001	1	0.001	1
$t_{1\text{-}5}$	0.02	20	0.002	2	$t_{1\text{-}5}$	0.002	2	0.002	2
t_0	0.974	978	0.996	1000	t_0	0.996	1000	0.996	1000
Head hair not washed*									
Hd2 worn 7 days before					**Hd2 worn 14 days before**				
	Mask to head Hd2					**Mask to head Hd2**			
	1-3 days		**7days**			**1-3 days**		**7days**	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution		Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$t_{>10}$	0.005	5	0.001	1	$t_{>10}$	0.001	1	0.001	1
$t_{5\text{-}10}$	0.015	15	0.001	1	$t_{5\text{-}10}$	0.001	1	0.001	1
$t_{1\text{-}5}$	0.68	683	0.002	2	$t_{1\text{-}5}$	0.002	2	0.002	2
t_0	0.3	301	0.996	1000	t_0	0.996	1000	0.996	1000

Table 6.10: Hd2 't' transfer probabilities under B1 are derived from Hp transfer data . *No data available, Dirichlet parameters based upon expectations from 1000 hypothetical observations (after adding prior counts).

6.4.3 Adventitious matches probability assignments (Node [10])

In order to evaluate the significance of the presence of fibres matching the mask, It is necessary to consider how likely it is that a particular target fibre type/ colour combination will be encountered by chance i.e. an 'adventitious' match. Since the probability of encountering an adventitious match will differ according to the fibre type/ colour combination in question (e.g. blue cottons, red acrylics), attempting to encompass all of these possibilities in a Bayesian network would result in a complicated architecture with questionable benefit.

Just (if not more importantly), this section illustrates the difficulty of obtaining numerical data for case specific fibres and the nature of the assumptions that have to be made in its absence. This situation is highlighted in a paper by *Vooijs, Vergeer et al., (2015)* and discussed in more detail in *Chapter 7*.

The pragmatic solution for the purposes of this thesis, is to provide fair and reasonable *generic* match probability estimates for 'rare' and 'common' target fibres. This will allow the effect of target fibre 'rarity' on the resultant likelihood ratio to be assessed.

According to *Palmer and Oliver, (2004),* blue cotton is encountered in head hair at a relative frequency of 0.23. The least likely fibre encountered in this study was green acrylic at a relative

frequency of 0.05. (*there being no specific data for red acrylic in this study*). Although these figures are very *generic* (i.e. they do not involve analytical comparison), they are useful as a base line comparison for more detailed estimates provided by colour block and target fibre studies.

6.4.3.1 Rare' fibre: Match probability estimation

The fibre population study of coloured fibres in head hair (*Palmer and Oliver, 2004*) provides the starting point for estimating a 'rare' fibre match probability.

As previously stated, there is no data available from this study specific to red acrylic fibres. Since we are ultimately trying to combine this study with a target fibre study relating to a specific red acrylic fibre, the most appropriate data to employ would be that relating to 'red synthetic' fibres as it is this group which the relevant target fibre studies initially recovered for further analysis against the specific target fibre.

The frequency of 'red synthetic' fibres in head hair has been estimated as 5%, based upon the 441 observations in this study.

The target fibre study relating to red acrylic fibres on cinema seats (*Palmer and Chinherende, 1996*) found a total of 16 matching targets fibres which had been subjected to the full instrumental methods of analysis and comparison, from a total of 824 red synthetic fibres initially recovered. Full analytical comparison in this study therefore gives a relative frequency of approximately 2%.

Similarly, the pan-European target fibre study involving red acrylic fibres (*Bruschweiler and Grieve, 1997*) found a total of 2 matching target fibres which had been subjected to the full instrumental methods of analysis and comparison, from a total of 435 fibres examined. Full analytical comparison in this study therefore gives a relative frequency of approximately 0.5%.

Since the data from the population study and target fibres studies are not strictly compatible in that there is no fibre population data relating to the specific target fibre type used in the relevant target fibre studies, it would appear pragmatic to base the estimates of the match probability in terms of theoretical counts (i.e. what we might expect had the data from each study been compatible). This essentially informs an expectation of outcome from a combination of theoretically compatible studies i.e. ;

824 (*Palmer and Chinherende, 1996*) + 435 (*Bruschweiler and Grieve, 1997*) =1259

Total number of matching fibres = 18, therefore frequency = 18/1259 = 0.014

Palmer and Oliver, (2004) Frequency estimate = 0.05

0.05 X 0.014 ~ 1400, gives a Dirichlet, *Dir* (1,1400), adding prior *Dir* (1,1) gives Dir (2,1401)

The final frequency estimate for 'rare' fibres is therefore 2/1401 **= 0.0014**

6.4.3.2 'Common' fibre: Match probability estimation

Again, the fibre population study of coloured fibres in head hair (*Palmer and Oliver, 2004*) provides the starting point for estimating a 'rare' fibre match probability. The 'commonest' types of fibre likely to be found in head hair are black/ grey and blue cotton. Since there is much more data concerning the discrimination of blue cotton fibres compared to black/ grey, data relating to blue cotton will be used to form a global estimate for the match probability of a 'common' fibre type.

The frequency of blue cotton fibres in head hair is reported by *Palmer and Oliver, (2004)* as 23%.

The unpublished data from a colour block study relating to blue cotton fibres on cinema seats (*Palmer and Luff, 2013*) found the most common distinguishable group accounted for 9% of 114 blue cotton fibres which had been subjected to MSP analysis.

Similarly, a parallel study involving blue cotton fibres on bus seats (*Palmer and Wagner, 2013*) found the most common distinguishable group accounted for 12% of 102 blue cotton fibres which had been subjected to MSP analysis.

Looking at the results of each of these colour block studies, a 'global' estimate of the frequency obtained for this fibre type colour combination using instrumental analysis of 10% seems fair and reasonable.

Using this frequency estimate with that obtained from the population study (0.23 x 0.1) therefore gives a frequency estimate of 0.023. This estimate is based upon 657 (441+114+102) observations. In consideration of the colour block and the population studies

we could expect to find 15 matching fibres (0.023 x 657) and 642 non- matching fibres (657-15).

Adding prior Dirichlet counts *Dir* (1,1) gives a distribution of *Dir* (16, 643). The maximum likelihood estimate is therefore **0.025** (16/643) for 'common' fibres**.**

These maximum likelihood estimates have been used to inform nodes [10] and [19] and represent the probability of finding 1 foreign fibre group containing an adventitious match with the target garment being comprised of a 'rare' or 'common' fibre type. The results also form the basis for calculating the probability that 2-5 foreign fibre groups and > 5 foreign fibre groups would contain an adventitious match (i.e. the match probabilities are obtained when the number of FFGs increases (Node [10] and node [19]) by considering for a group with a match probability of f and the probability of having at least one matching group with the total number of group = k. The probability is obtained using 1 minus the probability of having no correspondence). This was calculated using an R script shown *in Appendix 4*.

Node [12] effectively allows switching between the 'rare' and the 'common' match probability data for inclusion in the likelihood ratio generation.

The above illustrates the difficulty of obtaining compatible *case specific* information from population, colour block and target fibre studies which can inform the chances of obtaining adventitious matches for a given scenario. This situation will be further discussed in *Chapter 7*.

6.4.4 Foreign fibre group probability assignments (Nodes [9] and [11])

In the case of substrates such as pillowcases and head hair, these are highly likely to come into contact with items such as clothing, head gear, towels, bed linen and other textile items related to an individual's environment on a daily basis. The possibility of encountering more than two foreign fibre collectives is therefore very high.

Consequently, this means that substrates such as hair and pillowcases will (in a normal situation) be highly unlikely to be devoid of 'background' fibre collectives.

Casework experience (*Palmer, 2008*) and the results of studies (*Palmer and Oliver, 2004, Palmer and Banks, 2005*) support this view.

No. of FFG's	Maximum Likelihood Estimate	Dirichlet Parameters*
0	0.001	2
1	0.001	2
2-5	0.498	499
>5(max 20)	0.5	501

Table 6.11: Probability assignments for the number of foreign fibre collectives. *No data available, Dirichlet parameters based upon expectations from 1000 hypothetical observations (after adding prior counts).

For this reason, the probability assignments for foreign fibre collectives being present (nodes [9] and [17]) are the same for the primary and secondary 'transfer blocks' (B1 & B2) of the Bayesian network are shown in *Table 6.11*;

The above estimates would appear to be at odds with the results of a study reported by *Roux and Margot, (1997a)* concerning car seats. They reported the frequency figures for the number of background foreign fibre groups *of similar size to the crime relevant group* on 22 car seats as; no groups (1), 1 group (6), 2-5 groups (15) and more than 5 (0). The results however need to be considered in context, as cars are effectively 'semi-closed systems' with very different transfer and persistence characteristics compared to the substrates under consideration in this chapter.

Due to the extreme paucity of empirical data concerning this parameter on the substrate relevant to this chapter, the assignments have been made according to casework experience of the author using counts according to 50 hypothetical observations from hair. These are shown in *Table 6.12*.

Size. of FFG's	Maximum Likelihood Estimate	Dirichlet Parameters*
<=10	0.9	46
>10	0.1	6

Table 6.12: Probability assignments for the size of foreign fibre collectives. *Dirichlet parameters based upon expectations from 50 hypothetical observations (after adding prior counts).

The node states and definitions for block B2 are shown in *Table 6.13.* Node [15], contains the assigned secondary fibre transfer probability values which have been informed by the results of the study into the secondary transfer of fibres from head hair to pillow cases by Palmer and Banks, (2005). These values have been assigned for >10 fibres, between 1-10 fibres and 0 fibres. Note that for the 'secondary transfer block' of the network (B2), the transfer probabilities are designated 's'.

6.5 Secondary transfer block (B2) probability assignments

Node	States	Definition of states
14	Matching type M Fibres not type M	Recovered fibres indistinguishable from mask Recovered fibres distinguishable from mask
15	s>10 s1-10 s0	Finding >10 fibres under Hp, Hd1, Hd2 Finding 1-10 fibres under Hp, Hd1, Hd2 Finding 0 fibres under Hp, Hd1, Hd2
16	s>10 s1-10	finding > 10 non matching fibre finding 1-10 non matching fibres

	1nm Fibres No fibres	finding 1 non matching fibre groups finding no fibres
17	5-20 FFG 2-5 FFG 1 FFG 0 FFG	finding 5-20 foreign fibre groups finding 2-5 foreign fibre groups finding 1 foreign fibre group finding no foreign fibre groups
18	Small (<=10) Large (>10)	Sizes of FFG's under consideration
19	FFG matching type M FFG not type M	Probability assignment for an adventitious match with the fibres comprising the mask, given the number of FFG's recovered. Probability assignment for no adventitious matches with the fibres comprising the mask, given the number of FFG's recovered.
20	M(>10)/>1nG M(1-10)/>1nG M(>10)/ 1nG M(1-10)/ 1nG M(>10) M(1-10) >2nG 2nG 1nG No fibres	Considered outcomes for the combination of numbers matching fibres and non-matching fibre groups.
21	s>10/>1nG s1-10/>1nG s>10/1nG s1-10/1nG s>10 s1-10 No Match fibres No fibres	Considered outcomes for the combination of numbers matching fibres and non-matching fibre groups. conditioned by Node 20

Table 6.13: Description of nodes relating to secondary transfer block (B2)

6.5.1 Secondary transfer and persistence (s values)

The data provided by the study of the secondary transfer of fibres from head hair to pillowcases by *Palmer and Banks, (2005)* shows that wool, cotton and acrylic fibres all have different secondary transfer characteristics. Again, attempting to encompass all of these possibilities in a Bayesian network would result in an extremely complicated architecture with questionable benefit. As before, a fair and reasonable *generic* estimate based upon 'upper' and 'lower' limits of observed secondary transfer has been obtained from the data shown in *Figure 6.5*;

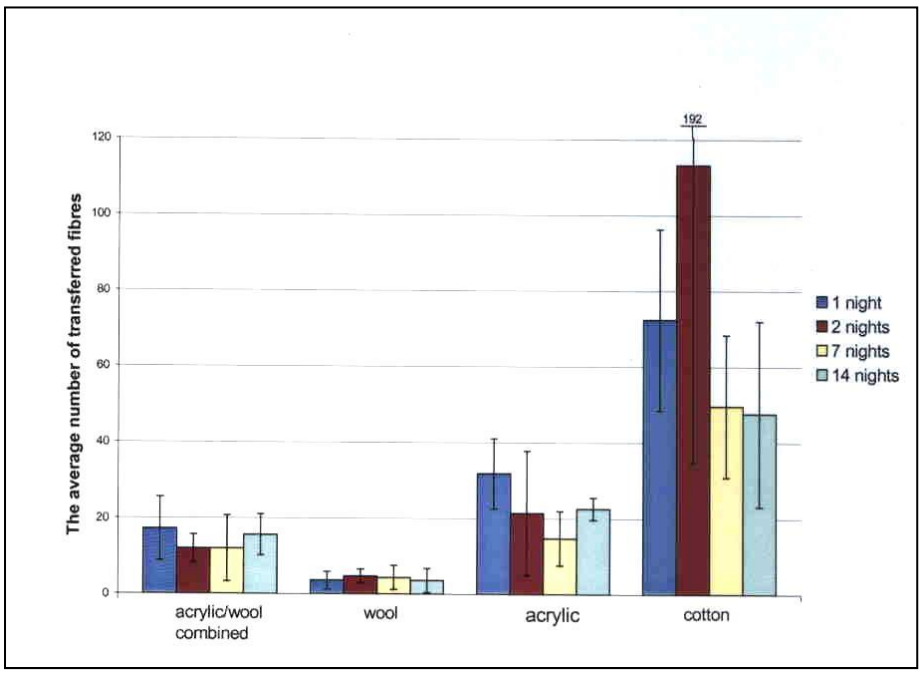


Figure 6.5: Persistence data on fibres secondarily transferred from head hair to pillowcases (*Palmer and Banks, 2005*).

Figure 6.5 shows the mean number (with standard deviations marked) of wool, acrylic and cotton fibres persisting over a 2 week period following secondary transfer from head hair to pillowcases. In considering the variation around the mean values for acrylic and cotton, it can be seen that there would be a very high expectation of recovering more than 10 of these fibre types over a 2 week period. It can be seen that the persistence data for secondarily transferred items on this substrate is very 'flat' (i.e. does not change significantly) over the time periods considered in this scenario compared to that for primary fibre transfer to head hair.

B1	Mask to Hair+			
	t>10			
B2	Hair to pillow			
	1-3 days		7days	
	Maximum Likelihood Estimate	Dirichlet Parameters	Maximum Likelihood Estimate	Dirichlet Parameters
s>10	0.6	50	0.6	50
s1-10	0.39	32	0.39	32
s0	0.01	1	0.01	1
B1	Mask to Hair+			
	t5-10			
B2	Hair to pillow			
	1-3 days		7days	
	Maximum Likelihood Estimate	Dirichlet Parameters	Maximum Likelihood Estimate	Dirichlet Parameters
s>10	0.6	50	0.6	50
s1-10	0.39	32	0.39	32
s0	0.01	1	0.01	1
B1	Mask to Hair+			
	t1-5			
B2	Hair to pillow			
	1-3 days		7days	
	Maximum Likelihood Estimate	Dirichlet Parameters	Maximum Likelihood Estimate	Dirichlet Parameters
s>10	0.3	25	0.3	25
s1-10	0.69	57	0.69	57
s0	0.01	1	0.01	1
B1	Mask to Hair*			
	t=0			
B2	Hair to pillow			
	1-3 days		7days	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameters
s>10	0.001	1	0.001	1
s1-10	0.003	3	0.003	3
s0	0.996	999	0.996	999

Table 6.14: Transfer probability assignments for secondary transfer (B2) under Hp based on *Palmer and Banks (2005)*. +Dirichlet parameters based upon a total of 80 observations (after adding prior counts). *No data available, Dirichlet parameters based upon expectations from 1000 hypothetical observations (after adding prior counts).

This is reflected in the 's' probability assignments in *Table 6.14.*

The transfer probability assignments for 's' under Hd1, are shown in *Table 6.15*;

Head to pillow Hd1				
Hp	**1-3 days**		**7days**	
	Maximum Likelihood Estimate	Dirichlet Parameters	Maximum Likelihood Estimate	Dirichlet Parameters
$S_{>10}$	0.001	2	0.001	2
S_{5-10}	0.003	4	0.003	4
S_0	0.996	997	0.996	997

Table 6.15: Transfer probability assignments for 's' under Hd1

The assignments remain the same irrespective of washing/ non washing of the donor head hair.

Since it has been demonstrated that fibres secondarily transferred to pillowcases can persist for up to 14 days (no data available beyond this), 's' transfer probability under Hd1 can be applied to Hd2 if the effective time of persistence is the same (i.e. 7 days pre- offence Hd2, 7 days post offence recovery).

Based upon the data from the *Palmer and Banks, (2005)* study, fair and reasonable 's' transfer probability assignments for Hd2 are illustrated in *Table 6.16*;

Hd2 = 7 days (80)				
Hp	**1-3 days**		**7days**	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$S_{>10}$	0.3	25	0.3	25
$S_{1\text{-}10}$	0.69	57	0.69	57
S_0	0.01	1	0.01	1
Hd2 = 14 days (1000*)				
Hp	**1-3 days**		**7days**	
	Maximum Likelihood Estimate	Dirichlet Parameter Distribution	Maximum Likelihood Estimate	Dirichlet Parameter Distribution
$S_{>10}$	0.3	301	0.1	100
$S_{1\text{-}10}$	0.65	652	0.85	853
S_0	0.05	50	0.05	50

Table 6.16: Hd2 Transfer probabilities assignments for 7 and 14 days pre-offence transfer under (B2\B1). *1000 hypothetical observations used for 14 days pre-offence wear under Hd2 as no experimental data available for this timeframe.

6.5.2 Adventitious matches probability assignments (Node [19])

Since the estimates of match probability estimates obtained for 'rare' and 'common' fibres are global in nature, assignments used for the conditional probability tables in node [10] in block B1 are also applicable to node [19] in block B2.

6.5.3 Foreign fibre group probability assignments (Nodes [17] and [18])

As stated in section 6.4.2, casework experience (*Palmer, 2008*) and the results of studies (*Palmer and Oliver, 2004, Palmer and Banks, 2005*) suggest that the number and size of foreign fibre groups are unlikely to be significantly different between hair and pillowcases. It may also be the case that the provenance of some allegedly foreign fibre groups on these

substrates may be determined as originating from the individual's environment. For this reason the conditional probability tables used for nodes [9] and [11] in block B1 have been deemed applicable to nodes [17] and [18] in block B2.

6.6 Case Scenario Parameters

In this Bayesian network model, we can condition transfer and persistence probability assignments (Nodes [7] and [15]) according to;

- How long after the incident it was before the suspect was apprehended and fibres recovered from his hair (Node [3],'Time of recovery since incident'). In this model the two possibilities are 3 days and 7 days.
- Whether or not the suspect washed his hair (Node [5], 'Hair washed prior to fibre recovery').
- *Under Hd2 only*, where the defence proposition is that the mask was worn prior to the incident but not during it (Node [4], 'Time of wear') 7 days and 14 days are the time periods considered.

Case Scenario Number		Code	1	2	3	4	5	6	7	8	9
Time of Recovery	1-3 Days	R1-3	0.5	1	1	1	1	0	0	0	0
	7 Days	R>7	0.5	0	0	0	0	1	1	1	1
Pre-Incident Wear	7 Days	W7	0.5	1	1	0	0	1	1	0	0
	14 Days	W14	0.5	0	0	1	1	0	0	1	1
Hair Washed?	Yes	Wa	0.5	1	0	1	0	1	0	1	0
	No	nWa	0.5	0	1	0	1	0	1	0	1

Table 6.17: Case scenario possibilities

Case	Codes under Hd1	Codes under Hd2
1	unspecified	unspecified
2	R1-3, Wa	R1-3, W7, Wa
3	R1-3, nWa	R1-3, W7, nWa
4		R1-3, W14, Wa
5		R1-3, W14, nWa
6	R>7, Wa	R>7, W7, Wa
7	R>7, nWa	R>7, W7, nWa
8		R>7, W14, Wa
9		R>7, W14, Wa

Table 6.18: Case scenario codes

Tables 6.17 and 6.18 lists the different case scenario possibilities applied by the Bayesian network model in this chapter and the corresponding codes used to describe them. *Table 6.18* shows the scenarios and codes relevant to Hd1 and Hd2. These tables are used to inform the evaluation of the contribution of the secondary transfer block B2 to the likelihood ratio in *Section 6.7* as well as to automate the simulation runs during the sensitivity analysis described in *Section 6.9.2.*

6.7 Evaluation of contribution of secondary transfers to the Likelihood Ratio

6.7.1 Case scenarios employed

The case scenarios and the relevant codes shown in *Table 6.17* and *6.18* described in *Section 6.6* used for the sensitivity analysis, are also used to inform the evaluation of the contribution of the secondary transfer block B2 to the likelihood ratios.

Under Hd1 (where the suspect denies wearing the mask) it can be seen that case scenario 3 (R1-3, nWa) is potentially the most favourable to the recovery of crime relevant fibres if Hp is correct, since the parameters provide the best conditions for the retention of transferred fibres. In contrast, case scenario 6 (R>7, Wa) is the least favourable to the recovery of crime relevant fibres if Hp is correct, since any fibres transferred at the relevant time would be unlikely to persist at the time of recovery.

Under Hd2 (where the suspect admits to wearing the mask prior to, but not at the time of the incident) it can be seen that case scenario 5 (R1-3, W14, nWa) is potentially most favourable to the recovery of crime relevant fibres if Hp is correct, since it is unlikely that any case relevant fibres would persist given the timescales specified under Hd2. In contrast, case scenario 6 (R>7, W7, Wa) is the least favourable to the recovery of crime relevant fibres if Hp is correct, since the parameters specified under Hd2 could potentially allow a small number of crime relevant fibres to persist , or none at all, if either Hp or Hd was true.

Case scenarios 3, and 6 will therefore be used to evaluate the contribution of the findings relating to the secondary transfer in block B2 of the Bayesian network under Hd1, with scenarios 5 and 6 used under Hd2.

In addition, the contribution of secondary transfer data of the pillowcases to the global LR will be considered in situations where no fibres are found in head hair when they might be expected (e.g. recovery 1-3 days) as well as when their absence may be explained (e.g. recovery 7 days).

6.7.2 Case scenario 3 under Hd1

Case scenario 3 is the situation where the suspect has been apprehended 1-3 days after the incident and his head hair has been taped and fibres recovered. His hair has not been washed since the incident. This scenario provides the best potential to recover crime relevant material, if the suspect had worn the mask as alleged.

Applying the above parameters to the Bayesian network in *pre-assessment mode* (i.e. where the expectations of fibre transfer for 'rare' fibres are calculated on the assumption that the prosecution proposition is correct) the results indicate the most likely outcome for secondary fibre transfer (in this case with a probability of 0.302) would be t(>10)/>5nm (i.e. more than 10 matching fibres found in the presence of more than 5 non-matching fibre groups) recovered from the head hair tapings for the primary transfer (B1). Likewise the most likely outcome for fibre transfer (in this case with a probability of 0.566) would be s(>10)/>5nm (i.e. more than 10 matching fibres found in the presence of more than 5 non-matching fibre groups) recovered from the pillow case tapings for the primary transfer (B2). The same predicted outcome occurred for common fibres (t(>10)/>5nm in B1 and s(>10)/>5nm in B2).

This is shown in *Figure 6.6;*

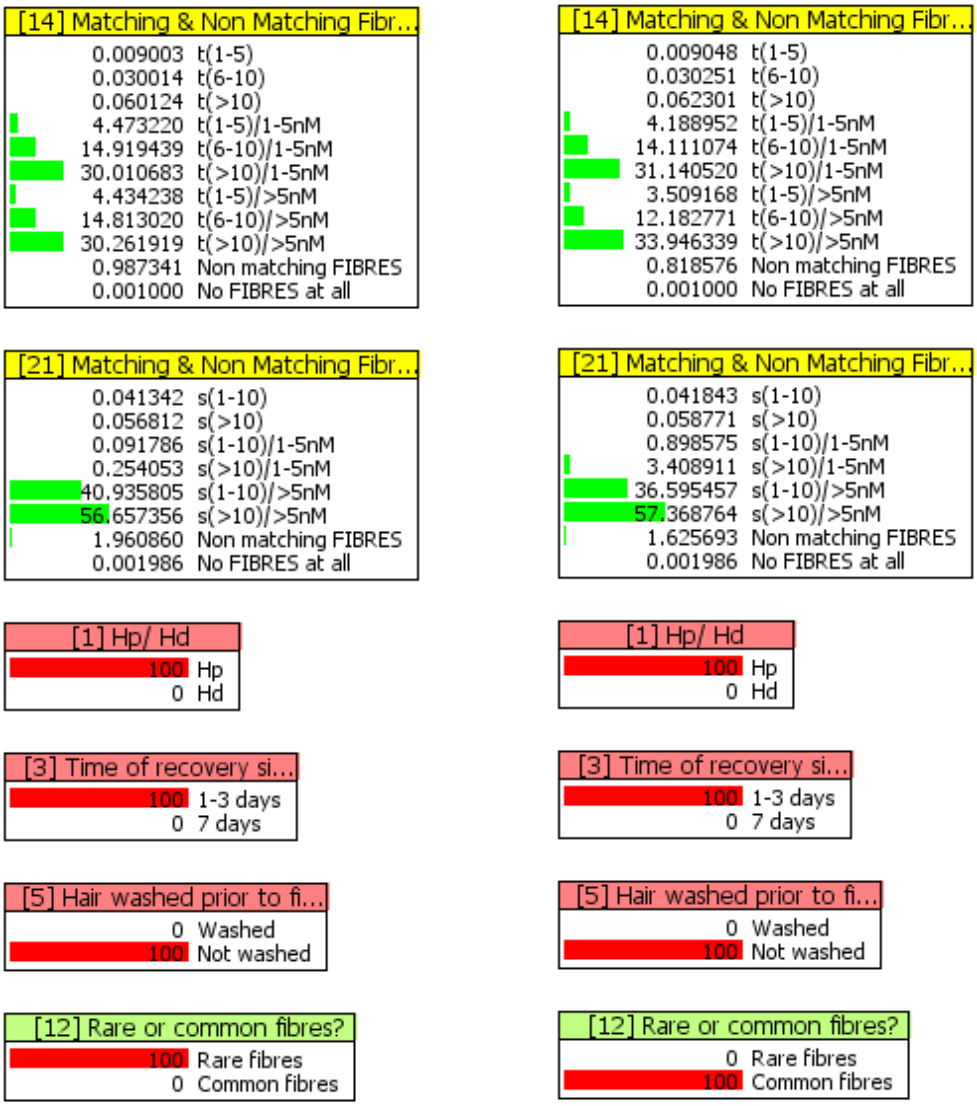


Figure 6.6: Bayesian network assessment of fibre transfer for case scenario 3 (B1) where Hp is true for respectively 'rare' and 'common' fibres.

The most likely outcomes obtained from the 'pre-assessment' mode (highlighted in yellow) given this scenario, (*Table 6.19*) were then used in the 'evaluative' mode of the Bayesian network to generate likelihood ratios for the primary transfer block only (LR(B1)), the secondary transfer block only (LR(B2)), where the secondary transfer is conditioned by the number of primary transferred fibres (LR(B2|B1)) and where the primary and secondary transfers are independent of each other (LR(B1, B2)).

Rare Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.009	1-10	0.041
6-10	0.030	>10	0.056
>10	0.060	1-10/1-5nm	0.091
1-5/1-5nm	4.473	>10/1-5nm	0.254
6-10/1-5nm	14.919	1-10/>5nm	40.935
>10/1-5nm	30.010	>10/>5nm	56.657
1-5/>5nm	4.434	Non Matching Fibres	1.960
6-10/>5nm	14.813	No Fibres	0.001
>10/>5nm	30.261		
Non Matching Fibres	0.987		
No Fibres	0.001		
Common Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.009	1-10	0.041
6-10	0.030	>10	0.058
>10	0.062	1-10/1-5nm	0.087
1-5/1-5nm	4.197	>10/1-5nm	3.315
6-10/1-5nm	14.135	1-10/>5nm	36.715
>10/1-5nm	31.107	>10/>5nm	57.357
1-5/>5nm	3.533	Non Matching Fibres	1.634
6-10/>5nm	12.25	No Fibres	0.001
>10/>5nm	33.849		
Non Matching Fibres	0.823		
No Fibres	0.001		

Table 6.19: Results showing the outcome probabilities in scenario 3 for 'rare' and 'common' fibre types in 'pre-assessment' mode under Hd1.

Results were obtained and compared using match probability assignments for 'rare' and 'common' fibres. This is shown in *Table 6.20.*

Fibre Type	p(E1|Hp)/ p(E1|Hd) (B1)	LR (B1)	p(E2|Hp)/ p(E2|Hd) (B2)	LR (B2)	p(E2|Hp)/ p(E2|Hd (B2|B1)	LR (B2|B1)	p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)	LR(B1, B2)
Rare	99.69/ 0.30	330	59.89/ 0.09	611	99.83/ 0.16	646	LR(B1) x LR(B2)	201630
Common	96.16/ 3.83	26	97.7/ 2.29	43	59.97/ 1.35	44	LR(B1) x LR(B2)	1118

Table 6.20: Results showing the effect of the inclusion of secondary transfer evidence in case scenario 3 for 'rare' and 'common' fibre types under Hd1.

The results show that for case scenario 3 (R1-3, W7, nWa), consideration of the presence of matching secondarily transferred fibres on the suspect's pillow case increases the significance of the fibre evidence as a whole.

In considering these likelihood ratio values in terms of the *Association of Forensic Science Providers, (2009)* verbal equivalence scale, this equates to a change from 'moderately strong' support to 'extremely strong' support for Hp, where the target fibre is a 'rare' type and the findings in B2 are not conditioned by B1. Where the target fibre is a 'common' type, the change in support for Hp increases from '*moderate*' support to '*strong*' support.

It can be seen from the results that for both rare and common fibres, LR(B2) and LR(B2|B1) are very similar and are almost double that of LR(B1). This demonstrates that under the scenario in question, the presence of large numbers of fibres in the head hair has a large conditioning effect on the number of fibres expected on the pillow case (the more fibres in the head hair, the more likely to be secondarily transferred to the pillowcase). Interestingly, this suggests that in such a casework situation, it may be strategically more effective to look for secondary transfers as a priority – a situation that would likely be counter intuitive to most fibre examiners or investigators.

6.7.3 Case scenario 6 under Hd1

Case scenario 6 (R>7, Wa) is the situation where the suspect has been apprehended 7 days after the incident and his head hair has been taped and fibres recovered. His hair has been washed since the incident. This scenario is therefore potentially the most favourable to the

defence in that the potential to recover crime relevant material, if the suspect had worn the mask as alleged, is low.

Applying the above parameters to the Bayesian network in *pre-assessment mode* (as described for scenario 3) the results indicate that for 'rare' fibres the most likely outcome for primary fibre transfer to head hair (B1) is t(1-5)/>5nm fibres and for the secondary transfer to pillowcase (B2) is s(1-10)>5nm with p(0.6) and p(1.53) respectively. A similar outcome was obtained for 'common' fibres t(1-5)/>5nm fibres for B1 and s(1-10)>5nm for B2). This is shown in *Table 6.21*.

As with the previous case scenario, the results most expected by the pre-assessment mode, were used to inform the 'evaluative' mode of the Bayesian network to generate likelihood ratios. Results were obtained and compared using match probability assignments for 'rare' and 'common' fibres respectively. This is shown in *Table 6.22.*

The results show that for case scenario 6, where 'rare' fibres are under consideration, the presence of matching secondarily transferred fibres on the suspect's pillow case increases the significance of the fibre evidence as a whole, albeit to a much lesser extent than in case scenario 3.

Again, using the *Association of Forensic Science Providers, (2009)* verbal equivalence scale, these likelihood ratio values, equate to a change from '*limited/ inconclusive*' support to '*moderate*' support for Hp, where the target fibre is a 'rare' type. The inclusion of findings from B2 has no impact when a 'common' target fibre is under consideration.

Rare Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.000463	1-10	0.000855
6-10	0.000263	>10	0.000474
>10	0.000215	1-10/1-5nm	0.222056
1-5/1-5nm	0.30945	>10/1-5nm	0.027904
6-10/1-5nm	0.210568	1-10/>5nm	1.538805
>10/1-5nm	0.125159	>10/>5nm	0.551510
1-5/>5nm	0.606577	Non Matching Fibres	97.560396
6-10/>5nm	0.509971	No Fibres	0.098811
>10/>5nm	0.193860		
Non Matching Fibres	97.944275		
No Fibres	0.099200		
Common Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.001518	1-10	0.002961
6-10	0.001322	>10	0.000728
>10	0.000461	1-10/1-5nm	3.655400
1-5/1-5nm	2.013518	>10/1-5nm	0.440263
6-10/1-5nm	1.928862	1-10/>5nm	12.638541
>10/1-5nm	0.518548	>10/>5nm	1.826313
1-5/>5nm	6.175145	Non Matching Fibres	81.336984
6-10/>5nm	6.125013	No Fibres	0.098811
>10/>5nm	1.479387		
Non Matching Fibres	81.657027		
No Fibres	0.099200		

Table 6.21: Results showing the outcome probabilities in scenario 6 for 'rare' and 'common' fibre types in 'pre-assessment' mode under Hd1.

Fibre Type	p(E1|Hp)/ p(E1|Hd) (B1)	LR (B1)	p(E2|Hp)/ p(E2|Hd) (B2)	LR (B2)	p(E2|Hp)/ p(E2|Hd (B2|B1)	LR (B2|B1)	p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)
Rare	59.49/ 40.50	2	64.98/ 35.01	2	22.94/ 0.82	28	4
Common	50.43/ 49.56	1	51 / 48.99	1	13.57/ 12.14	1	1

Table 6.22: Results showing the effect of the inclusion of secondary transfer evidence in case scenario 6 for 'rare' and 'common' fibre types under Hd1.

6.7.4 Case scenario 5 under Hd2

Case scenario 5 is the situation where the suspect has been apprehended 1-3 days after the incident and his head hair has been taped and fibres recovered. He maintains he wore the mask in question 14 days before the incident but did not wear it since then. His hair has not been washed since the incident. This scenario is therefore potentially the most favourable to Hp in that the potential to recover crime relevant material, if the suspect had worn the mask as alleged, is high, whereas if Hd2 is correct, it is unlikely that significant numbers of matching fibres would be recovered.

Again, applying the above parameters to the Bayesian network in pre-assessment mode (i.e. where the expectations of fibre transfer are calculated on the assumption that the prosecution proposition is correct) the results indicate the most likely outcome for 'rare' fibre transfer for B1 would be t(>10)/>5nm and s(>10)>5nm for B2. The similar outcome was predicted for 'common' target fibres except that the predicted outcome for B2 was s(1-10)>5nm. This is shown in *Table 6.23*.

As with the case scenarios under Hd1, the results most expected from the assessment mode, were used in the 'evaluative' mode of the Bayesian network to generate likelihood ratios as for the previous scenarios. Results were obtained and compared using match probability assignments for 'rare' and 'common' fibres. This is shown in *Table 6.24.*

Rare Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.009003	1-10	0.041342
6-10	0.030014	>10	0.056812
>10	0.060124	1-10/1-5nm	0.091786
1-5/1-5nm	4.473220	>10/1-5nm	0.254053
6-10/1-5nm	14.919439	1-10/>5nm	40.935805
>10/1-5nm	30.010683	>10/>5nm	56.657356
1-5/>5nm	4.434238	Non Matching Fibres	1.960860
6-10/>5nm	14.813020	No Fibres	0.001986
>10/>5nm	30.261919		
Non Matching Fibres	0.987341		
No Fibres	0.001		
Common Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.005184	1-10	0.053833
6-10	0.015732	>10	0.045174
>10	0.031284	1-10/1-5nm	1.159969
1-5/1-5nm	3.062702	>10/1-5nm	3.028629
6-10/1-5nm	8.010370	1-10/>5nm	47.354497
>10/1-5nm	15.785520	>10/>5nm	45.479122
1-5/>5nm	4.827900	Non Matching Fibres	2.875282
6-10/>5nm	9.174643	No Fibres	0.003493
>10/>5nm	17.631642		
Non Matching Fibres	41.404722		
No Fibres	0.0503		

Table 6.23: Results showing the outcome probabilities in case scenario 5 for 'rare' and 'common' fibre types in 'pre-assessment' mode under Hd2.

Fibre Type	p(E1|Hp)/ p(E1|Hd) (B1)	LR (B1)	p(E2|Hp)/ p(E2|Hd) (B2)	LR (B2)	p(E2|Hp)/ p(E2|Hd (B2|B1)	LR (B2|B1)	p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)
Rare	99.53/ 0.46	212	65.23/ 34.76	2	59.89/ 30.198296	2	420
Common	95.98/ 4.01	24	38.76/ 61.23	1	34.87/ 57.99	1	24

Table 6.24: Results showing the effect of the inclusion of secondary transfer evidence in case scenario 5 under Hd2 for 'rare' and 'common' fibre types.

The results show that for case scenario 5, under Hd2, consideration of the presence of matching secondarily transferred fibres on the suspect's pillow case has a very minimal effect on significance of the fibre evidence as a whole.

In considering these likelihood ratio values in terms of the *Association of Forensic Science Providers, (2009)* verbal equivalence scale, the inclusion of secondary transfer evidence from B2 does not change the verbal level of support from '*moderately strong*' support for Hp, where the target fibre is a 'rare' and B2 is not conditioned by B1. In the case of 'common' target fibres, the same is also true, except that the scale of support is lower at '*moderate*' support.

Interestingly when B2 is conditioned by B1, the level of support drops to '*limited/ inconclusive*', for both types of target fibres.

6.7.5 Case scenario 6 under Hd2

Case scenario 6 is the situation where the suspect has been apprehended 7 days after the incident and his head hair has been taped and fibres recovered. He maintains he wore the mask in question 7 days before the incident but did not wear it since then. His hair has been washed since the incident. This scenario is therefore potentially the most favourable to Hd, in that the potential to recover crime relevant material, if the suspect had worn the mask as alleged under Hp and Hd2, is very similar.

Applying the above parameters to the Bayesian network in assessment mode (as for the previous scenarios) the results indicate the most likely outcome for 'rare' fibre transfer for B1 would be t(1-5)/>5nm and s(1-10)>5nm for B2. The same outcome was predicted for 'common' target fibres, as shown in *Table 6.25*.

Results obtained using the same evaluation exercise performed in the previous sections were compared using match probability assignments for both 'rare' and 'common' fibres. The results of this evaluation are shown in *Table 6.26.*

Rare Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.000463	1-10	0.000855
6-10	0.000263	>10	0.000474
>10	0.000215	1-10/1-5nm	0.222056
1-5/1-5nm	0.309450	>10/1-5nm	0.027094
6-10/1-5nm	0.210568	1-10/>5nm	1.538805
>10/1-5nm	0.125159	>10/>5nm	0.551510
1-5/>5nm	0.606577	Non Matching Fibres	97.560396
6-10/>5nm	0.509971	No Fibres	0.098811
>10/>5nm	0.193860		
Non Matching Fibres	97.944275		
No Fibres	0.09920		
Common Fibres			
Outcome t values	**p**	**Outcome s values**	**p**
1-5	0.001518	1-10	0.002961
6-10	0.001322	>10	0.000728
>10	0.000461	1-10/1-5nm	3.655400
1-5/1-5nm	2.013518	>10/1-5nm	0.440263
6-10/1-5nm	1.928862	1-10/>5nm	12.638541
>10/1-5nm	0.518548	>10/>5nm	1.826313
1-5/>5nm	6.175145	Non Matching Fibres	81.336984
6-10/>5nm	6.125013	No Fibres	0.098811
>10/>5nm	1.479387		
Non Matching Fibres	81.657027		
No Fibres	0.0992		

Table 6.25: Results showing the outcome probabilities in scenario 6 for 'rare' and 'common' fibre types in 'pre-assessment' mode under Hd2.

Fibre Type	p(E1|Hp)/ p(E1|Hd) (B1)	LR (B1)	p(E2|Hp)/ p(E2|Hd) (B2)	LR (B2)	p(E2|Hp)/ p(E2|Hd (B2|B1)	LR (B2|B1)	p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)
Rare	54.33/ 45.66	1	2.20/ 97.79	0.2	22.94/ 68.35	0.3	0.2
Common	50.21/ 49.78	1	17.15/ 82.8	0.2	13.57/ 61.03	0.2	0.2

Table 6.26: Results showing the effect of the inclusion of secondary transfer evidence in case scenario 6 under Hd2 for 'rare' and 'common' fibre types.

The results show that for case scenario 6, under Hd2, consideration of the presence of matching secondarily transferred fibres on the suspect's pillow case produces a likelihood ratio which slightly favours Hd2 regardless of target fibre type as opposed to a purely 'neutral' evaluation from B1 alone.

In considering these likelihood ratio values in terms of the *Association of Forensic Science Providers, (2009)* verbal equivalence scale, the change in likelihood ratio amounts to '*limited*' support for Hd2.

6.7.6 Case where no matching fibres found in head hair under Hd1

Whilst the previous examples examined the effect of finding matching fibres on the head and pillowcase on the resultant likelihood ratio, the following examples consider the effect of finding matching fibres on the pillowcase, but no fibres on the head hair of the suspect under *Hd1*. The effect is examined using case scenarios 2 and 3 where one may expect to find fibres in the suspects hair if Hp is true (i.e. R1-3, W and R1-3, nW) and in case scenarios 6 and 7 where finding no fibres in the suspects head hair may not be unexpected (i.e. R>7, W and R>7, nW). The latter scenarios will address questions 3 and 4 posed at the beginning of the chapter concerning the strategic value of seizing pillowcases where the suspect has been apprehended outside the expected period of persistence of fibres in head hair.

Fibre recovery 1-3 days post-incident

Suspect apprehended 1-3 days post incident, with no matching fibres found in head hair. The two possible (positive) outcomes for B2 (s(>10)/>5nm and s1-10)>5nm) are evaluated for these scenarios where the hair has been subjected to washing, or not. *Table 6.27* shows the results of this evaluation.

Fibre recovery >7 days post-incident

Suspect apprehended >7 days post incident, with no matching fibres found in head hair. The two possible (positive) outcomes for B2 (s(>10)/>5nm and s1-10)>5nm) are evaluated for these scenarios where the hair has been subjected to washing, or not. *Table 6.28* shows the results of this evaluation.

1-3 Days Post Incident (Hair Not Washed)							
s(>10)/>5nm							
Fibre Type	**p(E|Hp)/ p(E|Hd) (B1)**	**LR (B1)**	**p(E|Hp)/ p(E|Hd) (B2)**	**LR (B2)**	**p(E|Hp)/ p(E|Hd) (B2|B1)**	**LR (B2|B1)**	**LR(B1, B2)**
Rare	0.99/ 99.0	0.01	99.84/ 0.16	624	0.19/ 0.09	2	6
Common	0.99/ 99.0	0.01	97.70/ 2.29	43	1.46/ 1.35	1	4
(Hair Washed)							
s(>10)/>5nm							
Fibre Type	**p(E|Hp)/ p(E|Hd) (B1)**	**LR (B1)**	**p(E|Hp)/ p(E|Hd) (B2)**	**LR (B2)**	**p(E|Hp)/ p(E|Hd) (B2|B1)**	**LR (B2|B1)**	**LR(B1, B2)**
Rare	9.09/ 90.9	0.1	99.79/ 0.21	475	0.19/ 0.09	2	47
Common	9.09/ 90.9	0.1	97.09/ 2.90	33	1.46/ 1.34	1	3
(Hair Not Washed)							
s(1-10)/>5nm							
Fibre Type	**p(E|Hp)/ p(E|Hd) (B1)**	**LR (B1)**	**p(E|Hp)/ p(E|Hd) (B2)**	**LR (B2)**	**p(E|Hp)/ p(E|Hd) (B2|B1)**	**LR (B2|B1)**	**LR(B1, B2)**
Rare	0.99/ 99.0	0.01	98.02/ 1.98	50	1.12/ 0.83	1	0.5
Common	1.07/ 98.93	0.01	75.14/ 24.85	3	12.35/ 12.14	1	0.03
(Hair Washed)							
s(1-10)/>5nm							
Fibre Type	**p(E|Hp)/ p(E|Hd) (B1)**	**LR (B1)**	**p(E|Hp)/ p(E|Hd) (B2)**	**LR (B2)**	**p(E|Hp)/ p(E|Hd) (B2|B1)**	**LR (B2|B1)**	**LR(B1, B2)**
Rare	9.09/ 90.9	0.1	98.02/ 1.79	55	1.12/ 0.83	1	5
Common	9.09/ 90.9	0.1	77.4/ 22.59	3	12.35/ 12.14	1	0.3

Table 6.27: Effect of finding no fibres in head hair on the global likelihood ratio (1-3 days post incident recovery) under Hd1.

For fibre recovery occurring 1-3 days post incident, the results (*Table 6.25*) show that irrespective of whether the head has been washed or fibre rarity, both observational outcomes, are virtually inconclusive for Hp and Hd1 when node [15] (secondary transfer) is conditioned by node [7] (primary transfer), i.e. B2|B1.

Under B1,B2 the results provide weak support, irrespective of rarity, for Hp when s(>10)/>5nm transferred fibres are recovered from pillowcases when hair washing has not occurred. When s(1-10)/>5nm transferred fibres are recovered from pillowcases when no hair washing occurred, rare fibres produce weak support for Hd1 whilst common fibres produce moderate support.

Where the hair has been washed, under B1,B2, s(>10)/>5nm transferred fibres recovered from pillowcases provide moderate support for Hp when the fibres are rare, but weak support for Hp when they are common. When s(1-10)/>5nm transferred fibres are recovered from pillowcases, rare fibres provide weak support for Hp whilst common fibres provide weak support for Hd1.

For fibre recovery occurring > 7 days post incident, the results *(Table 6.28*) again, show that irrespective of whether the head has been washed or fibre rarity, both observational outcomes, are virtually inconclusive for Hp and Hd1 when node [15] (secondary transfer) is conditioned by node [7] (primary transfer), i.e. B2|B1.

Under B1,B2 for rare fibres, the results provide moderate support, for Hp when s(>10)/>5nm transferred fibres are recovered from pillowcases when hair washing has not occurred, but only weak support in the case of common fibres. When s(1-10)/>5nm transferred fibres are recovered from pillowcases when no hair washing occurred, again, rare fibres produce moderate support for Hp whilst common fibres are inconclusive for Hp and Hd1.

Where the hair has been washed, under B1,B2, s(>10)/>5nm transferred fibres recovered from pillowcases provide weak support for Hp when the fibres are rare, but are inconclusive for Hp and Hd when they are common. When s(1-10)/>5nm

transferred fibres are recovered from pillowcases the results are inconclusive for Hp and Hd1 irrespective of rarity.

>7 Days Post Incident (Hair Not Washed)							
s(>10)/>5nm							
Fibre Type	**p(E1|Hp)/ p(E1|Hd) (B1)**	**LR (B1)**	**p(E2|Hp)/ p(E2|Hd) (B2)**	**LR (B2)**	**p(E2|Hp)/ p(E2|Hd (B2|B1)**	**LR (B2|B1)**	**p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)**
Rare	23.07/ 6.92	0.3	99.56/ 0.42	235	0.19/ 0.09	2	70
Common	23.07/76.92	0.3	94.8/ 5.19	18	1.46/ 1.34	1	6
(Hair Washed)							
s(>10)/>5nm							
Fibre Type	**p(E1|Hp)/ p(E1|Hd) (B1)**	**LR (B1)**	**p(E2|Hp)/ p(E2|Hd) (B2)**	**LR (B2)**	**p(E2|Hp)/ p(E2|Hd (B2|B1)**	**LR (B2|B1)**	**p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)**
Rare	49.79/ 50.2	1	85.59/ 14.4	6	0.19/ 0.09	2	6
Common	49.79/ 50.2	1	57.49/ 42.5	1	1.46/ 1.34	1	1
(Hair Not Washed)							
s(1-10)/>5nm							
Fibre Type	**p(E1|Hp)/ p(E1|Hd) (B1)**	**LR (B1)**	**p(E2|Hp)/ p(E2|Hd) (B2)**	**LR (B2)**	**p(E2|Hp)/ p(E2|Hd (B2|B1)**	**LR (B2|B1)**	**p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)**
Rare	23.07/ 76.92	0.3	99.28/ 1.71	60	1.12/ 0.83	1	20
Common	23.07/ 76.92	0.3	79.08/ 20.91	4	12.35/ 12.14	1	1
(Hair Washed)							
s(1-10)/>5nm							
Fibre Type	**p(E1|Hp)/ p(E1|Hd) (B1)**	**LR (B1)**	**p(E2|Hp)/ p(E2|Hd) (B2)**	**LR (B2)**	**p(E2|Hp)/ p(E2|Hd (B2|B1)**	**LR (B2|B1)**	**p(E1,E2)|Hp)/ p(E1,E2)|Hd) (B1,B2)**
Rare	49.79/ 50.2	1	64.58/ 35.01	2	1.12/ 0.83	1	2
Common	49.79/ 50.2	1	51.00/ 48.99	1	12.35/ 12.14	1	1

Table 6.28: Effect of finding no fibres in head hair on the global likelihood ratio (> 7 days post incident recovery) under Hd1

It can be seen from the results that the LR's generated for B1 (primary transfer to head hair) in all circumstances are very low, due to the expectation that if Hp was true, one would expect to recover matching fibres given the time scales and circumstances under consideration. Since the outcomes relating to B2 (secondary transfer to pillow cases) are conditioned by B1 (i.e. B2|B1), the significance of finding secondarily transferred fibres is

considerably reduced. In a case scenario where matching fibres may be expected to be recovered from a suspects head hair, this conditioning can be considered appropriate.

However, where the case circumstances suggest that fibres from the head hair have resulted in a secondary transfer, but *the primary transfer has subsequently been removed* (through washing or as a consequence of time) the conditioning of transfer node [15] by transfer node [7], may in such circumstances not be reasonable. In such a very specific scenario, it may be more appropriate to consider using the likelihood ratio generated for B2 alone since this is likely to provide a more robust evaluation of the evidence in such circumstances.

6.7.7 Implications of results

The results of this analysis show that the contribution of secondary transfer evidence in these case scenarios has a high impact under Hd1 (i.e. in a scenario where the suspect denies wearing the mask), but minimal or no impact under Hd2 (i.e. in a scenario where the suspect admits to wearing the mask but sometime previous to the commission of the crime).

The reason for the results relating to Hd2 is likely to be due to the 'flat' nature of the persistence characteristics of secondary transferred fibres on pillowcases, the transfer node [15] (for B2) unlike transfer node [7] (for B1), is not 'time sensitive'. The main influence in the secondary transfer block (B2) would therefore appear to be the nodes concerning match probability ('rarity'). This appears to be confirmed by the results of the sensitivity analysis in S*ection 6.8.1.*

The results relating to the inclusion of secondary fibre transfer results, in the absence of any demonstrable primary transfer, appear to depend on whether the given case circumstances/ scenario justify a demonstrable secondary transfer being conditioned by an observable primary transfer to hair.

In terms of assessment and examination strategy the defence proposition is therefore the main driver in this case type, since in one scenario the examination of seized pillowcases increases the evidential value, whereas in another it adds nothing. This illustrates the context sensitivity of forensic evidence and the importance of understanding the framework of circumstances of a particular case to provide the most effective examination and interpretation.

From a practical perspective, it would be nevertheless desirable to at least seize pillowcases in such cases, since in this authors experience defence propositions are often lacking (e.g. 'no comment' by suspect) or change during the investigation of the case.

In addition to providing 'added value' in terms of evidential significance, the strategy of seizing pillow cases may also be useful when the suspect is apprehended outside an expected window of persistence in head hair, but this would appear to depend upon the 'rarity', the number of fibres found and the case circumstances.

The implications of these findings will be further discussed in *Chapter 7.*

6.8 Sensitivity analysis

In order to determine which parameters (e.g. fibre transfer probabilities, presence and numbers of foreign fibre groups, etc.) have the most influence on the overall weight of the evidence in such cases, the analysis of the contribution of each of these is performed by simulating casework scenarios 1-9 (*Tables 6.17 and 6.18*) using the Bayesian network.

Since the number of parameters involved have complex interdependencies, performing this manually would be very tedious and time consuming, consequently the use of computer based methods is employed for this purpose, namely;

'R' is an open source statistical package which is described by its developers (http://r-project.org) as '***a language and environment for statistical computing and graphics'*** providing a ***'wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering,....)***' The developers state that the package should be thought of as *'* ***an environment within which statistical techniques are implemented'*** rather than as a statistics package.

'Rhugin' (http://rhugin.r-forge.r-project.org) is an open source software package containing functions which allows the Hugin Bayesian network package to be controlled within the R environment. The functions in RHugin allow 'automatic' control over the propagation and retrieval of evidence from the Bayesian network, as well as statistical treatment of its output within R itself, rather than manually interacting with the Bayesian network interface.

'RStudio' (http://www.rstudio.com) is an open source program providing an 'integrated development environment' for *R,* allowing greater control over the execution of R code, its associated functions and graphical output.

One of the main advantages of *RStudio* is its use of a 'R markdown document'. This file format allows the integration of text content, R code and graphical output into a HTML, PDF or WORD document format. Such documents are extremely useful for open source research, allowing other researchers to test the results for themselves, or perform further development.

The use of the markdown file will be discussed in *Section 6.9.4*.

6.8.1 Parameter sensitivity

Since the probability assignments used for the various parameters within the Bayesian network (e.g. foreign fibre groups, transfer probabilities etc.) are based upon belief obtained from empirical data and/ or personal experience, it is important to understand;

1. How the extensiveness or paucity of this data impinges upon the likelihood ratio obtained.
2. Which parameters are having the greatest impact upon the likelihood ratios.
3. What is the effect of increased knowledge regarding the sensitive parameters on the likelihood ratio?

The identification of 'sensitive' parameters will serve to inform future research strategies concerning most effective investment of time and resources by identifying priorities and benefits associated with more extensive, specific data acquisition.

6.9 Analysis methodology

The architecture of the secondary transfer block B2 is identical to that of B1. Apart from the transfer node [15] the conditional probability tables for the remaining nodes relating to size and number of foreign fibre groups (FFG's) and fibre 'rarity' are identical to that in B1 (see *Section 6.4.3*). In addition the secondary transfer node [15] in B2 exhibits a very 'flat' distribution and is much less time sensitive than the primary transfer node [7] in B1 (see *Section 6.6.1*), meaning that the biggest contribution to the LR in this block relates to the nodes dealing with FFG's and match probability. Consequently there would appear to be very little to be gained by running the same sensitivity analysis in B2 as for B1 since the outcome would be virtually identical.

For this reason, the sensitivity analysis has only been carried out on the primary transfer block (B1).

6.9.1 Simulations of case scenarios 1-9

By simulating a particular case scenario (see *Tables 6.17 and 6.18*) a given number of times, the effect of the current state of our data for various parameter values on the resultant likelihood ratios can be assessed. This is because for each simulation iteration, the sampling from the corresponding Dirichlet distribution will return a slightly different value for a particular parameter state, according to the parameters of the Dirichlet distribution associated with that node.

In order to identify and quantify the effect of the various inter-relating parameters, it is necessary to perform multiple simulations of each of the possible case scenarios (1-9) described in *Section 6.5,* re-sampling from the Dirichlet distributions for each parameter in a sequential manner. Interquartile range (IQR) measurements of the obtained likelihood ratios are used to express the variability induced by the simulation process. This process is first carried out using the functions 'as- is' (i.e. reflecting our current state of knowledge concerning the various parameters). The process is then repeated after increasing the parameters of the Dirichlet distribution for each parameter (i.e. simulating an increase in data points or 'knowledge') and the IQR measurements compared against the 'baseline' values.

6.9.2 Assignment of the parameters of the Dirichlet distributions

Based upon the data available, the parameters of the Dirichlet distributions have been assigned (see *Section 6.4)* and are summarised as follows;

- Transfer of fibres mask to hair, recovery 1-3 days, washed; *Dir (38 ,66, 66, 18)*, not washed; *Dir (113, 56, 17, 2)*
- Transfer of fibres mask to hair, recovery 7 days, washed; *Dir (2, 2, 4, 996)*, not washed; *Dir (2, 3, 128, 56)*
- Match probability assignment for 'Rare' and 'Common' fibres; *Dir* (2, 1401) and *Dir (16, 643)* respectively.
- Probability assignment for number of FFG's ; *Dir (2, 2, 499, 501)*
- Probability assignment for size of FFG's; *Dir (46, 6)*

6.9.3 R Markdown Document

A R markdown document ('*RSimulations_HeadhairV8cc.RMD'*), containing the necessary code to; access the Bayesian network, perform the necessary simulations of the various case scenarios, simulating from the Dirichlet distributions the different parameters to inform nodes, and calculate as well as display the IQR of the resultant likelihood ratios has been developed by *Champod, (2015)* in collaboration with the author. The pdf document titled "*Sensitivity Analysis on The Case Involving Head Hair*" has been produced from the original RMD file and is appended to this thesis and will be made available for open source use.

This section describes the various outputs which can be generated from the embedded code of the document.

'Baseline' likelihood ratio calculations

In this section, the likelihood ratio for each possible case scenario (1-9) is calculated for 'rare' and 'common' fibre types. There is no resampling from the Dirichlet distributions to the parameter node assignments in this situation, the MLE's are used directly. Consequently there is no need for multiple simulations to be generated. The output from this section of

code can therefore serve as a ‘baseline’ reference point, since it represents the likelihood ratios that would be obtained from the Bayesian network informed by its current parameters.

Calculation of likelihood ratio variation by resampling from the Dirichlet distribution for each parameter node.

In this section, resampling from Dirichlet distributions are used for the nodes concerning; number of FFG’s (node [9]), size of FFG’s (node [11]), transfer and persistence (node [7]) and rarity (node [12]) with multiple simulations run. The code allows the number of simulations to be defined, however, this has been set to 100000 for all analysis. The output from this code consists of a calculation of the resultant likelihood ratios displayed as a ‘box’ and ’whisker’ plot, the ‘box’ indicating the range containing 50% of the data, the ‘whiskers’ on each side indicating the range of 25% of the upper and lower result limits.

The output provides a measure of how the sensitivity of the parameter, as a whole, influences the calculation of the likelihood ratios for each case scenario, but does not identify which node (or nodes) exerts the greatest influence.

Identification of sensitive node parameters

In this section of code, the initial IQR/median obtained by the combination of all Dirichlet distributions for each parameter node are computed using the current state of knowledge from the actual experimental data (i.e. the Dirichlet values as they currently stand). These are then compared against a sequential addition of an incremental increase by a factor of 10, in the Dirichlet distribution for each node parameter in turn. The effect upon the IQR/ median LR (for what is effectively an increase in data points or ‘knowledge’) of each parameter, can therefore be assessed. The IQR/ median is therefore used as a generic descriptor of the range of likelihood ratios obtained following the simulation of 10000 cases.

6.10 Results

The code within the markdown file is capable of interacting with the Bayesian network and analysing the output for each possible case scenario and observed outcomes. More examples of outputs relating to the specific case scenarios and outcomes are appended to this thesis within the markdown document report.

6.11 Parameter sensitivity

'Baseline' Results

Before performing multiple simulations on the different case scenarios using the underpinning Dirichlet distributions of each node, it is necessary to establish 'baseline' likelihood ratios for comparison using the data in the BN 'as is' for Hd1 and Hd2, for each potential outcome for each case scenario. This involves calculating likelihood ratios for each potential examination outcome, in each case scenario, using only the assigned maximum likelihood estimates (MLE's) for each parameter in a 'non simulation' mode. These results act as a point of reference for results generated in 'simulation mode'.

All of the outputs can be viewed in the markdown document appended to this thesis. *Figures 6.7 and 6.8* illustrate the results of this process using the examination outcome t(>10)/5nm (i.e. more than 10 matching fibres in the presence of 5 non-matching fibre groups) under Hd1 and Hd2 respectively.

As well as providing 'baseline' LR's for the different scenarios, these also serve to identify (or indeed confirm) which case scenario is likely to be most or least favourable to Hp and Hd for that outcome *(see Section 6.7*).

As previously discussed in *Section 6.7.1*, in considering Hd1 it can be seen that case scenario 3 is the most favourable to Hp. This is because that particular scenario relates to a recovery of fibres within 3 days of the offence with no washing of the hair occurring, maximising the chances of recovering crime relevant fibres if Hp is true. Hence the observed outcome is congruous with expectations and support for Hp is high. Likewise, it can be seen that in case scenario 6, where fibre recovery has taken place 7 days after the offence and the hair has been washed, the observed outcome is incongruous with expectations of recovering crime relevant fibres and hence the

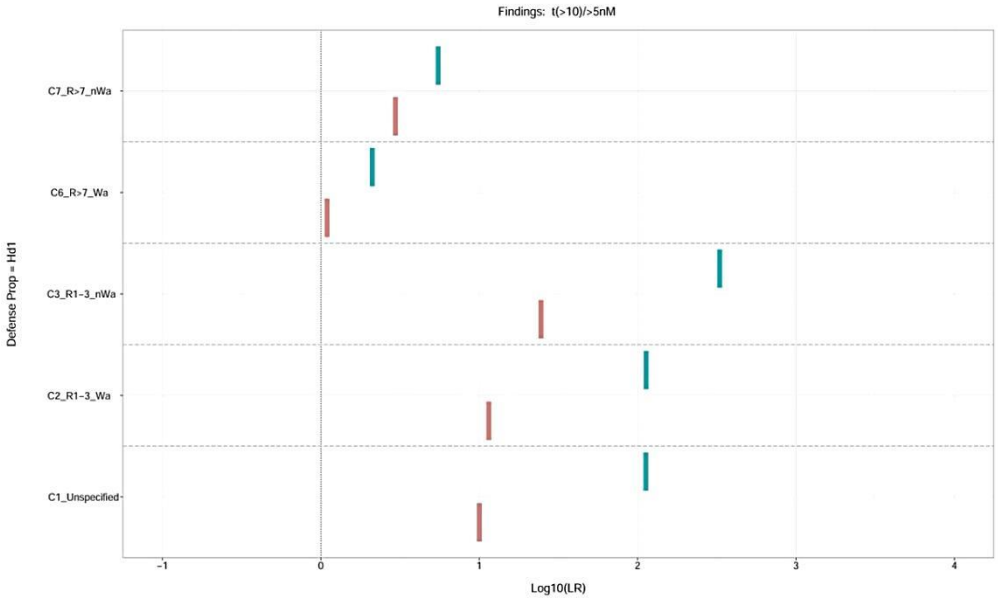
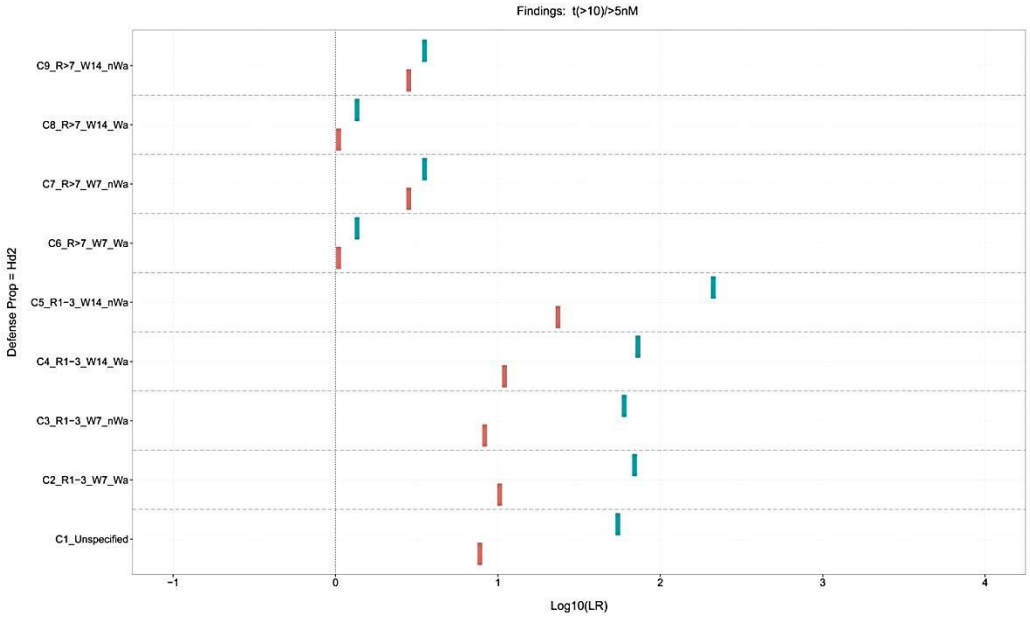


Figure 6.7: Likelihood ratios (expressed as Log (LR)) generated by the BN for the outcome t(>10)/5nm, using data 'as –is' for the different case scenarios under Hd1. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.



igure 6.8: Likelihood ratios (expressed as Log (LR)) generated by the BN for the outcome t(>10)/5nm, using data 'as –is' for the different case scenarios under Hd2. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.

support for Hp falls. Case scenario 1 describes a situation where a state of 'ignorance' concerning the framework of circumstances exists. It can be seen that the global likelihood ratio obtained is of a similar magnitude to that of scenarios 2, but considerably higher than those for scenarios 6 and 7.

These findings illustrate the dangers of evaluating the strength of evidence outside the conditioning effects of the context of the case circumstances. This will be discussed in more detail in *Chapter 7*.

A similar pattern emerges when considering the same outcome but with Hd2 as an alternative proposition (i.e. where wearing the mask is not in dispute, but the time of wear is), however, the computed likelihood ratios are generally smaller than for Hd1 especially for rare fibres. This is because under Hd2 (where the persistence of fibres over time is questioned) the 'rarity' of the recovered fibres has less impact on the calculated likelihood ratio compared to transfer and persistence (see *Figure 6.15*).

Having considered an outcome where 'many' matching fibres have been recovered, the effect of an outcome where no matching fibres have been recovered is now examined to illustrate some of the major trends.

Figures 6.9 and 6.10 show the likelihood ratios for each case scenario where no matching fibres have been found in the head hair under Hd1 and Hd2 respectively.

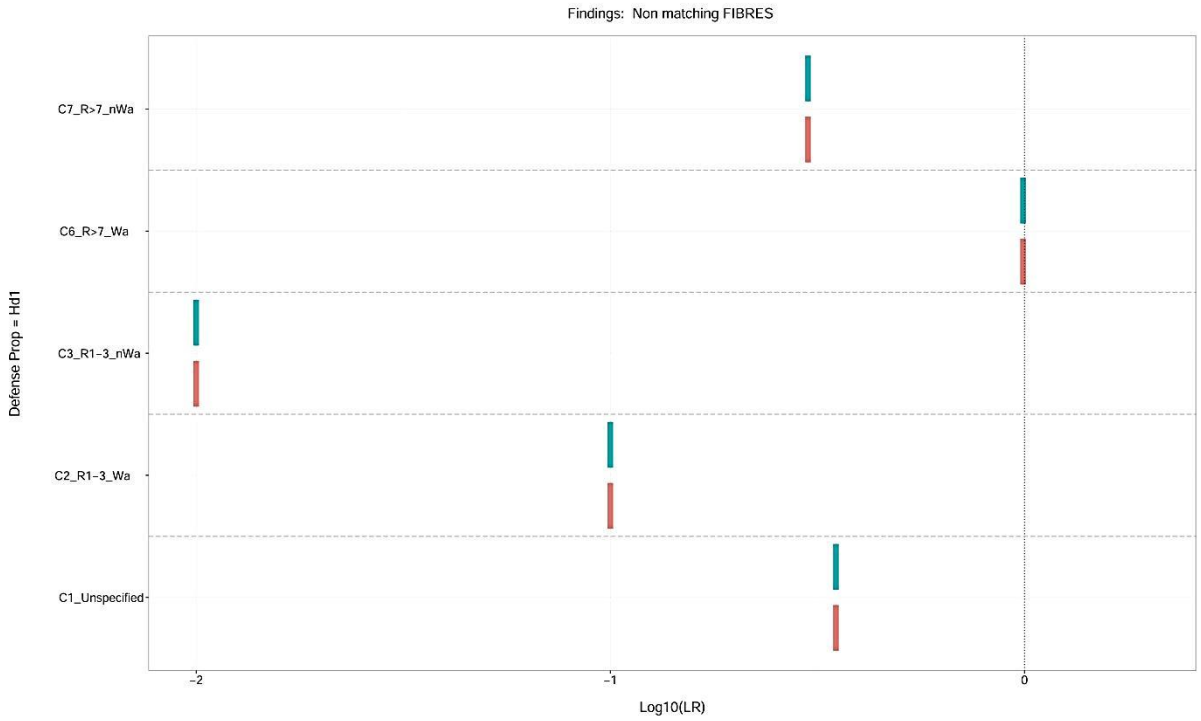


Figure 6.9: Likelihood ratios (expressed as Log (LR)) generated by the BN under Hd1 where no matching fibres have been recovered. using data 'as –is' for the different case scenarios. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.

It can be seen that support for Hd1, given this particular observed outcome, considerably increases in scenarios where fibre recovery has taken place within 3 days of the offence – particularly when the suspect has not washed his hair. Under Hd2, the results are similar for the same reasons, particularly when there is a pre-incident wear time of 14 days and the hair has not been washed (scenario 5). Again, this is due to these scenarios being contrary to expectations if Hp is true.

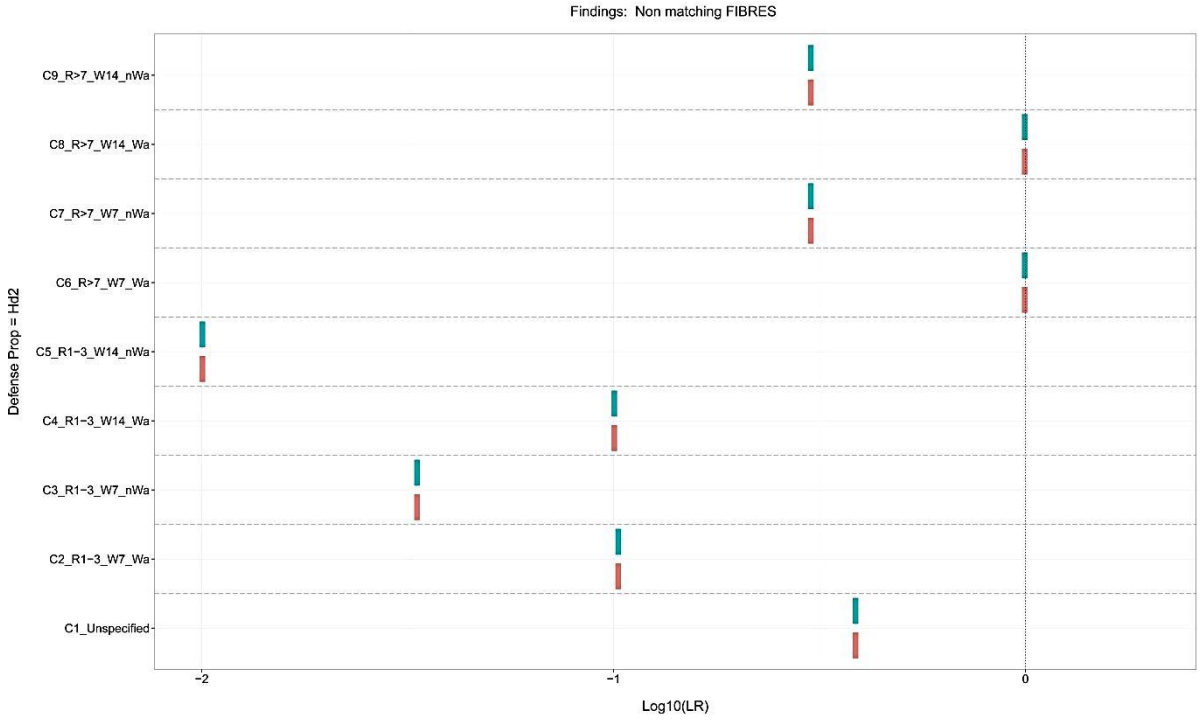


Figure 6.10 Likelihood ratios (expressed as Log (LR)) generated by the BN under Hd2 where no matching fibres have been recovered. using data 'as –is' for the different case scenarios. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.

Similarly in scenario 6 under proposition Hd1 (where the recovery of fibres has taken place after 7 days and the hair was washed), the expectations regarding recovery of crime relevant fibres are such that the observed outcome is equally likely given Hp or Hd1. For the same reasons, the results obtained under Hd2 for case scenarios 6 and 8 for this observed outcome (i.e. no matching fibres) irrespective of washing, are the same as for Hd1.

Under proposition Hd1, case scenario 1 (where there is a state of ignorance concerning the case circumstances) provides a compatible degree of support for scenarios 7 where fibre recovery has occurred more than 7 days post incident. Under Hd2, case scenario 1 provides a compatible degree of support for scenarios 7 and 9 (where the post incident recovery is greater than 7 days, no washing occurred and irrespective of pre-incident wear of 7 or 14 days). The results from this analysis, re-iterates the difficulty in evaluating evidence when there is no information regarding the case circumstances.

Figures 6.11 and 6.12 show the likelihood ratios obtained for the outcome t(>10) i.e. where > 10 matching fibres have been recovered in the absence of non-matching fibre groups, or, where the non-matching groups can be disregarded (e.g. where their provenance can be established).

The pattern of likelihood ratios across each case scenario under Hd1 and Hd2 is very similar to that calculated for the outcome t(>10)/>5nm), however, the LRs for the outcome t(>10) are more favourable to Hp. As illustrated in *Section 4.4,* this is because the lack of conditioning by FFG's effectively decreases the chances of adventitious matches, increasing the significance of the presence of the target fibres.

As with the outcome t(>10)/>5nm, under Hd2 for the outcome t(>10), there is a smaller difference in the likelihood ratios obtained for rare and common fibres. This observation is due to the importance of transfer and persistence over time under Hd2 as well as the lack of conditioning by FFG. This is illustrated in *Figure 6.16*, where it is demonstrated that under Hd2 for this outcome, rarity and FFG have little influence compared to the transfer parameter, especially for rare fibres.

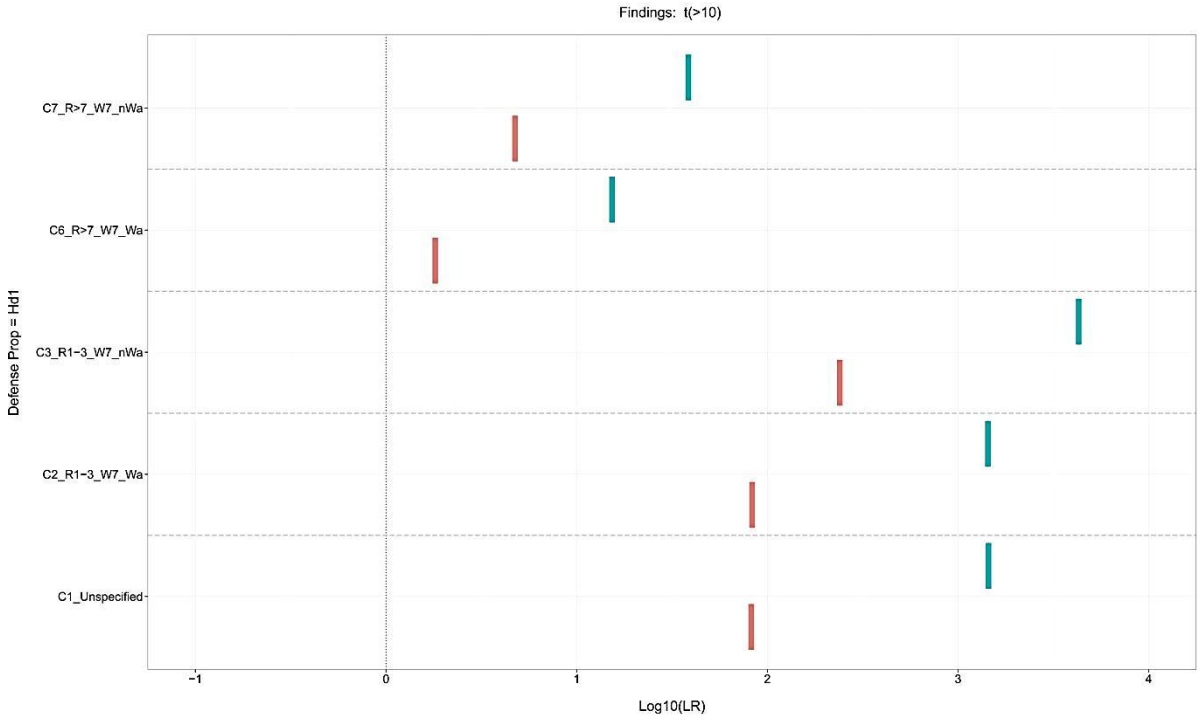


Figure 6.11: Likelihood ratios (expressed as Log (LR)) generated by the BN for the outcome t(>10), using data 'as –is' for the different case scenarios under Hd1. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.

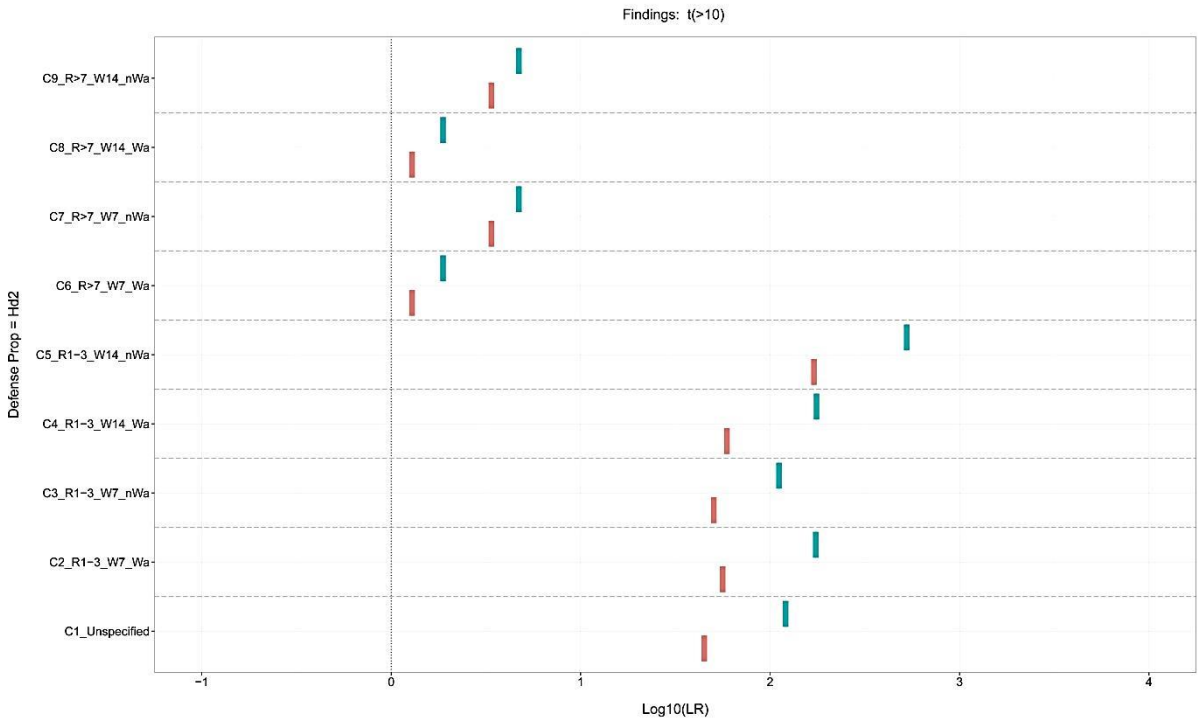


Figure 6.12: Likelihood ratios (expressed as Log (LR)) generated by the BN for the outcome t(>10)/5nm, using data 'as –is' for the different case scenarios under Hd2. The blue rods represent the obtained LR for 'rare' fibres in each case scenario, the red rods representing the results for 'common' fibres.

Again, these findings demonstrate the effect of the case circumstances, choice of proposition and observed outcome on the likelihood ratio.

The results for all outcomes considered by the BN are available in the appendix of this thesis.

Likelihood Ratio Uncertainty

After establishing the 'baseline' LR's, multiple simulations (n=100000) are run through the BN, this time re-sampling from the Dirichlet distributions, instead of using the maximum likelihood estimates (MLE's) for each parameter node.

The limited amount of background data points to inform each conditional probability table (as ascertained from the Dirichlet counts), results in a range or 'spread' of likelihood ratios for a given case scenario and observed examination outcome as opposed to the single LR values obtained using MLE's in 'baseline' non-simulation mode.

The output is presented as a 'box/whisker' plot representing range of the LR's for each examination outcome, in each case scenario. As previously stated, it should be noted that the 'box' component of the plot represents 50% of the data, with the 'whisker' on either side each representing 25%. This is exemplified in *Figures 6.13 and 6.14.*

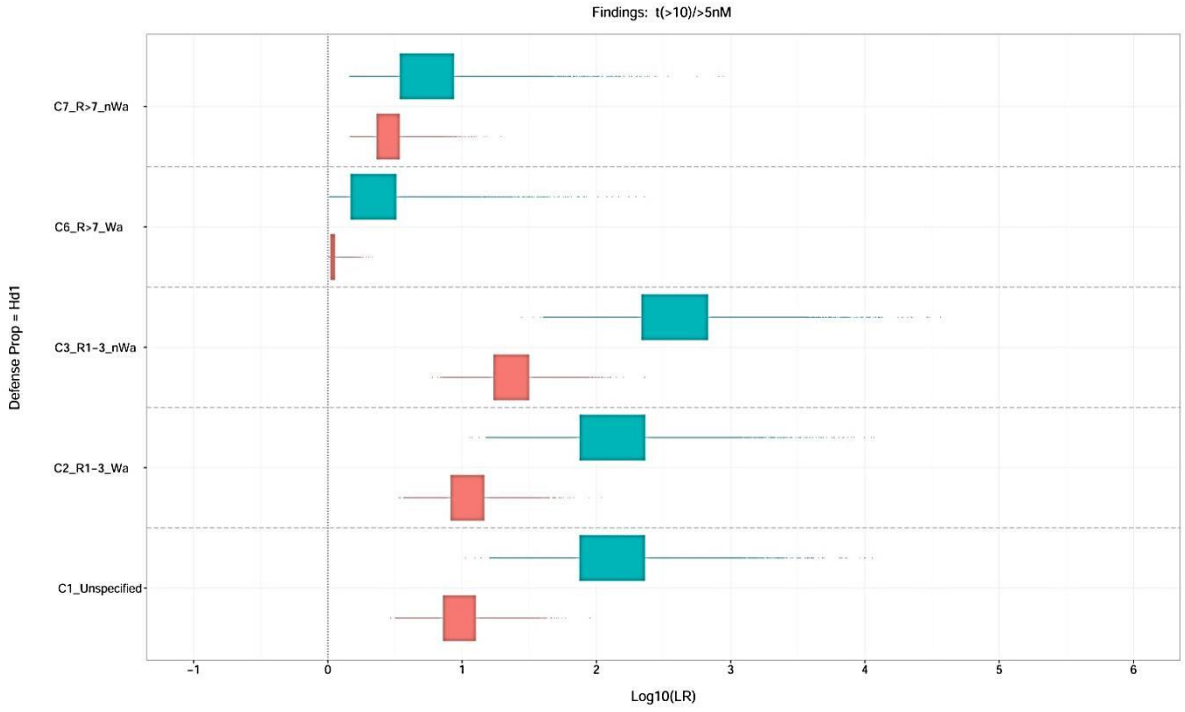


Figure 6.13: Distributions of likelihood ratios (expressed as Log (LR)) for each case scenario under Hd1 for the outcome t(>10)/5nm. The blue plots represent the LR's for 'rare' fibres, the red plots for the 'common' fibres.

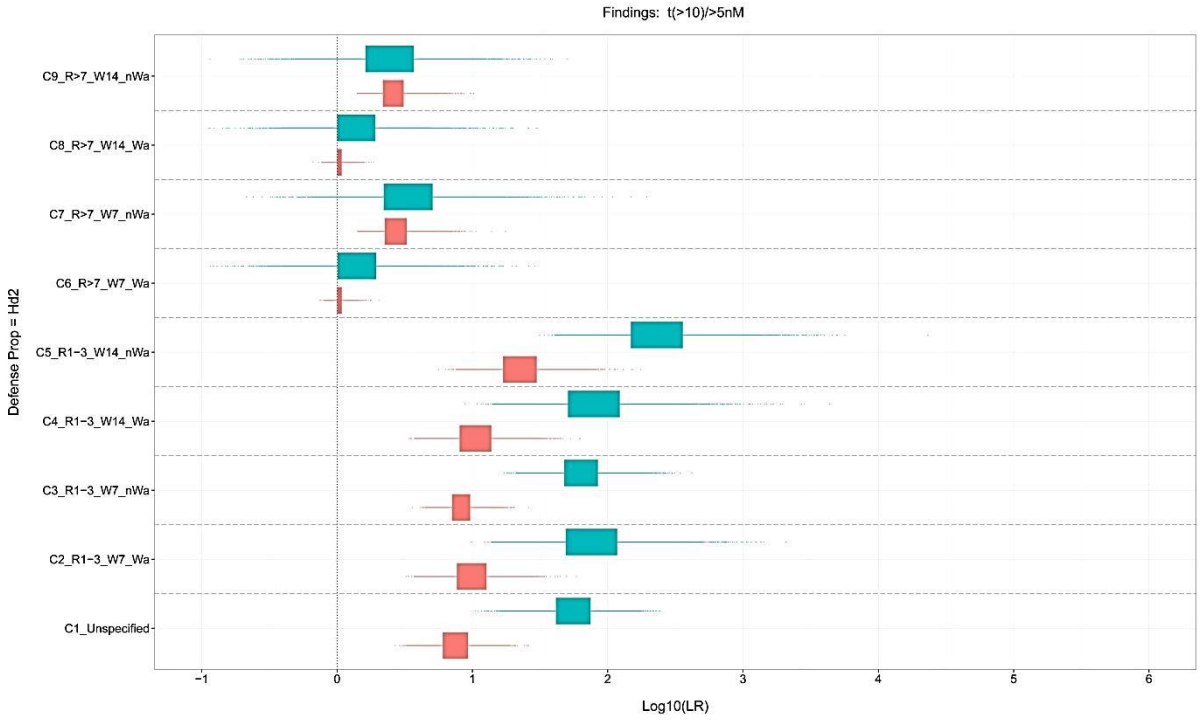


Figure 6.14: : Distributions of likelihood ratios (expressed as Log (LR)) for each case scenario under Hd2 for the outcome t(>10)/5nm. The blue plots represent the LR's for 'rare' fibres, the red plots for the 'common' fibres.

The results show that the extent of variation of the LR changes according to case scenario, observed outcome, and defence proposition. As with the previous computations, the difference between the likelihood ratios for rare and common fibres is smaller, as well as under Hd2. Again, this is due to high conditioning effect of transfer under Hd2.

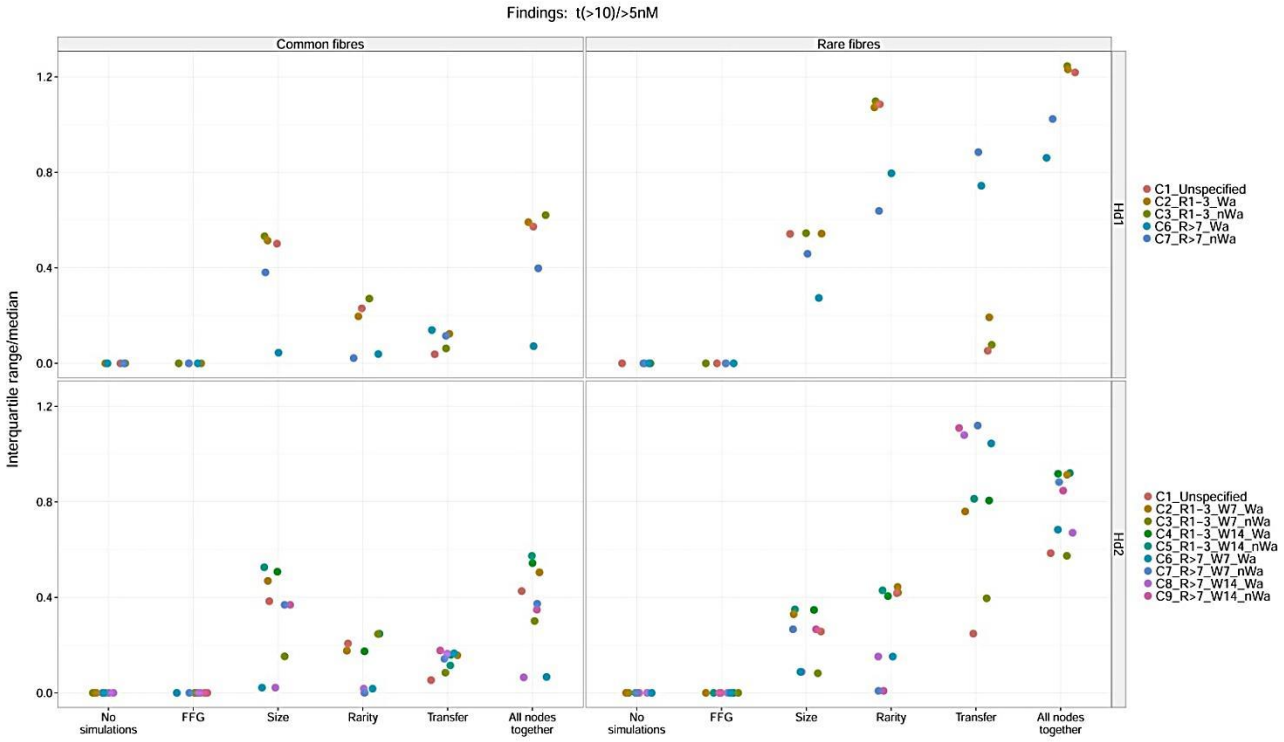
Under both Hd1 and Hd2, the results show that for certain case scenarios where the LR's are of a low magnitude (i.e. under Hd1, case scenarios 6 and 7, under Hd2, scenarios 6-9), the possibility exists that where there is a lack of knowledge concerning a particular parameter, the likelihood ratio range could extend from initially favouring Hp to actually favouring Hd. This will be discussed further in *Chapter 7*.

It can be expected that where the knowledge of a particular parameter is high, a smaller range of computed likelihood ratios would be expected, and *vice versa*. The results of this

analysis therefore show that where there are limited data points informing a particular parameter node or nodes, variation in the LR occurs during the simulation runs. Whilst the results demonstrate that the 'degree of knowledge' concerning a parameter has an effect on the LR, it is not possible from this analysis to identify which particular parameter(s) exert the greatest influence.

Identification of Parameter Influence

In order to identify which parameters have the greatest effect on the LR's, the IQR's normalised by the median of the LR (i.e. IQR/ median) are calculated for each case scenario, using the Dirichlet distributions for 10000 simulations for each parameter in turn and then for all parameters together. *Figure 6.15* illustrates the results of this comparison for each case scenario under both Hd1 and Hd2 for the observed outcome t(>10/>5nm). Each case scenario is assigned a different colour.



ure 6.15: The effect of each parameter on the interquartile range/ median of likelihood ratios for each case scenario under Hd1 and Hd2 for the outcome t(>10)/>5nm.

Note that the results for all outcomes considered by the BN are available in the appendix.

The simulation runs depicted on the x-axes are as follows;

- **No simulations**: IQR/ Median of LR's for each case scenario using original BN MLE's in non-simulation mode (i.e. a reference point of zero).
- **FFG**: IQR/ Median of LR's for each case scenario re-sampling only from the Dirichlet distribution for the number of FFG's.
- **Size**: IQR/ Median of LR's for each case scenario re-sampling only from the Dirichlet distribution for the size of FFG's.
- **Rarity**: IQR/ Median of LR's for each case scenario re-sampling only from the Dirichlet distribution for 'Rarity'.
- **Transfer**: IQR/ Median of LR's for each case scenario re-sampling only from the Dirichlet distribution for 'Transfer'.
- **All nodes together**: IQR/ Median of LR's for each case scenario re-sampling from the Dirichlet distributions for all of the above parameters jointly.

For rare fibres it can be seen that under Hd1, rarity (for all case scenarios) has the greatest effect on the extent of variation observed between LR's, with the size of FFG and transfer parameters also contributing, but to a lesser extent. Under Hd2 however, it can be seen that for rare fibres the parameter which has the greatest effect on the LR's is the transfer parameter, with size and rarity contributing to a much lesser extent.

For rare fibres under Hd1, scenarios 6 and 7 (i.e. where post-incident recovery occurred after 7 days) transfer has a greater effect than rarity. For common fibres, the same effect is seen albeit to a lesser extent.

For rare fibres under Hd2, transfer has the greatest effect on scenarios 6-9 whilst rarity has the least effect, regardless of the alleged time of pre-incident wear.

For common fibres, the size of the FFG group has the greatest influence along with (to a lesser extent) rarity and transfer, under both Hd1 and Hd2.

Given the fundamental differences in Hd1 and Hd2 these findings are not surprising and serve to illustrate the effect of proposition and setting as well as case circumstances on the influence of different parameters in the evaluative process.

This is illustrated in *Figure 6.16* which demonstrates the effect of the different parameters on the likelihood ratio for each case scenario under Hp1 and Hd2 but now for the outcome t(>10). The analysis is the same as for that shown in *Figure 6.15*.

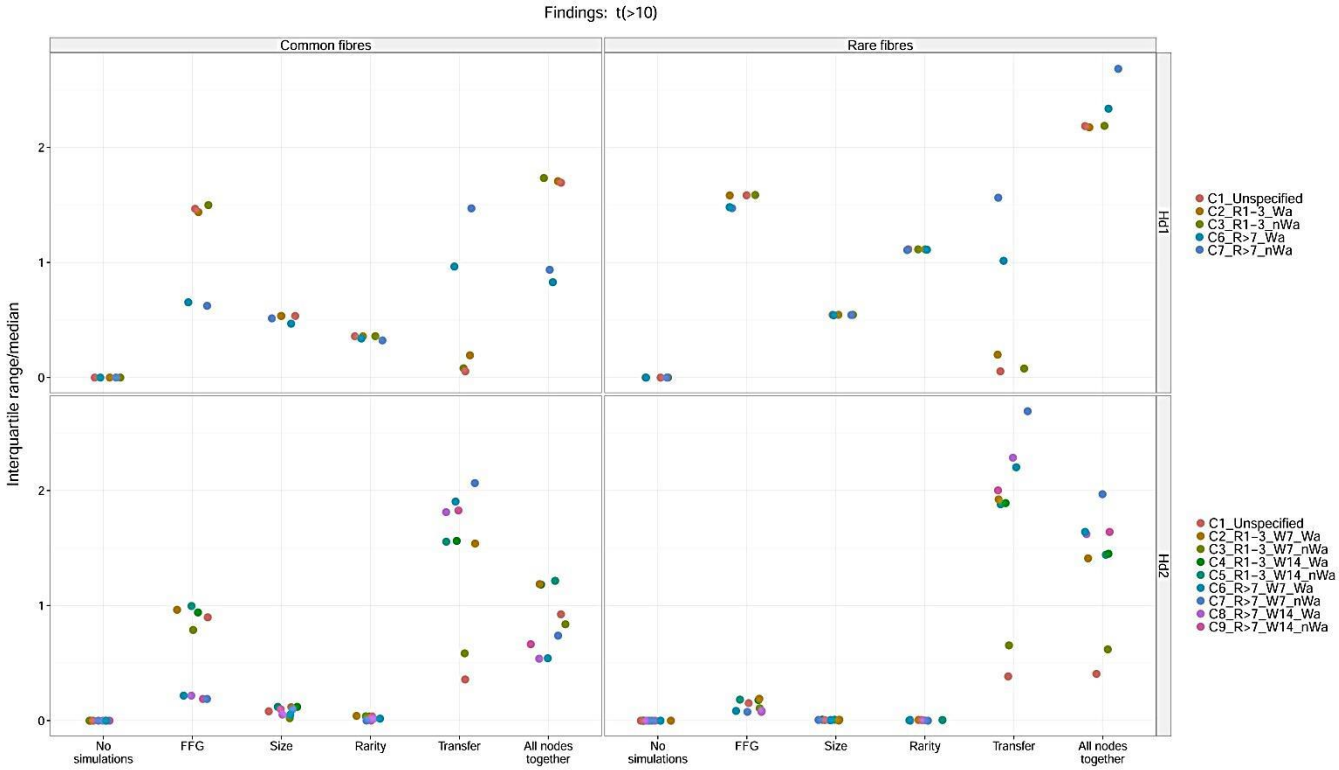


Figure 6.16: The effect of each parameter on the interquartile range/ median of likelihood ratios for each case scenario under Hd1 and Hd2 for the outcome t(>10).

For the outcome t(>10), the effect of the different parameters for each case scenario is very different to that for the outcome t(>10)/>5nm. Under Hd1 and Hd2 transfer is the only parameter to demonstrate a significant effect according to case scenario –regardless of whether the fibre is common or rare. By contrast the rarity parameter has the same influence on each case scenario. For this particular observed outcome, i.e. t(>10), these findings may be expected since the conditioning effect of FFG on the rarity parameter has been removed and hence for each case scenario the effect of this parameter is the same.

The results relating to parameter influence under these two observed outcomes are summarised in *Table 6.29*.

t(>10)/>5nm		
Fibre Type	**Hd1**	**Hd2**
Rare	Rarity	Transfer
Common	FFG Size	FFG Size
t(>10)		
	Hd1	**Hd2**
Rare	Transfer	Transfer
Common	Transfer	Transfer

Table 6.28: Summary of parameters with greatest influence on the LR according to fibre type, observed outcome and Hd under consideration.

The Effect of Parameter 'Knowledge'

In order to establish which of the parameters are sensitive to an 'increase in knowledge', a similar exercise is performed however, in this case plotting the IQR/ median of the LR for each case scenario using multiple simulations with the Dirichlet distributions 'as is' and comparing this to the results of simulations where a single parameter and multiple parameters have been subjected to a ten-fold increase in the Dirichlet distribution counts (increased 'knowledge'). A decrease in the likelihood ratio IQR/ median for a single parameter or combination of parameters, can then be identified. Again, this is simulated 10000 times for each case scenario and each potential observed outcome. Where a decrease is observed in the IQR/ median for a given parameter, this demonstrates that its effect on the variation associated with the LR's is sensitive to the amount of knowledge concerning it.

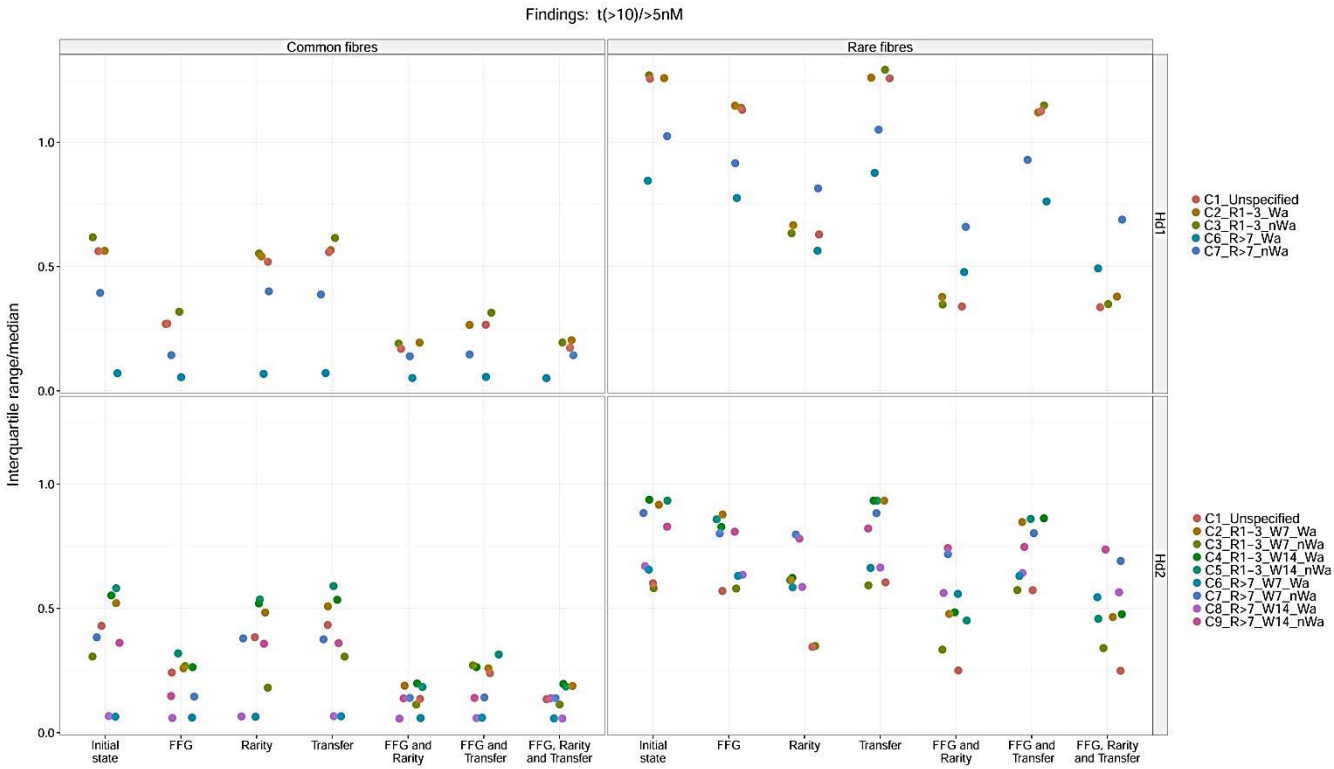


Figure 6.17: Effect on interquartile range/ median of the likelihood ratio for each case scenario after a sequential ten-fold increase on Dirichlet distributions for each parameter in turn under Hd1 and Hd2 for the outcome t(>10)/5nm.

Figure 6.17, demonstrates the 'effect of knowledge' on the IQR/ median of the LR for each of the parameters. Each case scenario is depicted with a particular colour and relates to the observed outcome t(>10)>5nm under Hd1 and Hd2. The results relating to other outcomes considered are available in the appendix.

The simulation runs depicted on the x-axes are as follows;

- **Initial state**: IQR/ Median of the LR's for each case scenario with all parameters set at the initial Dirichlet parameters.
- **FFG**: IQR/ Median of the LR's for each case scenario with the Dirichlet parameters for the number and size of FFG's, increased by a factor of ten.
- **Rarity**: IQR/ Median of the LR's for each case scenario with the Dirichlet parameters for 'Rarity' *only*, increased by a factor of ten.
- **Transfer**: IQR/ Median of the LR's for each case scenario with the Dirichlet parameters for 'Transfer' *only*, increased by a factor of ten.

- **FFG and Rarity**: IQR/ Median of the LR's for each case scenario with the Dirichlet parameters for FFG's and 'Rarity', only, increased by a factor of ten.
- **FFG and Transfer**: IQR/ Median of the LR's for each case scenario with the Dirichlet parameters for FFG's and 'Transfer', only, increased by a factor of ten.
- **FFG, Rarity and Transfer**: IQR/ Median of the LR's for each case scenario with *all* above considered Dirichlet parameters increased by a factor of ten.

It should be noted that in this analysis, data from FFG number and FFG size are combined in one plot. Since we are interested in the effect of increasing the knowledge concerning FFG in general, both size and number would both be informed in this process. This is also the case shown in Figures 6.18 - 6.21.

The results show that for the outcome t(>10)/5nm, the parameters most sensitive to an increase in background knowledge under both Hd1 and Hd2 for rare fibres, is rarity and to a lesser extent FFG. In the case of common fibres, it can be seen that the most sensitive parameter is FFG and to a much lesser extent rarity. This effectively gives support for 'targeting' research to acquire a greater data set regarding these variables.

Figures 6.18 and 6.19 illustrate the results of the same analysis but using boxplots to better visualise the results. These show the effect on the distribution of the LR's of the individual case scenarios, where the Dirichlet distribution has been increased by a factor of 10 and applied to FFG, Rarity and Transfer and compared to the initial Dirichlet parameters.

The results of this analysis further illustrate those shown in *Figure 6.16,* in that for this particular outcome, rarity is the most sensitive parameter for rare fibres whilst FFG is the most sensitive for common fibres. In addition, the results of this particular analysis, demonstrates that the degree of sensitivity exhibited by these parameters varies according to the case scenario. For example, it can be seen that virtually no sensitivity occurs for common fibres under Hd1 and Hd2 where fibres have been recovered after 7 days when the suspect has washed. Likewise, the sensitivity of rarity is lessened for rare fibres in case scenarios where fibres have been recovered after 7 days.

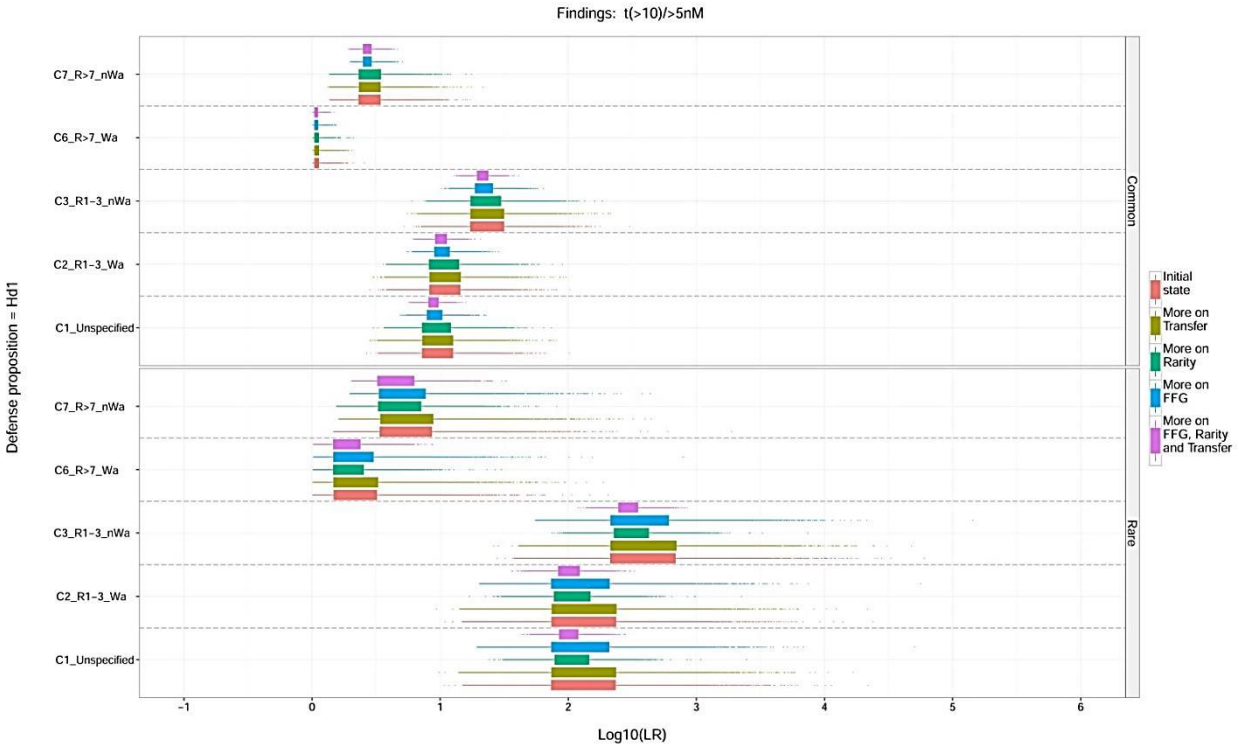
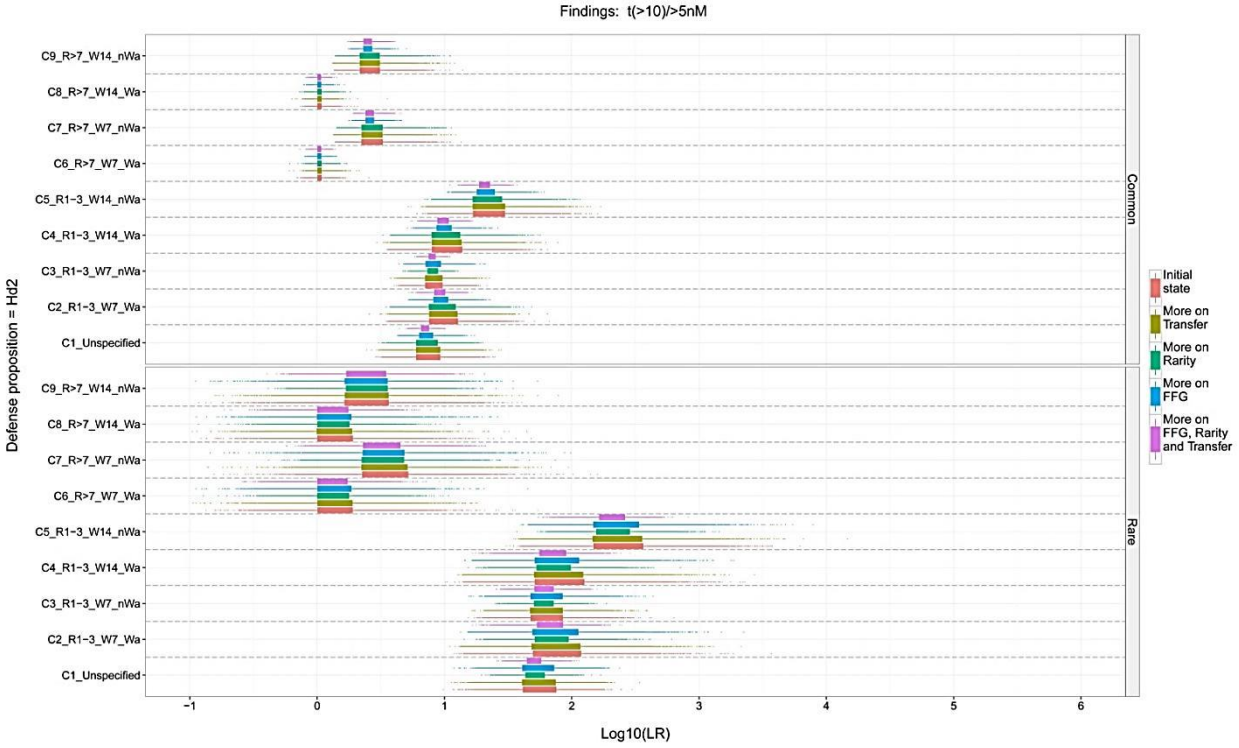


Figure 6.18: Effect on distribution (shown with boxplots) of the log(10) likelihood ratio ranges for each case scenario after a ten-fold increase on the parameters of the Dirichlet distributions for FFG's, Rarity and Transfer parameters under Hd1 for outcome t(>10)/>5nm.



igure 6.19: Effect on distribution (shown with boxplots) of the log(10) likelihood ratio ranges for each case scenario after a ten-fold increase on the parameters of the Dirichlet distributions for FFG's, Rarity and Transfer parameters under Hd2 for outcome t(>10)/>5nm.

Just as importantly, the impact of the particular parameter on the computation of the LR for a given case scenario will also be dependent on the observed outcome of the case examination. *Figures 6.20 and 6.21,* show the results of the same computation summarised in *Figures 6.18 and 6.19*, with the exception that the outcome of t(>10) rather than t(>10)/>5nm has been considered.

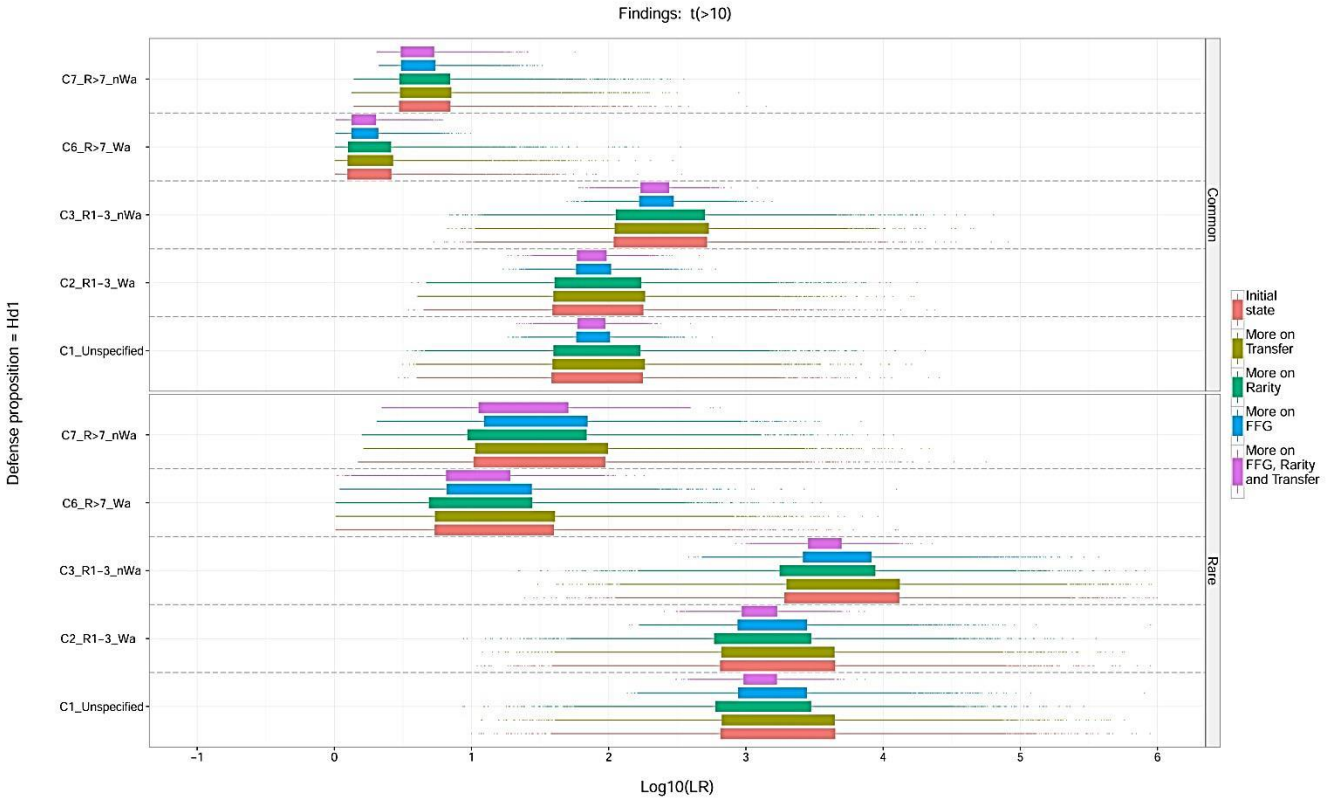


Figure 6.20: Effect on distribution (shown with boxplots) of the log(10) likelihood ratio ranges for each case scenario after a ten-fold increase on the parameters of the Dirichlet distributions for FFG's, Rarity and Transfer parameters under Hd1 for outcome t(>10).

The results show that compared to the outcome regarding t(>10)/>5nm, for Hd1 the parameter demonstrating the greatest effect on the LR is now FFG for both rare and common fibres, whilst now under Hd2, all parameters have an equal influence on the LR for all case scenarios involving rare fibres.

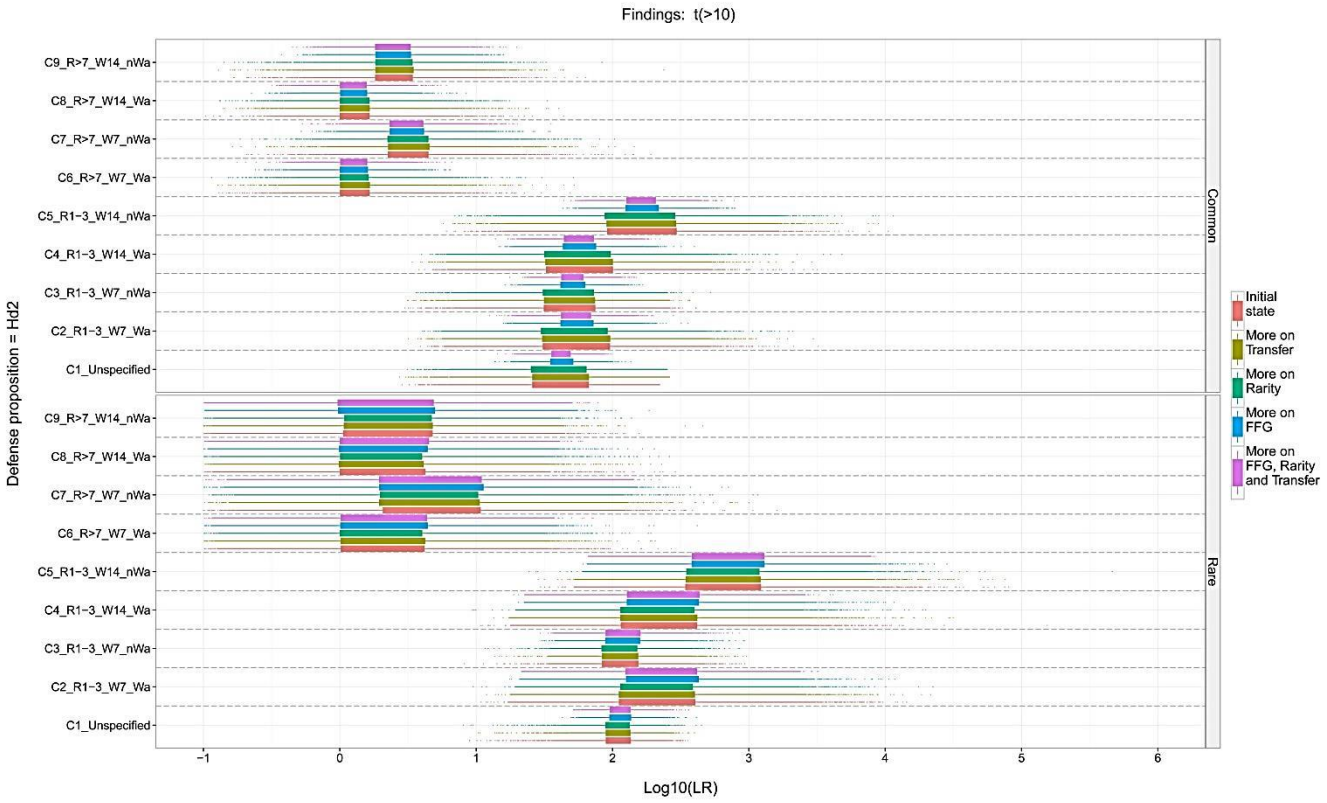


Figure 6.21: Effect on distribution (shown with boxplots) of the log(10) likelihood ratio ranges for each case scenario after a ten-fold increase on the parameters of the Dirichlet distributions for FFG's, Rarity and Transfer parameters under Hd2 for outcome t(>10).

By examining the results of this analysis across all of the possible outcomes used in the BN (*see Appendix*), the range of impact of these parameters can be compared according to the observed outcome of analysis. Again, this serves to inform where best to employ resources in research.

The results relating to parameter sensitivity under these two observed outcomes are summarised in *Table 6.30*.

t(>10)/>5nm		
	Hd1	**Hd2**
Rare	Rarity	Rarity
Common	FFG	FFG
t(>10)		
	Hd1	**Hd2**
Rare	FFG	None
Common	FFG	None

Table 6.30: Summary of the most sensitive parameters for the observed outcomes, according to fibre type, and Hd under consideration

6.12 Implications of these results

The results of the sensitivity analysis indicate that it is worthwhile investing resources into studies concerning the size and number of extraneous fibre collectives on a variety of substrates. In this specific case, hair and bedding would be particularly relevant.

In addition, further studies investigating the rate of adventitious matches for specific fibre type colour combinations would also be a worthwhile research strategy, this perhaps being of no surprise when one considers the difficulty of obtaining case specific data as discussed in *section 6.4.2*.

The results also demonstrate the importance of the state of Hd and the need for a full understanding of the framework of circumstances concerning a particular case (e.g. time of wear, recovery, washing). This is particularly evident when comparing LR calculated for case scenario 1 (i.e. where there is a degree of ignorance concerning the case circumstances) against other case scenarios which have specific case information conditioning the calculation of the LR.

Importantly, it can be seen from the results that due to the conditioning effects of time frames and transfer and persistence data, the presence of a ‘rare’ target fibre may not always produce the ‘best’ evidence.

Given the current economic climate where time, money and resources are limited, the results of this analysis can inform the most effective (in terms of case assessment, interpretation and reporting) strategies for research, by identifying the parameters which would benefit most from an increased data set.

This will be discussed further in *Chapter 7.*

7 DISCUSSION

In this chapter, the results and conclusions of the work of this thesis in evaluating the impact of new data obtained to address gaps in our knowledge of the factors influencing the evaluation of fibre evidence is considered. An overview of the findings relating to fibre evidence recovered from skin and hair is given. An evaluation of the use of Bayesian networks as tool in case assessment, strategy setting and interpretation and the role of the expert are discussed. The criticality of knowledge, framework of circumstances and robust proposition setting as well as the role of the expert, are stated. Future perspectives in strategic research initiatives informed by the sensitivity analysis performed on critical factors are considered and the implications for practitioners discussed.

The purpose of this thesis was to identify, evaluate and address 'gaps' in key areas of our present knowledge of the factors influencing the interpretation of fibre evidence and assess these against the potential benefits in evidence evaluation. Data from studies carried out by the author and others which has addressed gaps in key areas have been presented and applied to real casework scenarios in *Chapters 5 & 6* and the impact of these from a practitioner perspective have been evaluated. In addition, the 'sensitivity' of key parameters governing the evaluation of fibre evidence has been evaluated.

In this chapter, these findings will be discussed with reference to implications for the practitioner, not only in terms of case assessment and interpretation but also for informing the strategic planning of operationally relevant future research.

7.1 Bayesian Networks

As discussed in *Chapters 2* and *4* and demonstrated in *Chapters 5* and *6,* Bayesian networks are an extremely useful tool in modelling the complex interdependencies of various conditioning factors within the framework of circumstances of a given case. As well as providing a means of case assessment and evaluation of observed outcomes, it has proven its value not only in evaluating the impact of different datasets, but also on the usefulness of the published data itself. Using a BN in combination with the *'RHugin'* statistical package (as applied in *Chapter 6*) has proven to be a particularly powerful and versatile application.

The use of Bayesian networks in this thesis has also demonstrated the potential added value in case assessment and interpretation by allowing the practitioner to consider 'what if?' scenarios through the ability to modify aspects of the framework of circumstances which condition the observed outcomes and the associated likelihood ratios. Using the example of the effect of head hair washing on the persistence of fibres in hair (see *Chapter 6*), in many real-life situations it may not be known whether or not, (or to what degree) this has been carried out by a suspect in a given framework of circumstances. The value of the Bayesian network in such circumstances is that it allows the practitioner to easily observe the impact of whether this activity has been carried out or not, or, just as importantly, if this information is not known.

The use of the Bayesian network also allows a more robust means of case assessment by informing case examination strategy. In *Section 6.7.5,* a case scenario where a suspect admits wearing a balaclava mask 7 days before a crime, but not at the time of the crime, is considered. *Table 6.26* shows that, searching for fibres in the head hair of the suspect will be uninformative, but carrying out an examination for secondarily transferred fibres on the pillowcase will assist either the prosecution or defence. Consequently the examination strategy and priority in such a framework of circumstances would be to look only for secondarily transferred fibres. The results also show that where the target fibre is a 'common' type in this scenario, fibre examinations will be ineffective.

For the practitioner then, the use of Bayesian networks provides a much more flexible and versatile, yet transparent method of pre-assessment and evaluation than the simple 'expectation matrix' described in *Section 2.6,* particularly when dealing with complex major enquiries such as the Ipswich serial killings. However, what has been demonstrated in this thesis, is that the effectiveness of this tool depends on the data underpinning its use and the need for data, as stated by *Grieve and Wiggins (2001*), is greater than ever.

7.2 Fibres on Skin

Prior to the author's studies relating to fibre persistence on the skin of living and dead subjects, no published data was available to inform case assessment or interpretation in

cases circumstances such as the Ipswich serial killings, where this would have been particularly useful. This became the driver for subsequent research.

In *Chapter 5* the impact of the data from the authors' study (*Palmer and Burch, 2009*) relating to the persistence of fibres on the skin of living subjects was considered against the framework of circumstances of the Ipswich serial killings, since it was known that each of the victims had bathed or showered immediately prior to their disappearance.

Prior to the *Palmer and Burch, (2009)* study, a prevailing view amongst many practitioners was that skin could be regarded as a non-retentive surface and that fibres would not be expected to persist for any prolonged period of time. The inference being that the presence of crime relevant fibres on the skin of living subjects was likely to represent evidence of recent contact due to an alleged event.

The results of this study demonstrate that the consideration of skin as a non-retentive surface is somewhat simplistic, as the results suggest its persistence characteristics are more akin to that of a textile garment unless it is washed or bathed, when none may be expected to persist.

This study also demonstrated that the relative frequencies of fibre type/ colour combinations on skin were in general accordance with studies involving other substrates. Whilst in the case of the Ipswich serial killings (modelled in *Chapter 5*) such information is of little relevance (due to the fact that the provenance of the crime relevant fibres was accepted), however, in other similar cases where both source and activity level issues are disputed (as is considered in *Chapter 6*), such information is likely to be crucial.

As stated in *Chapter 5,* all of the land deposited victims were known to have bathed or showered shortly before their disappearance (this information having been obtained from witness statements of partners or family). Since the suspect's explanation for the presence of numerous fibre collectives relating to his environment on each of the victims was that he had sex with each of them 2 days before their disappearance, the witness information became crucial, particularly in light of subsequent research by the author.

Using a Bayesian network to model the circumstances of this case, the impact of the data from the *Palmer and Polwarth, (2011)* data was compared to that of the results of the *Krauss and Hildebrand, (1996)* study, this being the only source of data available to address the

issues of transfer and persistence of fibres on cadavers deposited outdoors in this case, at that time.

During the trial, the situation was similar to that of *R v Reed and Reed, (2009)* and *R v Weller, (2010)* in that an opinion as to the persistence of fibres on the skin following washing was given in the absence of published data, but based upon past casework experience. Had the data from the *Palmer and Burch, (2009)* study been available at that time, a more informed evaluative opinion could clearly have been given.

It was also argued by the defence that although there were numerous fibre collectives present on the victims' bodies which (it was accepted) originated from items relating to the environment of the suspect, the relatively small numbers found were as a consequence of contact with the suspect at the time he alleged which had survived washing by the victims. At the time of the trial no data was available to assist in addressing this issue. Using the data from the *Krauss and Hildebrand, (1996)* study within the context of the documented meteorological data relating to the area the three land deposited victims were found, as well as the estimates of time of death and deposition, the opinion was expressed that the findings represented only 'remnants' of those originally transferred around the time of deposition. Again, had the data from the *Palmer and Polwarth, (2011)* been available, a more informative evaluative opinion concerning the propositions involved could have been given.

During the crime scene examinations relating to the victims deposited on land in the Ipswich serial killings, there was actually a debate by the investigative team over whether or not to attempt fibre recovery given the prevailing weather conditions. Luckily the decision was made to take surface debris from the victims, despite the perceived lack of expectation of success. The results obtained from subsequent examination of the surface debris tapings in this case, demonstrated that significant numbers of crime relevant fibre collectives can still be recovered in circumstances in which there would ostensibly seem little possibility of doing so.

As discussed in *Chapter 5*, the actual observed outcomes of the fibre recovery from the victims deposited at different times appear to be similar to predicted outcomes by the BN incorporating the *Palmer and Polwarth, (2011)* results, but incongruous with the predicted transfer and persistence characteristics obtained from the *Krauss and Hildebrand (1996),* study. This observation suggests that the methodology employed by the *Palmer and*

Polwarth, (2011) study produces data more consistent with a real case scenario and is therefore more accurate and robust.

Whilst it must be conceded that such conclusions could be drawn from an examination of the data in the absence of a Bayesian network, its use does allow a more efficient means of examining the effect of varying parameters relating to the specific framework of circumstances on the likelihood ratio (e.g. considering the effect of different weather conditions). In addition, the use of the Bayesian network has demonstrated how crucial the MLE's for the initial number of transferred fibres (in node [2]) are 'driving' the calculation of the global likelihood ratio, since small changes in these values will have a large conditioning effect on the expected number of persisting fibres (node [3]). The MLE's used in node [2] have been estimated for polyester microfibres, which are known to shed copiously. In similar case scenarios where garments of different fibre construction are under consideration, the use of the Bayesian network would allow us to easily determine the effect of target fibres with less shedding potential than microfibres, on the likelihood ratio.

7.3 Fibres in head hair

As with the case scenario discussed in *Chapter 5*, the author's experience of the circumstances of a real case became the driver for subsequent research to address a lack of published data.

In *Chapter 6,* the case of a series of armed robberies is discussed, where the perpetrators had left a balaclava mask (used to conceal identity) at the crime scene. Suspects were subsequently apprehended 10 days later, outside the expected window of persistence of primary transferred fibres in head hair, suggested by published transfer and persistence studies (*Ashcroft, Evans et al., 1988, Salter and Cook, 1996*). Anecdotal information concerning a case study suggested that the secondary transfer of crime relevant fibres from head hair to pillowcases could be a useful investigative strategy when those suspected of wearing masks in the commission of a crime are apprehended outside the expected window of persistence for primary transfer (*Clayson and McKnight, 2001*). However, no published data concerning the mechanism or persistence characteristics for such transfers was available.

The data from the author's studies relating to the secondary transfer of fibres from head hair to pillowcases (*Palmer and Banks, 2005*) was used along with those concerning primary transfer studies (*Ashcroft, Evans et al., 1988, Salter and Cook, 1996*) in the construction of a Bayesian network to model different case scenarios where evidence in the form of primary and secondary fibre transfers to and from head hair can occur (i.e. where the perpetrator of a crime has worn a mask to conceal their identity).

As discussed in Chapter 6, the framework of circumstances is crucial in addressing these questions and in particular what defence proposition is being considered i.e. the suspect stipulating that he had never worn the mask (any mask), or, had worn it at some time before the offence but not at the time of the offence.

The BN was used to;

1. Evaluate the impact of the author's study into secondary transfers in terms of evidential value and consequent strategic value
2. Determine the degree of sensitivity of the data in the different relevant interrelated parameters.

7.4 Impact analysis

The results of the 'impact' analysis showed that when the defence dispute wear of the mask, analysis of the pillowcases will augment the contribution of primary transfer evidence considerably, especially when the time of recovery of fibres form head hair results in a low expectation of fibre persistence had the suspect worn the item as alleged. Where the circumstances are such that the absence of a primary transfer may be expected (e.g. 7 days post incident recovery with hair washed), moderately strong evidence supporting Hp can be obtained by demonstrating the presence of secondarily transferred fibres on pillowcases. Likewise, where the circumstances are such that a demonstration of secondary transfer would be expected under Hp, (whilst this is not observed) support for Hd is provided.

The results demonstrate that when wearing the mask is disputed by the defence, searching for secondarily transferred fibres not only augments the evidence of primary transfer of fibres in head hair, but in certain case circumstances, may be the first priority examination.

Where wearing the mask is not in dispute, but the question of when it was worn is presented as a proposition by the defence, the examination of the suspect's pillowcase is not probative in such circumstances.

For the practitioner, this serves to illustrate the importance of setting and addressing the correct proposition particularly with reference to Hd.

7.5 Sensitivity

In *Chapter 6*, the 'sensitivity' of the various inter-related parameters to the effect of the increased related data sets ('knowledge') was assessed within a specific case context involving fibre transfers from balaclavas to head hair. The results demonstrate that the sensitivity of a given parameter in terms of its contribution to the computation of the likelihood ratio is governed principally by the case scenario (framework of circumstances), the propositions under consideration, as well as the observed examination outcome. Importantly, the results also demonstrate that the degree of sensitivity of the various parameters can result in a range of computed likelihood ratios for a particular outcome and case scenario under consideration.

Whilst only a limited number of outcomes have been considered and discussed in the results section, the methodology produced results for all outcomes considered in each case scenario (available in the appendix). Whilst the conclusions drawn from the results relating to the limited number of outcomes considered may not be valid globally, this methodology nevertheless allows us to consider specific outcomes in particular case scenarios under consideration. This is discussed further in this thesis.

7.5.1 Fibre 'Rarity'

The results of the analysis regarding rarity demonstrated it to be the most sensitive parameter for rare fibres, whilst FFG was the most sensitive for common fibres. In addition, the degree of sensitivity exhibited by these parameters varied according to the case scenario (e.g. virtually no sensitivity occurred for common fibres under Hd1 and Hd2 where fibres have been recovered after 7 days when the suspect has washed. Likewise, the sensitivity

of rarity was smaller for rare fibres in case scenarios where fibres have been recovered after 7 days.

As discussed in *Chapter 6*, global estimates of 'rarity' were assigned using the most appropriate data available for fibre types/ colour combinations found in masks. These estimates were based upon population studies, colour block studies and target fibres studies relating to blue cotton and red acrylic which strictly speaking were not compatible in terms of data relating to the specific colour type in question. Consequently this data was used to inform Dirichlet counts for 'virtual' experiments where the maximum likelihood estimates were based upon the incidence of adventitious matches given a defined set of observations.

This illustrates the difficulty and uncertainty in providing estimates of adventitious matches for given fibre type colour combinations. Given the innumerable dye, fibre type and morphological combinations possible, it is extremely difficult to carry out such studies which are strictly relevant to target fibres in a specific case. This illustrates the difficulty in obtaining 'globally relevant' data, and has implications for future research which will be discussed later in this chapter.

7.5.2 Foreign Fibre Groups (FFG's)

The findings demonstrated that estimates for the number of recovered non-matching foreign fibre groups (FFG's) were the most sensitive in that the degree of uncertainty relating to estimates for their presence, had the greatest effect on the *range* of the likelihood ratios across all scenarios involving 'common' fibres.

As with "rarity", there is a paucity of case specific data concerning the number and size of foreign fibre groups on specific substrates. Since the presence and number of FFG's condition the maximum likelihood estimate for an adventitious match with a given fibre type colour combination, it is perhaps not surprising that the degree of uncertainty over expected numbers present on a particular substrate strongly influence the calculated likelihood ratio, particularly in scenarios involving common fibres (since in such circumstances the chances of the observed outcome being adventitious is greater).

Whilst a number of studies have cited the importance of FFG estimation in the interpretative/ evaluative process of fibre evidence e.g. *Grieve and Dunlop, (1992)*, *Champod and Taroni,*

(1996), *Roux, Chable et al., (1996)*, *Coulson, Elliot et al., (2006)*, their significance is not universally accepted.

Many practitioners, whilst accepting that the greater number of fibres recovered from a crime relevant surface may increase the chances of an adventitious match being found, argue that estimates from target fibre studies already factor in this effect, since the targets are recovered from tape lifts in which other non-matching populations are present. The argument therefore proposes that by considering the presence of FFG's in the interpretation process, one is 'over-compensating' by effectively duplicating this effect (*Palmer and Booth, 2010*, *EFG personal communication, 2013*).

As discussed in *Chapter 4* the effect of the presence of non-matching FFG's on likelihood ratio estimation can be reasonably ignored when the provenance of those present can be established or, is not in dispute (as in *Chapter 5*). In the cases considered in *Chapters 5 and 6* (skin and head hair pillow/ cases), there exists the possibility that many of the non-matching FFG's present may relate to the environment of the individual in question. Consequently there is a danger that indiscriminate use of FFG's to condition adventitious match estimation may result in evidence being understated.

7.5.3 Transfer

As seen in *Figure 6.15,* in the case scenarios and outcomes considered, the transfer parameter has a significant effect on the calculated likelihood ratios across all scenarios involving rare fibres, particularly for case scenarios where fibres have been recovered at > 7 days. The effect is most marked under Hd2, since in these scenarios the time of wear is in dispute. Its contribution in scenarios involving common fibres is smaller, with size of FFG and rarity being more influential.

However, despite its importance in the scenarios and outcome considered, the transfer parameter demonstrated no sensitivity to increased 'knowledge' in terms of its effect on the calculated likelihood ratios, across all case scenarios. This observation is likely to be due to the fact that the scenarios chosen relate to head hair and that the transfer data used is much more specific to such cases than that used to inform the MLE's for the rarity and FFG parameters. Clearly in cases where a different substrate is under consideration, the sensitivity of the transfer parameter may be much greater.

7.5.4 Effect of case outcome

The observations considered in this discussion have so far related to an examination outcome involving a large number of matching fibres in the presence of a number of non-matching fibre groups (e.g. t(>10)/>5nm). The contribution to the range of likelihood ratios by the various parameters under a different observational outcome can be seen in *Figure 6.20,* where a large number of matching fibres (i.e. t(>10)) is recovered in the absence of foreign fibres groups (or where they can be reasonable disregarded). It can be seen that in this particular outcome, the effect of the transfer parameter is much more pronounced (especially for common fibres) under both Hd1 and Hd2, with the effect of the size and rarity parameters being considerably diminished under all scenarios.

In terms of parameter sensitivity, under this observed outcome it can be seen in *Figures 6.20 and 6.21* that compared to the outcome t(>10)/>5nm, rarity parameter is no longer sensitive when rare fibres are considered under Hd1 and Hd2.

The effect of the full range of observational outcomes on the influence of parameter sensitivity and likelihood ratio computation in the different case scenarios, under different Hd propositions, can be seen in the R markdown document appended to the thesis.

Clearly, as identified by the sensitivity analysis, it is worth investing time and resources on further study into the number and prevalence of FFG's and rarity on different substrates. Although the transfer parameter did not demonstrate any sensitivity in the case scenario considered, this may not be the situation in cases involving different substrates. The potential for further research into transfer and persistence is therefore discussed later in this chapter.

The results of the sensitivity analysis in this thesis have shown that the level of sensitivity of different parameters and its effect on the likelihood ratio, will vary from case to case, depending on the framework of circumstances, as well as different observed outcomes. The implications of this for the practitioner are considered in the next section.

7.6 Implications for the practitioner

7.6.1 Case assessment and interpretation

Evaluation of the authors' work in *Chapters 5 and 6* have demonstrated the importance of understanding the framework of circumstances within a given case and how changes within this framework can affect the evaluation of the significance of observed examination outcomes. This is particularly evident in *Chapter 6*, where nine different variants of case circumstances of a given case were used to calculate likelihood ratios for different examination outcomes (*Figures 6.7 and 6.8*). This demonstration of the inherent context sensitivity of forensic evidence, provides a powerful argument against those who advocate denying the forensic practitioner access to case relevant information e.g. *Dror, (2013)*, *Dror, Kassan et al., (2013).* In addition, such an approach may be useful and informative to the practitioner in situations where the circumstances of a case are poorly understood, incomplete or subject to a 'no comment' by the accused.

The author's studies concerning fibre persistence on the skin of living and dead subjects has addressed lack of published data concerning this substrate. The results of these studies should benefit the practitioner in both the assessment and interpretation of relevant casework. The prevailing assumption by practitioners prior to the *Palmer and Burch, (2009)* study was that skin was essentially a non-retentive substrate. In light of the authors' data from this study, it would seem likely that in some circumstances, the assessment of past relevant cases are likely to have been flawed in terms of expectations of finding crime related fibres. This may have resulted in potentially probative fibre recovery being disregarded under the assumption such an approach would be futile , or, unwarranted support being given to a prosecution proposition, where only a small number of crime relevant fibres had been recovered.

The current data provided by this study is therefore likely to provide a much more robust case assessment, particularly when time since an alleged activity is known.

As with case assessment, the results provided by this study may assist in providing a much more robust evaluation of the significance of an observed outcome, particularly when timescales for an alleged activity are in question.

In addition to transfer and persistence data, this study also provides information regarding fibre populations found on skin. These will also assist in addressing source level

propositions. However, it needs to be considered that there is a likelihood that the fibre populations observed in this study may very well be related to items of clothing worn by the victims or from other textile sources in their environment. As discussed in the previous section and in *Chapter 4,* if this provenance can be established, then the consideration of FFG's in source level proposition can be ignored. This is further discussed later in this chapter.

The results of the study by the author relating to the persistence of fibres on the skin in an outdoor homicide deposition scenario (*Palmer and Polwarth, 2011*) augment and refine the results of the only previous study relating to this substrate. One of the main benefits of this study is that it provides empirical evidence to support anecdotal information (*Spencer, 1994, Palmer, 2008, De Wael, 2009, De Wael, 2010*) that case relevant fibres can still be recovered from homicide victims exposed to adverse conditions over significant periods of time.

It is hoped that the information from this study will result in policy changes to crime scene examination that will end the debate (such as encountered in the Ipswich serial killings) regarding the value of recovering surface debris from homicide victims deposited outdoors.

As with the *Palmer and Burch, (2009)* study, the *Palmer and Polwarth, (2011*) study is potentially able to assist in a much more robust case assessment concerning the expectations of recovery of crime relevant material. Where reasonable timescales for death and deposition can be established (as in the Ipswich serial killings), the results provide a potential means of determining the nature and degree of the initial fibre transfer.

The use of the results of this study in the evaluation of fibre evidence recovered from homicide victims outdoors is likely to be more robust than the previous study of *Krauss and Hildebrand, (1996)* – especially when the bodies of homicide victims have not been subjected to rainfall.

The *Palmer and Oliver, (2004)* study is the only fibre population study to date which deals specifically with head hair as a substrate. Importantly for the practitioner, the results of this study are generally in line with those reported for other substrates and demonstrate that at the generic level, fibres frequently used in the construction of commercially made balaclavas, are found in low numbers in head hair. This information is of potential value to

the practitioner in addressing source level propositions, not only in cases involving the use of masks to conceal identity, but also in homicides, kidnapping etc. The results are also likely to be of value in the investigative phase of an investigation, as well as its evaluative phase.

The results of the *Palmer and Banks, (2005)* study are, to the author's knowledge, the only published data relating to the secondary transfer of fibres since the study by *Lowrie and Jackson, (1994).* Whilst the *Lowrie and Jackson, (1994)* study sought to provide a greater understanding of the mechanisms of secondary transfers and how these may be distinguished from primary transfers, the purpose of *Palmer and Banks, (2005)* study was to investigate the transfer and persistence characteristics of secondarily transferred fibres with regard to a very specific investigative application as reported by *Clayson and McKnight, (2001*). From a practitioner perspective, it was hoped that the results of the *Palmer and Banks, (2005)* study would:

- Augment those provided from the studies concerning primary transfer of fibres to hair.
- Assist in evaluating fibre evidence in case scenarios such as reported by *Clayson and McKnight, (2001*)
- Provide a justification for changes to investigative strategy in such cases

The results of the BN analyses of this data in *Chapter 6*, demonstrates its value can be variable depending on specific case circumstances, or indeed of no value if wearing a questioned item is not in dispute, but the time of wear is.

From a practitioner perspective these results create somewhat of a problem in terms of case examination strategy assessment and subsequent evidence evaluation. In the author's experience, it is not uncommon (or indeed frequently the case) that when a suspect is arrested in connection with such an offence, they provide 'no comment' to questions regarding the allegations against them. It is usually the case (again in the author's experience), that when full disclosure of the evidence against the accused is later issued, a defence proposition designed to account for the evidence is then provided.

The results from *Chapter 6,* show that in such circumstances there is the possibility of carrying out a time consuming, expensive examination of the pillowcases which could ultimately be ineffective or extremely probative for a particular proposition, depending on

information which may not be available at that time. Given the drivers to provide 'value for money' and shorter turn-around times in forensic fibre examinations (see *Chapter 1*), it is clear to see the conflict of priorities.

The potential way around this situation would be to seize the pillow cases regardless and recover surface debris via tape lifts. These '*contingency*' tapings (*Palmer and Booth, 2010*) would not be examined until information regarding the relevance was known. It is nevertheless crucial that such an approach is discussed with the investigative officer in charge of the case, since depending on the 'seriousness' of the crime, he or she may wish to have these examined at an early stage – regardless of 'no-comment' by the accused.

Such a situation may also benefit from a 'staged' examination strategy. By looking at the case circumstances that are known, such as the time of hair taping after incident, this will provide expectations regarding the presence of crime relevant fibres in the suspect's hair. Where subsequent examination of debris from the suspect's head hair confirms the expectation, this may assist the decision as to whether or not to proceed with the examination of pillowcases. As demonstrated in *Chapter 6,* it may be that the case circumstances dictate that searching for secondarily transferred fibres to pillowcases first, is the most effective examination strategy.

The results of this study have illustrated to the practitioner how crucial it is to have a complete understanding of the framework of circumstances of the case and appropriate propositions to address within these circumstances. As previously stated, in many cases it is common for the accused to return a 'no comment' concerning the allegations against them (for example at the time of arrest of Steve Wright, in the Ipswich serial killings) however, the case circumstances themselves are often well understood. Since a 'no-comment' by the accused amounts to an absence of a defence proposition, the practitioner is faced with the problem of evaluating his or her evidence.

In this author's experience, there is no one generally accepted method amongst practitioners of dealing with this situation (*Palmer and Booth, 2010*).

The ENFSI guideline for evaluative reporting in forensic science (*ENFSI, 2015*), suggests three options in dealing with the absence of an alternative proposition;

- Adopt alternative propositions that most likely and reasonably reflect the accused's position and produce an evaluative report.
- State the examination outcomes and offer explanation(s) for these in a non-evaluative (investigative) report.
- State the findings in a technical (factual) non-evaluative report

In dealing with the absence of a defence proposition, it is this author's opinion that the most effective option for the practitioner is to 'retreat' to an 'investigative mode' i.e. offer explanations for observations, whilst making it clear an evaluation can be performed only if relevant information becomes available.

In this thesis, the use of the Bayesian network has been demonstrated to be useful to the practitioner in such circumstances. In *Chapter 6,* where the significance of presence of fibres in head hair was investigated, hair washing and time of pre-incident wear of the questioned item were found to be important conditioning factors in evaluating the evidence. However, in a 'no-comment' situation, this information would be unknown. The Bayesian network provides the flexibility for the examiner to assign equal weight to different possibilities for different conditioning factors (e.g. hair washing) as well as to observe the effect of lack of knowledge on the evaluation of the evidence (this is illustrated by case scenario 1 in *Figures 6.7-6.12*). From a practitioner perspective, the use of the Bayesian network can therefore assist in informing investigative opinion in 'no-comment' situations.

The methodology employed in this thesis provides a means of improving data integration relating to casework, providing information regarding how various inter-related parameters influence the evaluation of the strength of evidential findings. Whilst this methodology has been applied to specific cases where a paucity of knowledge concerning particular parameters was known to exist, it can also be employed in a more global context; to construct Bayesian networks relating to cases that are identified as being frequently submitted / encountered in casework and refining specific scenarios around these. These could then be used to identify any parameter sensitivity which is common to different case types and those which are case specific. This would serve to not only assist the practitioner in providing more robust case assessment and interpretation, but also inform strategies/ priorities for future research.

7.6.2 Reporting uncertainty

One very important aspect to emerge from the sensitivity analysis in *Chapter 6* is that the degree of 'knowledge' of a particular parameter (as defined by the parameters of the Dirichlet distributions), can result in a *range* of computed likelihood ratios for a given observational outcome and case scenario (see *Figures 6.13 and 6.14*), illustrating that there is a degree of variation associated with the likelihood ratios computed under different instances of data underpinning the BN. In terms of reporting, this presents a conundrum for the practitioner – should this 'variability' be expressed and if so, how?

The recent papers by *Taroni, Bozza, et al, (2016)*, *Nordgaard, (2016)* and *Sjerps, Alberink, et al, (2016),* provide and illustrate different opinions and approaches to reporting likelihood ratio variability.

Taroni, Bozza, et al, (2016), state that the evaluation of forensic evidence in court is an expression of personal belief which often requires empirically derived data combined with personal experience and knowledge of the case circumstances. They point out that data used for parameter estimation may be comprehensive, incomplete or not known and hence (as demonstrated in this thesis) its use in computing a likelihood ratio introduces a degree of uncertainty over the evaluation of the evidence. These authors argue that it is inappropriate to express the uncertainty of the likelihood ratio by replacing this with an interval estimate of the true value, since the initial value of the LR (itself expressing uncertainty) would be 'blurred' by an additional level of uncertainty.

These authors advocate avoiding the use of likelihood ratios in reporting, and instead devote efforts to communicating the best representation of the value of the evidence based on their knowledge and experience.

In response to *Taroni, Bozza, et al, (2016), Nordgaard, (2016)* points out that the background of the majority of reporting forensic scientists is in biology and/ or chemistry with only a basic (classical) knowledge of statistics. The author argues that as a consequence, many reporting scientists find it difficult to understand the subtleties, language and concepts of Bayesian inference, as well as thinking in terms of personal beliefs, instead of relative frequencies when considering probability. Many forensic practitioners, the author argues, find it more reassuring to express uncertainty in their probability estimations through the use

upper and lower estimations of frequency based upon personal experience. The author further maintains that even if statisticians can prove that this approach is flawed, the arguments used are not easily appreciated by those practitioners making these assignments in daily casework. The author concludes that rather than openly criticising this practice, it is more pragmatic to accept that at an early stage a practitioner will tend to report a range of likelihood ratios, but statisticians should strive progressively to assist the practitioner, using good examples from real cases, to illustrate why it is unsound to accompany likelihood ratios with intervals.

By contrast, *Sjerps, Alberink et al, (2016),* advocate the reporting of the uncertainty of the LR by estimating its variance. They maintain the arguments presented by *Taroni, Bozza, et al, (2016)* as facts or logic, represent opinion or options and that there is no mathematical or logical reason to prefer one approach over another. They conclude that where the uncertainty of the LR is not addressed in a report, this deprives the criminal justice system of essential information needed to assess the reliability of the evidence.

These three papers illustrate the difference of opinion in dealing with the uncertainty inherent in the calculation of the likelihood ratio. It should be noted that each of these papers consider parameter uncertainty within source level propositions. When activity level propositions are involved, the situation becomes even more complex, where no case specific data may be available for transfer and persistence parameter estimation.

This author agrees with *Nordgaard, (2016),* that subtleties of the statistical concepts behind the opposing arguments are unlikely to be fully understood by the majority of practicing forensic scientists, however, the concept of expressing uncertainty over an existing expression of uncertainty (as described by *Taroni, Bozza, et al, 2016* and advocated by *Sjerps, Alberink, et al, 2016*) does seem intuitively complicated, and of questionable necessity. In addition, it would, in this author's opinion, be both impractical and extremely difficult (in the UK at least) to educate lay persons in the criminal justice system (e.g. juries) many of whom have only a basic education, in the subtleties of these statistical concepts.

It is this author's opinion that existing methods of evaluative reporting already deal with the uncertainty involved in the computation of a single likelihood ratio. Whilst the use of LR verbal equivalence scales proposed by *Association of Forensic Science Providers, (2009)* and *Nordgaard, Ansell et al., (2012)* have come under recent criticism (*Mullen, Spence et*

al., 2014, *Martire, Kemp et al., 2014* and *Martire and Watkins, 2015*), it may be argued that since each verbal expression of support is associated with a *range* of likelihood ratios, their use encompasses the inherent uncertainty expressed by a single likelihood ratio. In this author's opinion, this is a justification for their continued use.

One further method of expressing uncertainty (particularly addressing parameter estimation) may be to qualify a conclusion with a phrase such as;

"..based upon the information provided to me and *the current knowledge concerning fibre evidence,* in my opinion the findings provide X support for ….."

This would make it clear to the lay person that expert's opinion on the value of their findings is governed by the degree of knowledge of their area of expertise.

7.7 Future Perspectives

What has become clear from this thesis is that whilst much of the published data is useful in the interpretation of fibre evidence, the difficulty encountered is obtaining case specific data. This is particularly apparent when attempting to address source level issues, i.e. what are the chances that apparently crime relevant recovered fibres are in fact adventitious matches? *Vooijs, Vergeer, et al, (2015)* point out that current research of this type addresses only a small proportion of textile fibres encountered in casework and in particular, there is no fixed 'standard' or coordinated approach for this type of work.

This is exemplified in *Chapter 6*, when attempting to provide global estimates for adventitious matches of the target fibres considered in the BN model of the case scenario involving head hair. Whilst fibre population studies, colour block studies and target fibres studies provide complimentary data addressing source level issues, it is clear from the published literature, that there is often a lack in continuity of data between them concerning specific fibre type colour combinations.

These types of studies have been carried out over the past three decades, however, the fundamental experimental design of these has not varied throughout this time. It would seem that there is a need for some form of 'hybrid' experimental design which encompasses all of the complementary information provided by these studies, but which provides a continuity

of progression from generic frequency estimates to analytical discrimination for given fibre type/ colour combinations.

As well as having the advantage of providing better fibre colour type specific data, the advantage of such an experimental design would be in time savings in sample collection. At the present each of the different study types (fibre population studies, colour block studies and target fibres studies) have involved separate sampling methodologies and substrates. A proposed 'hybrid' type study would use the same recovery samples (usually tape lifts) from a specific substrate source (e.g. cinema seats). This would therefore provide consolidation, not only in terms of fibre specific data, but also substrate.

An experimental design which could be employed in such a study is illustrated in *Figure 7.1*.

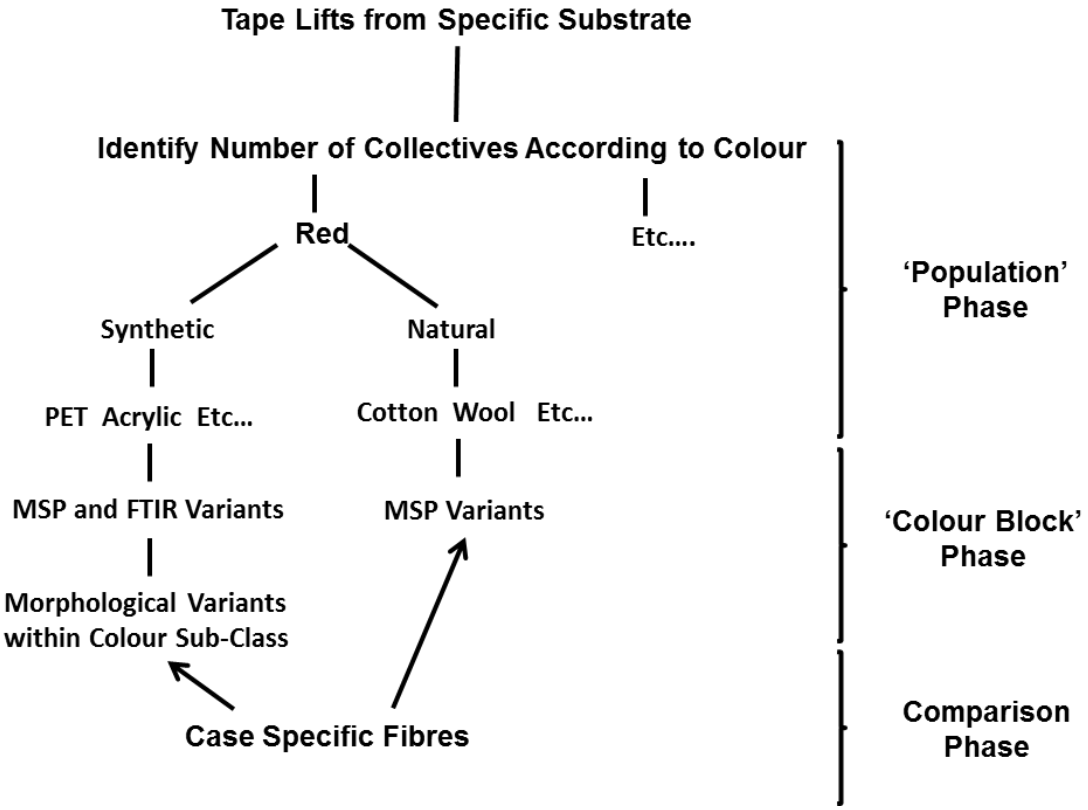


Figure 7.1: Experimental design of proposed 'hybrid study'

The first phase of such a study would essentially be very similar to a fibre population study, in that recovered fibres would be grouped according to generic colour and fibre type and the relative frequencies of such groupings determined. The next phase would be to sub-categorise the generic data into specific colour block variants using MSP and (in the case of

synthetic fibres) chemical sub-class via FTIR. This could then be followed by a further sub-categorisation according to morphological features (e.g. cross section shape, delustrant).

Once this work is completed the relative frequency of individual sub-groupings could then be determined. At that stage, the 'rarity' of case specific fibres could be established by simply comparing the features of the constituent fibres of a given garment to determine whether or not these where represented in any of the final sub-class categories. The caveat with this data is of course, that in dealing only with 'trace', such a survey does not inform us whether the variation observed is due to different sources and/ or intra sample variability of the same source(s) – especially where natural fibres are concerned.

Whilst it is clear that such a study would involve a copious amount of work and time, this could be significantly reduced if it was performed as a collaborative venture. For example; one group could, after sampling a particular fibre colour group (e.g. red) from the tapings, pass this on to another group to sample their designated colour group (e.g. green), and so on. Once the work of each group is complete, then the data would then be collated.

Whilst there is no doubt that even as a collaborative exercise such a study would be a huge endeavour, the advantage would be that once a more comprehensive data set concerning the probability of adventitious matches specific fibre variants was obtained, it would be possible to assess the 'rarity' of fibres from *case-specific* garments quickly and easily. This would address the present difficulties identified by this thesis and *Vooijs, Vergeer, et al, (2015)* of obtaining case relevant data relating to source level determinations.

One other advantage of such a study would be that the data could be used to provide information on the size and number of foreign fibre groups on the particular substrate under investigation. In terms of further investigation into the influence of FFG's on source level determination, would be to determine what degree of provenance can be attributed to FFG's on substrates where there may be an expectation that these have originated from the environment of the victim or accused. Substrates such as skin and car seats are obvious candidates for such a study. Although very different substrates, surface debris recovered could be searched to determine the nature, size and number of collectives present. An 'intelligence based' exercise could then be performed to establish if and to what degree any of these fibre groups could be attributed to the relevant individual's clothing and environment.

In terms of informing activity level propositions, there are a number of potential refinements to the dataset that could be carried out.

In *Chapter 6* the results of the sensitivity analysis showed that although the transfer parameter had an important influence on the computed likelihood ratio, this parameter exhibited little if any sensitivity concerning the degree of knowledge concerning it. In the author's opinion, this is because of the case scenario chosen and the fact that the data used was from case specific research. In other different case types, this is unlikely to be the situation. Contrary to the results of the sensitivity analysis of the transfer parameter in this thesis, it is this author's opinion that there are still gaps in our knowledge concerning transfer which need to be addressed.

As discussed in *Chapter 6*, the current published data concerning the primary transfer and persistence data relating to hair is over 20 years old. Whilst this in itself does not invalidate the use of such data, the review of the literature carried out in *Chapter 3* demonstrated that in the study of *Ashcroft, Evans et al, (1988),* the authors state that repeated washing would be required to remove all fibres, however, no data is provided in the published paper relating to day 7 after washing.

Similarly, In the study by *Salter and Cook, (1996),* data regarding hair washing is only presented for 1 subject at day 1 and whist they concur with *Ashcroft, Evans, et al, (1988)* that a single hair washing would not be expected to remove all transferred fibres, and that there is little expectation of finding fibres after 7 days, no data is presented for 3 or 7 days post washing. In addition the general method of data presentation in this paper makes it difficult to obtain precise information regarding washing or non-washing (e.g. the persistence graphs presented do not represent all subjects).

Whilst the authors of each of these studies conclude that there is little expectation of finding fibres after 7 days following washing, there is actually no data from these or subsequent studies to corroborate this.

It would therefore be a wise investment for future research to refine and re-run these studies to provide greater clarity on the persistence of fibres in hair, with clearly defined washing times over a time scale of 10-14 days.

The survey by *De Wael, (2010)* relating to the experience of case working practitioners' expectations concerning the persistence of fibres in the hair of homicide victims deposited and immersed in water, gave estimates ranging between 0-80%, after 2 hours, 0-50% after 2 days and less than 25% after 2 weeks. This is corroborated by this authors experience in the Ipswich serial killings (*Palmer, 2008*). Clearly, the casework experience of practitioners appear incongruous with the data from the studies relating to live subjects and washing of hair. The need for research to resolve this apparent disparity is therefore clear, however, an experimental design which would simulate an appropriate realistic scenario is fraught with practical and ethical difficulties.

This situation could potentially be resolved by collaboration with institutions such as The University of Tennessee at Knoxville, USA, who have a human taphonomic facility (so-called '*body farms*') where donated human cadavers could potentially be used. At the present time there are no such facilities in the UK or Europe.

In terms of the studies relating to the persistence of fibres on the skin of homicide victims deposited outdoors, no further studies have been carried out since the *Palmer and Polwarth, (2011)* publication. As discussed in *Chapter 5*, the use of pig carcasses appears to produce data similar to that encountered in actual casework experience (*Palmer, 2008*) rather than using small two-dimensional sections of pig skin used in the *Krauss and Hildebrand, (1996)* study. Despite this, there is still a need for refinement of the experimental design of the *Palmer and Polwarth, (2011)* study.

Only one day of rainfall was encountered in this study which was carried out during the summer. The small amount of rainfall encountered, was nevertheless observed to accentuate fibre loss. The obvious refinement to this study would therefore be to carry out the same experiment during the winter months, when (in the UK at least) there is a higher probability of frequent rainfall. In addition, it would be useful to carry out such experiments using different fibre types to test the assumption that the actual persistence characteristics are unlikely to differ with different fibre types. Such refinements, combined with the data from the original study, would give a much more robust dataset, encompassing a larger variety of conditions likely to be encountered in the case of an outdoor deposition following a homicide.

Recent studies by *Lepot, Van Den Driessche, et al, (2014)* and *Lepot, Lunstroot, et al, (2015)* have investigated the persistence characteristics of fibres transferred to articles of clothing

immersed in still and running water using dummies. The results of these studies show that crime relevant fibres would be expected to persist in such scenarios.

Again, refinements to such studies would be to use a human taphonomic facility such as that suggested for the investigation of the persistence of fibre in hair immersed in water. This would clearly create a much more realistic and robust experimental design.

By increasing and refining our knowledge concerning source and activity level propositions regarding fibre evidence as suggested, the establishment of an 'expert system' using Bayesian networks encompassing the refined datasets becomes a real possibility.

7.8 The importance of collaboration

Whilst the proposed studies are in themselves comparatively inexpensive in terms of consumables, it must be conceded however, that they are time and resource intensive. There is however a means of mitigating this, namely greater collaboration. *Palmer, (2013)* states*;*

'The process of logical, evaluative reasoning in the interpretation of forensic evidence needs continued support through the provision of data from basic research into the factors governing the dynamics of a particular evidence type. Whilst funding for research continues to be an issue in many countries, it needs to be borne in mind that much of the cogent research in the forensic examination of fibres is [of] high value. International collaboration between the various working groups, agencies and institutions, will continue to be crucial in delivering this basic research'.

In order for collaborative research to be effective, there needs to be a general consensus of where resources can be best employed and a strategic plan drawn up to address priorities and division of labour.

Taking the example of the *Palmer and Polwarth, (2011)* study, the experimental method was very time consuming and consequently only two experiments using two different target fibres were carried out. Had this study been part of strategic plan, a larger data set could have been obtained though collaboration with other researchers carrying out additional experiments.

In identifying strategic priorities of research, canvassing practitioners regarding the types of cases in which they feel more data is required, can identify those areas of research which will

have a global impact as well as those that are very case specific. The various specialist working groups have an important role to play in this regard.

In Australia and Asia, the need for strategic collaborative research is actively being addressed.

Representatives from the University of Canberra, University of Technology, Sydney and the Australian Federal Police formed a fibres and textiles research group in 2013. At the first meeting the gaps and future needs for fibre and textile research in forensic science were discussed and several areas of possible focus were identified. These included, but were not limited to; understanding background fibre populations and how these may play a more important role, transfer and persistence (especially on footwear) and textile damage (*Roux, 2012*).

Interestingly, the areas of research identified by this group are those identified by the sensitivity analysis carried out in *Chapter 6* of this thesis.

The Asian Forensic Sciences Network (AFSN) (the Asian equivalent of ENFSI) has a trace evidence working group (TEWG) comprising 36 members from 8 Asian countries and 10 organisations. One of the stated aims of this group is to foster research and development, and collaborative research among member institutes and other networks *(Lim, 2012)*.

7.9 The role of the expert

Although the use of Bayesian networks has shown to be a useful tool in this thesis, it needs to be emphasised that it does not replace or diminish the role of the expert. One illustration of this is the use of global estimates of rarity to determine the potential effect of adventitious fibre matches on the global likelihood ratio for fibres in head hair and on pillowcases (*Chapter 6*). Whilst the use of such estimates are likely to be fair and reasonable in the majority of circumstances, it may be (for example) that a case specific target fibre is encountered which is known by the expert to be extremely rare (e.g. a pink bi-component acrylic). In such a situation it would be entirely justifiable for the expert to increase the strength of report based upon his or her experience of that particular piece of evidence, within the framework of circumstances. This could also be achieved by simply adjusting the ‘rarity’ parameter in the BN.

For robust and effective casework assessment, interpretation and reporting, it is essential that the practitioner has a thorough and up to date understanding of the body of knowledge concerning transfer and persistence, background populations, adventitious matches (‘rarity’) as well that concerning instrumental analysis and methods of fibre recovery and evidence preservation. For this reason, the author of this thesis cannot agree with *Roux, Talbot-Wright, et al, (2015),* who advocate that the forensic practitioner should be more of a ‘generalist’ rather than a ‘specialist’. Whilst the author of this thesis agrees entirely that forensic practitioners (of any discipline) need to ensure they take a ‘holistic’ approach to casework assessment and examination, it is his experience that given the demands on operational forensic provision in this day and age, multi-disciplinary practitioners have difficulty in acquiring and maintaining current specialist knowledge of the different evidence types they report (*Palmer and Booth, 2010*). It is therefore this author’s opinion that creating ‘multi-disciplinary practitioners’ creates a high risk of the diminishment of their specialist knowledge.

Stoney and Stoney, (2015) maintain that technical advances and increased emphasis on scientific practices has reduced the viability of the trace evidence ‘generalist practitioner’, however, they agree with *Roux, Talbot-Wright, et al, (2015)* that increased specialisation runs the risk of the practitioner being separated from the actual case specific issues to be addressed. In this author’s opinion however, there is no evidence (in Europe at least) to suggest that practitioners specialising in fibre evidence are becoming detached from casework. If one considers that the majority of published and unpublished research over the last 10 years has been carried out by specialist operational practitioners, often in response to issues arising from casework (these authors and their studies are catalogued by *Palmer, (2010a), Palmer, (2010b), Palmer, (2013)*) the contrary would appear to be true.

The role of the expert in performing case driven research, whether published or unpublished, is absolutely essential in addressing gaps in our understanding of the factors influencing the evaluation of fibre evidence.

8 CONCLUSION

In this chapter, the findings of this thesis are summarised and their implications in a global context of the interpretation and reporting of forensic evidence are considered.

The stated purpose of this thesis, is to identify, evaluate and address ‘gaps’ in key areas of our present knowledge of the factors influencing the interpretation of fibre evidence which inform a more effective casework assessment and interpretation process, ultimately resulting in the greater effectiveness of fibre examinations.

Throughout this thesis, the rationale and application of the use of a Bayesian framework to underpin the assessment and interpretation processes of forensic evidence have been discussed and key concepts defined. The author has presented data from various studies arising through operational casework experience which identified areas of deficiencies and, or, requirement for refinements in our knowledge of the processes governing the interpretation of fibre evidence. The results obtained through the use of Bayesian networks to model real specific case scenarios and evaluate the impact of the authors work, have proven these to be an invaluable and versatile tool for casework assessment and evaluation.

As well as providing an analysis of the impact of the author's data acquisition work, the BN has allowed an evaluation of the sensitivity of the data used in terms of our current state of knowledge concerning a given parameter and its effect on the likelihood ratio. Importantly, the results have shown that the effect of a given parameter on the evaluation of evidence varies according to the framework of particular case scenario, examination outcome and proposition setting. The sensitivity analysis has proved to be a useful method in specifically identifying which parameters will benefit from a greater knowledge base, thus informing which areas of research should be targeted as priorities.

The sensitivity analysis has also illustrated how the degree of paucity of information concerning a particular parameter contributes to a possible range of likelihood ratios for a given observational outcome and case scenario. Whilst the subject of encompassing the uncertainty of the likelihood ratio in reports for the judiciary is a controversial topic, the author believes that the present method of expressing the strength of evidence using LR verbal equivalence scales provides the most pragmatic approach in reflecting the 'uncertainty' inherent in a single likelihood ratio value. In addition, the author proposes the modification of language used within evaluative reports to reflect the effect of knowledge in forming their opinion, in a manner comprehensible to the lay person.

For the practitioner, the results reported in this thesis provide a powerful justification for the provision of information relating to the circumstances of a particular case, rather than operating within an information vacuum as proposed by a number of researchers.

In addition, the methodology employed in this thesis has provided a robust, transparent means of data integration, resulting in a greater understanding of how different but inter-related parameters influence the evaluation of the strength of evidential findings. In this thesis,

this methodology has been applied to specific cases where a paucity of knowledge concerning particular parameters was known to exist. However, for the practitioner, this methodology can be employed using a more generalised approach;

- As a collaborative exercise, identify types of cases that are submitted frequently
- Construct Bayesian networks for these types of cases
- Refine with specific scenarios around the type of case under consideration (if necessary)
- Establish the presence and degree of any parameter sensitivity
- Identify any parameter sensitivity which is common to different case types and those which are case specific
- Target research accordingly

As well as informing which areas of research are likely to benefit a variety of different case types, this methodology will also inform the practitioner's understanding of the significance of the various parameters governing the evaluation of fibre evidence and the complex interdependencies that exist between them.

In the current economic climate the challenge relating to the forensic examination of fibres (and indeed other evidence types) is to improve the effectiveness and value for money of these examinations, by providing a more robust framework of casework assessment, strategy setting and interpretation. *Palmer, (2013)* states;

'The present global economic situation has meant that all aspects of forensic science provision (whether in the public or private sector) are likely to become under even greater scrutiny in terms of effectiveness/ delivering value for money. The key to this is in better case assessment as well as a more transparent, robust, context sensitive interpretation reporting of casework results'.

In terms of a driver for research, this translates into the need for more empirical data which can address the paucity of knowledge underpinning casework assessment and interpretation.

The current challenge relating to the forensic examination of fibres (and indeed other evidence types) is to improve the effectiveness of these examinations, by providing a more robust framework of casework assessment, strategy setting and interpretation. In many ways,

the situation is very much the same as described by *Grieve and Wiggins, (2001)* 15 years ago.

The results of the author's studies have been shown to address gaps in case relevant published literature. In addition, the impact of these studies in terms of assessment and interpretation from the perspective of the practitioner has been established and discussed.

The 'sensitivity' of data relating to key parameters involved in the interpretation of fibre evidence has been evaluated and the implications of the results in terms of casework assessment and interpretation, as well as informing future research strategies have been identified.

Whilst the results and conclusions from this thesis have related to the evaluation of fibre evidence in the investigation of major crime, it is the author's opinion that many of the inferences drawn, particularly with regard to implications for the practitioner, are valid in the evaluation of forensic evidence, regardless of the discipline.

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APPENDIX 1

Node MLE's for Chapter 5 Bayesian Network regarding fibre persistence on skin.

The Bayesian network and any associated files can be obtained on request by email from the following;

ray.palmer@northumbria.ac.uk

genevieve.massonnet@unil.ch

christophe.champod@unil.ch

[1]Propositions(Prop)

Hp: The suspe	0.5
Hd: The suspe	0.5

[2]Number of fibrestransferred to victim's skin @ time T0 under Hp(Transfer_Head_1)

t=0	0.0050
t1-10	0.05
t11-20	0.05
t21-30	0.1
t31-40	0.1
t41-50	0.2
t51-100	0.495

[3]Number of fibresrecovered from the victim's skin @ time Tx(Transfer_Head)

Prop	Hp: The suspect was in contact during deposition									
C1	[0;25] %							[25;35] %		
Transfer_Head	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t1
t=0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.5	
t1-10	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.5	
t11-20	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	
t21-30	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	
t31-40	0.0	0.0	0.0	0.0	0.5	0.5	0.3333333...	0.0	0.0	
t41-50	0.0	0.0	0.0	0.0	0.0	0.5	0.3333333...	0.0	0.0	
t51-100	0.0	0.0	0.0	0.0	0.0	0.0	0.3333333...	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									
C1	[25;35] %					[35; 45] %				
Transfer_Head	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t3
t=0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.0	0.0	
t1-10	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	
t11-20	0.5	0.6	0.0	0.0	0.0	0.0	0.0	0.5	1.0	
t21-30	0.0	0.4	1.0	0.0	0.0	0.0	0.0	0.0	0.0	
t31-40	0.0	0.0	0.0	0.4	0.3333333...	0.0	0.0	0.0	0.0	
t41-50	0.0	0.0	0.0	0.6	0.3333333...	0.0	0.0	0.0	0.0	
t51-100	0.0	0.0	0.0	0.0	0.3333333...	0.0	0.0	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									
C1	[35; 45] %			[45 ; 55] %						
Transfer_Head	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t5
t=0	0.0	0.0	0.0	1.0	0.5	0.0	0.0	0.0	0.0	
t1-10	0.0	0.0	0.0	0.0	0.5	0.9	0.1	0.0	0.0	
t11-20	0.5	0.0	0.0	0.0	0.0	0.1	0.9	0.9	0.5	
t21-30	0.5	0.6	0.25	0.0	0.0	0.0	0.0	0.1	0.5	
t31-40	0.0	0.4	0.25	0.0	0.0	0.0	0.0	0.0	0.0	
t41-50	0.0	0.0	0.25	0.0	0.0	0.0	0.0	0.0	0.0	
t51-100	0.0	0.0	0.25	0.0	0.0	0.0	0.0	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									
C1	[45 ; 55] %	[55 ;65] %							[65 ;75] %	
Transfer_Head	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t
t=0	0.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	
t1-10	0.0	0.0	0.5	1.0	0.5	0.0	0.0	0.0	0.0	
t11-20	0.0	0.0	0.0	0.0	0.5	1.0	0.8	0.25	0.0	
t21-30	0.25	0.0	0.0	0.0	0.0	0.0	0.2	0.25	0.0	
t31-40	0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.25	0.0	
t41-50	0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.25	0.0	
t51-100	0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									
C1	[65 ;75] %						[75 ;85] %			
Transfer_Head	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t2
t=0	0.5	0.0	0.0	0.0	0.0	0.0	1.0	0.8	0.0	
t1-10	0.5	1.0	1.0	0.5	0.05	0.0	0.0	0.2	1.0	
t11-20	0.0	0.0	0.0	0.5	0.95	0.3333333...	0.0	0.0	0.0	
t21-30	0.0	0.0	0.0	0.0	0.0	0.3333333...	0.0	0.0	0.0	
t31-40	0.0	0.0	0.0	0.0	0.0	0.3333333...	0.0	0.0	0.0	
t41-50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t51-100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									
C1	[75 ;85] %				[85;95] %					
Transfer_Head	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t4
t=0	0.0	0.0	0.0	0.0	1.0	0.9	0.0	0.0	0.0	
t1-10	1.0	1.0	0.9	0.3333333...	0.0	0.1	1.0	1.0	1.0	
t11-20	0.0	0.0	0.1	0.3333333...	0.0	0.0	0.0	0.0	0.0	
t21-30	0.0	0.0	0.0	0.3333333...	0.0	0.0	0.0	0.0	0.0	
t31-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t41-50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t51-100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Prop	Hp: The suspect was in contact during deposition									Hd:
C1	[85;95] %		[>95] %							[0;
Transfer_Head	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	
t=0	0.0	0.0	1.0	0.95	0.9	0.9	0.9	0.9	0.0	
t1-10	1.0	0.5	0.0	0.05	0.1	0.1	0.1	0.1	1.0	
t11-20	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t21-30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t31-40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t41-50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t51-100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[0;25] %							[25;35] %	
Transfer_Head	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[25;35] %					[35; 45] %			
Transfer_Head	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[35; 45] %			[45 ; 55] %					
Transfer_Head	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[45 ; 55] %	[55 ;65] %							[65 ;75] %
Transfer_Head	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[65 ;75] %						[75 ;85] %		
Transfer_Head	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[75 ;85] %				[85;95] %				
Transfer_Head	t21-30	t31-40	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

Prop	Hd: The suspect had contact 2 days before death of victim								
C1	[85;95] %		[>95] %						
Transfer_Head	t41-50	t51-100	t=0	t1-10	t11-20	t21-30	t31-40	t41-50	t51-100
t=0	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...	0.9999400...
t1-10	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t11-20	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t21-30	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t31-40	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t41-50	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...
t51-100	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...	9.9994000...

[4]Raining?(Y/N)(C2)

Raining	0.5
Not Raining	0.5

[5]Time between body deposition and fibre recovery(TimeRecovery)

Time of deposi	0.2
1 day after dep	0.2
2 days after de	0.2
4 days after de	0.2
7 days after de	0.2

[6]Source of persistencedata regardingdead bodies(SourceData)

K&H	0.5
P&P	0.5

[7]Total Loss of fibres on deadbodies [%](C1)

C2	Raining									
SourceData	K&H					P&P				
TimeRecovery	Time of de	1 day after	2 days afte	4 days afte	7 days afte	Time of de	1 day after	2 days afte	4 days afte	7 d
[0;25] %	0.9998772...	1.2229993...	0.0015278...	1.2999989...	1.2999989...	0.9998772...	0.3767300...	0.0827396...	0.0434708...	
[25;35] %	1.0980003...	0.0014191...	0.0012938...	3.8799968...	3.8799968...	1.0980003...	0.0223376...	0.0540151...	0.0149117...	
[35; 45] %	1.2000003...	0.0080660...	0.0062228...	4.5859963...	4.5859963...	1.2000003...	0.0198899...	0.0643976...	0.0158774...	
[45 ; 55] %	9.0000027...	0.0301909...	0.0209045...	0.0030323...	0.0030323...	9.0000027...	0.0192710...	0.0756947...	0.0176896...	
[55 ;65] %	0.0	0.0830715...	0.0553937...	0.0140966...	0.0140966...	0.0	0.0202103...	0.0890723...	0.0206276...	
[65 ;75] %	0.0	0.1781659...	0.1228587...	0.0520909...	0.0520909...	0.0	0.0229394...	0.1065879...	0.0258741...	
[75 ;85] %	0.0	0.2962098...	0.2346947...	0.1593398...	0.1593398...	0.0	0.0297202...	0.1327648...	0.0364896...	
[85;95] %	0.0	0.3290338...	0.3714863...	0.4155916...	0.4155916...	0.0	0.0531215...	0.1871958...	0.0710982...	
[>95] %	0.0	0.0737202...	0.1856173...	0.3553497...	0.3553497...	0.0	0.4357800...	0.2075318...	0.7539605...	

C2	Raining	Not Raining								
SourceData	P&P	K&H					P&P			
TimeRecovery	7 days afte	Time of de	1 day after	2 days afte	4 days afte	7 days afte	Time of de	1 day after	2 days afte	4 d
[0;25] %	0.0178774...	0.9998772...	0.9998772...	0.9940688...	1.0	0.9999988...	0.9998772...	0.3767300...	0.0827396...	
[25;35] %	0.0037235...	1.0980003...	1.0980003...	0.0032709...	0.0	1.1999997...	1.0980003...	0.0223376...	0.0540151...	
[35; 45] %	0.0036973...	1.2000003...	1.2000003...	0.0014600...	0.0	0.0	1.2000003...	0.0198899...	0.0643976...	
[45 ; 55] %	0.0039317...	9.0000027...	9.0000027...	6.4458255...	0.0	0.0	9.0000027...	0.0192710...	0.0756947...	
[55 ;65] %	0.0044222...	0.0	0.0	2.6335201...	0.0	0.0	0.0	0.0202103...	0.0890723...	
[65 ;75] %	0.0053784...	0.0	0.0	8.7284096...	0.0	0.0	0.0	0.0229394...	0.1065879...	
[75 ;85] %	0.0075607...	0.0	0.0	2.0496265...	0.0	0.0	0.0	0.0297202...	0.1327648...	
[85;95] %	0.0149286...	0.0	0.0	0.0	0.0	0.0	0.0	0.0531215...	0.1871958...	
[>95] %	0.9384801...	0.0	0.0	0.0	0.0	0.0	0.0	0.4357800...	0.2075318...	

C2	Not Raining	
SourceData	P&P	
TimeRecovery	4 days afte	7 days afte
[0;25] %	0.0434708...	0.0178774...
[25;35] %	0.0149117...	0.0037235...
[35; 45] %	0.0158774...	0.0036973...
[45 ; 55] %	0.0176896...	0.0039317...
[55 ;65] %	0.0206276...	0.0044222...
[65 ;75] %	0.0258741...	0.0053784...
[75 ;85] %	0.0364896...	0.0075607...
[85;95] %	0.0710982...	0.0149286...
[>95] %	0.7539605...	0.9384801...

APPENDIX 2

‘R’ Script for estimating variance of fibre loss on skin

```
# Distribution of probabilities for range of losses as a function of a mean and variance

# for the loss

# C. Champod / 3.09.15

#Function to compute the parameter of a beta distribution based on the mean and variance

estBetaParams <- function(mu, var) {

  alpha <- ((1 - mu) / var - 1 / mu) * mu ^ 2

  beta <- alpha * (1 / mu - 1)

  return(params = list(alpha = alpha, beta = beta))

}

# Function to get the probability distribution

LossProba <- function(mu,var) {

  set.seed(123)

  Params <- estBetaParams(mu, var)

  Sample <- rbeta(10000000, shape1=Params$alpha, shape2=Params$beta)

  Sample <- na.omit(Sample)

  Histogram <- hist(Sample,
breaks=c(0,0.25,0.35,0.45,0.55,0.65,0.75,0.85,0.95,1))

  Histogram

  print(mean(Sample))

  print(var(Sample))

  Output <- Histogram$counts/sum(Histogram$counts)

}

# to use it:

test <- LossProba(0.05,0.01)

test
```

APPENDIX 3

Node MLE's for Chapter 6 Bayesian Network regarding fibre persistence in hair.

The Bayesian network and any associated files can be obtained on request by email from the following;

ray.palmer@northumbria.ac.uk

genevieve.massonnet@unil.ch

christophe.champod@unil.ch

[1]Hp/ Hd(Hp_Hd)

Hp	0.5
Hd	0.5

[2]Propositions(Prop)

Hp_Hd	Hp	Hd
Hp: The suspe	1.0	0.0
Hd1: The susp	0.0	1.0
Hd2: The susp	0.0	0.0

[3]Time of recoverysince incident(TimeRecovery)

1-3 days	0.5
7 days	0.5

[4]Time of Wearunder Hd2(TimeWear)

7 days before	0.5
14 days before	0.5

[5]Hair washed priorto fibre recovery(Washed)

Washed	0.5
Not washed	0.5

[6]Are FIBRESindistinguishablefrom MASK?(MatchMaskHair)

Prop	Hp: The su	Hd1: The	Hd2: The
Matching Type	1.0	0.0	1.0
Fibres of a diff	0.0	1.0	0.0

[7]Transfer (persistenceand recovery) of Fibresfrom MASK to HAIR (T)(Transfer_Head)

Prop	Hp: The suspect wore the mask at the time of the incident								Hd1: The
Washed	Washed				Not washed				Washed
TimeRecovery	1-3 days		7 days		1-3 days		7 days		1-3 days
TimeWear	7 days bef	14 days be	7 days bef	14 days be	7 days bef	14 days be	7 days bef	14 days be	7 days bef
t>10	0.2	0.2	0.0020	0.0020	0.6	0.6	0.0050	0.0050	0.0
t6-10	0.35	0.35	0.0020	0.0020	0.3	0.3	0.015	0.015	0.0
t1-5	0.35	0.35	0.0040	0.0040	0.09	0.09	0.68	0.68	0.0
t0	0.1	0.1	0.992	0.992	0.01	0.01	0.3	0.3	1.0

Prop	Hd1: The suspect never wore the (or any) mask							Hd2: The suspect wore
Washed	Washed			Not washed				Washed
TimeRecovery	1-3 days	7 days		1-3 days		7 days		1-3 days
TimeWear	14 days be	7 days bef	14 days be	7 days bef	14 days be	7 days bef	14 days be	7 days bef
t>10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0010
t6-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0050
t1-5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02
t0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.974

Prop	Hd2: The suspect wore the mask sometime before the incident					
Washed	Washed		Not washed			
TimeRecovery	7 days		1-3 days		7 days	
TimeWear	7 days bef	14 days be	7 days bef	14 days be	7 days bef	14 days be
t>10	0.0010	0.0010	0.0050	0.0010	0.0010	0.0010
t6-10	0.0010	0.0010	0.015	0.0010	0.0010	0.0010
t1-5	0.0020	0.0020	0.68	0.0020	0.0020	0.0020
t0	0.996	0.996	0.3	0.996	0.996	0.996

[8]Fibres from hair(non-)matching MASK(MaskFibres_on_Hair)

Transfer_Head	t>10		t6-10		t1-5		t0	
MatchMaskHai	Matching	Fibres of a	Matching	Fibres of a	Matching	Fibres of a	Matching	Fibres of a
t(1-5)	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
t(6-10)	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
t(>10)	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1nM fibres	0.0	1.0	0.0	1.0	0.0	1.0	0.0	0.0
NO FIBRES	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0

[9]Groups of Background fibres (FFGs) in Head Hair(Hair_FFGs)

0 FFG	0.0010
1 FFG	0.0010
2-5 FFGs	0.498
>5 FFGs (max	0.5

[10]one FGG = Target Fibre(Hair_FFG_matching_Mask)

Rarity	Rare fibres				Common fibres			
Hair FFGs	0 FFG	1 FFG	2-5 FFGs	>5 FFGs (m	0 FFG	1 FFG	2-5 FFGs	>5 FFGs (m
Yes, FFG= Typ	0.0	0.0014	0.00497916	0.018355	0.0	0.025	0.0822189	0.269749
No, FFG ≠ Typ	1.0	0.9986	0.995021	0.981645	1.0	0.975	0.917781	0.730251

[11]Size of Match. FFGin Head Hairs(SizeFFG_Hair)

Small (=<10)	0.9
Large (>10)	0.1

[12]Rare or commonfibres?(Rarity)

Rare fibres	0.5
Common fibre	0.5

[13]Background fibresin Head Hair(Background_Hair)

Hair_FFGs	0 FFG				1 FFG				2-5 FFGs	
Hair_FFG_mat	Yes, FFG= Type M		No, FFG ≠ Type M		Yes, FFG= Type M		No, FFG ≠ Type M		Yes, FFG=	
SizeFFG_Hair	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Lar
NO FIBRES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	
M(1-10)	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	
M(>10)	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	
M(1-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	
M(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
M(1-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
M(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
1nM	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	
2-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Hair_FFGs	2-5 FFGs			>5 FFGs (max 20)			
Hair_FFG_mat	Yes, FFG=	No, FFG ≠ Type M		Yes, FFG= Type M		No, FFG ≠ Type M	
SizeFFG_Hair	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1
NO FIBRES	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M(1-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M(1-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M(>10)/1-5nM	1.0	0.0	0.0	0.0	0.0	0.0	0.0
M(1-10)/>5nM	0.0	0.0	0.0	1.0	0.0	0.0	0.0
M(>10)/>5nM	0.0	0.0	0.0	0.0	1.0	0.0	0.0
1nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2-5nM	0.0	1.0	1.0	0.0	0.0	0.0	0.0
>5nM	0.0	0.0	0.0	0.0	0.0	1.0	1.0

[14]Matching & Non MatchingFibres from Hair(Results_Hair)

Background_H	NO FIBRES					M(1-10)				
MaskFibres_or	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO
t(1-5)	1.0	0.0	0.0	0.0	0.0	0.170922	0.0	0.0	0.0	
t(6-10)	0.0	1.0	0.0	0.0	0.0	0.555872	0.174	0.0	0.0	
t(>10)	0.0	0.0	1.0	0.0	0.0	0.273206	0.826	1.0	0.0	
t(1-5)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	
t(6-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	
t(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(1-5)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Non matching	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	

Background_H	M(1-10)	M(>10)					M(1-10)/1-5nM			
MaskFibres_or	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM
t(1-5)	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)	0.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.0	
t(1-5)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.170922	0.0	0.0	
t(6-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.555872	0.1731	0.0	
t(>10)/1-5nM	0.0	0.0	0.0	0.0	1.0	0.0	0.273206	0.8269	1.0	
t(1-5)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Non matching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_H	M(1-10)/1-5nM		M(>10)/1-5nM					M(1-10)/>5nM		
MaskFibres_or	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(
t(1-5)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(1-5)/1-5nM	0.43787	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)/1-5nM	0.43787	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/1-5nM	0.0	0.0	1.0	1.0	1.0	0.8756	1.0	0.0	0.0	
t(1-5)/>5nM	0.0621299	0.0	0.0	0.0	0.0	0.0	0.0	0.170922	0.0	
t(6-10)/>5nM	0.0621299	0.0	0.0	0.0	0.0	0.0	0.0	0.555872	0.1731	
t(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.1244	0.0	0.273206	0.8269	
Non matching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_H	M(1-10)/>5nM			M(>10)/>5nM					1nM	
MaskFibres_or	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(
t(1-5)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(1-5)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	
t(6-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(1-5)/>5nM	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)/>5nM	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/>5nM	1.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	
Non matching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_F	1nM				2-5nM				>
MaskFibres_or	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE	t(
t(1-5)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(1-5)/1-5nM	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	
t(6-10)/1-5nM	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	
t(>10)/1-5nM	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	
t(1-5)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(6-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
t(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Non matching	0.0	0.0	1.0	1.0	0.0	0.0	0.0	1.0	1.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_F	>5nM				
MaskFibres_or	t(1-5)	t(6-10)	t(>10)	1nM fibres	NO FIBRE
t(1-5)	0.0	0.0	0.0	0.0	0.0
t(6-10)	0.0	0.0	0.0	0.0	0.0
t(>10)	0.0	0.0	0.0	0.0	0.0
t(1-5)/1-5nM	0.0	0.0	0.0	0.0	0.0
t(6-10)/1-5nM	0.0	0.0	0.0	0.0	0.0
t(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0
t(1-5)/>5nM	1.0	0.0	0.0	0.0	0.0
t(6-10)/>5nM	0.0	1.0	0.0	0.0	0.0
t(>10)/>5nM	0.0	0.0	1.0	0.0	0.0
Non matching	0.0	0.0	0.0	1.0	1.0
No FIBRES at	0.0	0.0	0.0	0.0	0.0

[15]Transfer (persistenceand recovery) of Fibresfrom HAIR to PILLOWCASE (S)(Transfer_Pillow)

Transfer_Head	t>10									
TimeWear	7 days before incident						14 days before incident			
Prop	Hp: The suspect wore		Hd1: The suspect neve		Hd2: The suspect wore		Hp: The suspect wore		Hd1: The	
TimeRecovery	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7
s>10	0.6	0.6	0.0	0.0	0.3	0.3	0.6	0.6	0.0	
s1-10	0.39	0.39	0.0	0.0	0.69	0.69	0.39	0.39	0.0	
s0	0.01	0.01	1.0	1.0	0.01	0.01	0.01	0.01	1.0	

Transfer_Head	t>10			t6-10					
TimeWear	14 days before incident			7 days before incident					14
Prop	Hd1: The	Hd2: The suspect wore		Hp: The suspect wore		Hd1: The suspect neve		Hd2: The suspect wore	Hp:
TimeRecovery	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3
s>10	0.0	0.3	0.1	0.6	0.6	0.0	0.0	0.6	0.6	
s1-10	0.0	0.65	0.85	0.39	0.39	0.0	0.0	0.39	0.39	
s0	1.0	0.05	0.05	0.01	0.01	1.0	1.0	0.01	0.01	

Transfer_Head	t6-10						t1-5			
TimeWear	14 days before incident						7 days before incident			
Prop	Hp: The suspect wore		Hd1: The suspect neve		Hd2: The suspect wore		Hp: The suspect wore		Hd1: The	
TimeRecovery	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7
s>10	0.6	0.6	0.0	0.0	0.3	0.1	0.3	0.3	0.0	
s1-10	0.39	0.39	0.0	0.0	0.65	0.85	0.69	0.69	0.0	
s0	0.01	0.01	1.0	1.0	0.05	0.05	0.01	0.01	1.0	

Transfer_Head	t1-5									
TimeWear	7 days before incident			14 days before incident						7 d
Prop	Hd1: The	Hd2: The suspect wore		Hp: The suspect wore		Hd1: The suspect neve		Hd2: The suspect wore		Hp:
TimeRecovery	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3
s>10	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.3	0.1	
s1-10	0.0	0.69	0.69	0.69	0.69	0.0	0.0	0.65	0.85	
s0	1.0	0.01	0.01	0.01	0.01	1.0	1.0	0.05	0.05	

Transfer_Head	t0									
TimeWear	7 days before incident						14 days before incident			
Prop	Hp: The suspect wore		Hd1: The suspect neve		Hd2: The suspect wore		Hp: The suspect wore		Hd1: The	
TimeRecovery	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7 days	1-3 days	7
s>10	0.0010	0.0010	0.0010	0.0010	0.3	0.3	0.0010	0.0010	0.0	
s1-10	0.0030	0.0030	0.0030	0.0030	0.69	0.69	0.0030	0.0030	0.0	
s0	0.996	0.996	0.996	0.996	0.01	0.01	0.996	0.996	1.0	

Transfer_Head	t0		
TimeWear	14 days before incident		
Prop	Hd1: The	Hd2: The suspect wore	
TimeRecovery	7 days	1-3 days	7 days
s>10	0.0	0.3	0.1
s1-10	0.0	0.65	0.85
s0	1.0	0.05	0.05

[16]Fibres from Pillowcase(non-)matching MASK(MaskFibres_on_Pillow)

Transfer_Pillov	s>10		s1-10		s0	
MatchMaskPillc	Matching ˙	Fibres of a	Matching ˙	Fibres of a	Matching ˙	Fibres of a
s(1-10)	0.0	0.0	1.0	0.0	0.0	0.0
s(>10)	1.0	0.0	0.0	0.0	0.0	0.0
1nM fibres	0.0	1.0	0.0	1.0	0.0	0.0
NO FIBRES	0.0	0.0	0.0	0.0	1.0	1.0

[17]Groups of Background fibres (FFGs) on Pillowcase(Pillow_FFGs)

0 FFG	0.0010
1 FFG	0.0010
2-5 FFGs	0.498
>5 FFGs (max	0.5

[18]Size of Match. FFGon Pillowcase(SizeFFG_Pillow)

Small (=<10)	0.9
Large (>10)	0.1

[19]one FGG = Target Fibre (1)(Pillow_FFG_matching_Mask)

Rarity	Rare fibres				Common fibres			
Pillow FFGs	0 FFG	1 FFG	2-5 FFGs	>5 FFGs (n	0 FFG	1 FFG	2-5 FFGs	>5 FFGs (n
Yes, FFG= Typ	0.0	0.0014	0.00497916	0.018355	0.0	0.025	0.0822189	0.269749
No, FFG ≠ Typ	1.0	0.9986	0.995021	0.981645	1.0	0.975	0.917781	0.730251

[20]Background fibreson Pillowcase(Background_Pillow)

Pillow_FFGs	0 FFG				1 FFG				2-5 FFGs	
Pillow_FFG_m	Yes, FFG= Type M		No, FFG ≠ Type M		Yes, FFG= Type M		No, FFG ≠ Type M		Yes, FFG=	
SizeFFG_Pillow	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Large (>1	Small (=<	Lar
NO FIBRES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	
M(1-10)	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	
M(>10)	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	
M(1-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	
M(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
M(1-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
M(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
1nM	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	
2-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Pillow_FFGs	2-5 FFGs				>5 FFGs (max 20)			
Pillow_FFG_m	Yes, FFG=	No, FFG ≠ Type M			Yes, FFG= Type M		No, FFG ≠ Type M	
SizeFFG_Pillow	Large (>1	Small (=<	Large (>1		Small (=<	Large (>1	Small (=<	Large (>1
NO FIBRES	0.0	0.0	0.0		0.0	0.0	0.0	0.0
M(1-10)	0.0	0.0	0.0		0.0	0.0	0.0	0.0
M(>10)	0.0	0.0	0.0		0.0	0.0	0.0	0.0
M(1-10)/1-5nM	0.0	0.0	0.0		0.0	0.0	0.0	0.0
M(>10)/1-5nM	1.0	0.0	0.0		0.0	0.0	0.0	0.0
M(1-10)/>5nM	0.0	0.0	0.0		1.0	0.0	0.0	0.0
M(>10)/>5nM	0.0	0.0	0.0		0.0	1.0	0.0	0.0
1nM	0.0	0.0	0.0		0.0	0.0	0.0	0.0
2-5nM	0.0	1.0	1.0		0.0	0.0	0.0	0.0
>5nM	0.0	0.0	0.0		0.0	0.0	1.0	1.0

[21]Matching & Non MatchingFibres from Pillowcase(Results_Pillow)

Background_F	NO FIBRES				M(1-10)				M(>10)	
MaskFibres_or	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(
s(1-10)	1.0	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0	
s(>10)	0.0	1.0	0.0	0.0	0.5	1.0	0.0	0.0	1.0	
s(1-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	
s(>10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Non matching	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	

Background_F	M(>10)			M(1-10)/1-5nM				M(>10)/1-5nM		
MaskFibres_or	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM
s(1-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/1-5nM	0.0	0.0	0.0	0.5	0.0	0.8756	1.0	0.0	0.0	
s(>10)/1-5nM	0.0	1.0	0.0	0.5	1.0	0.0	0.0	1.0	1.0	
s(1-10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.1244	0.0	0.0	0.0	
s(>10)/>5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Non matching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_F	M(>10)/1-5nM		M(1-10)/>5nM				M(>10)/>5nM			
MaskFibres_or	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO
s(1-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/1-5nM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)/1-5nM	0.8756	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/>5nM	0.0	0.0	0.5	0.0	1.0	1.0	0.0	0.0	0.0	
s(>10)/>5nM	0.1244	0.0	0.5	1.0	0.0	0.0	1.0	1.0	1.0	
Non matching	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_F	M(>10)/>!	1nM				2-5nM				>
MaskFibres_or	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(1-10)	s(>10)	1nM fibres	NO FIBRE	s(
s(1-10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/1-5nM	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(>10)/1-5nM	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	
s(1-10)/>5nM	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	
s(>10)/>5nM	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	
Non matching	0.0	0.0	0.0	1.0	1.0	0.0	0.0	1.0	1.0	
No FIBRES at	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Background_F	>5nM			
MaskFibres_or	s(1-10)	s(>10)	1nM fibres	NO FIBRE
s(1-10)	0.0	0.0	0.0	0.0
s(>10)	0.0	0.0	0.0	0.0
s(1-10)/1-5nM	0.0	0.0	0.0	0.0
s(>10)/1-5nM	0.0	0.0	0.0	0.0
s(1-10)/>5nM	1.0	0.0	0.0	0.0
s(>10)/>5nM	0.0	1.0	0.0	0.0
Non matching	0.0	0.0	1.0	1.0
No FIBRES at	0.0	0.0	0.0	0.0

APPENDIX 4

R Script to Inform Match probabilities when the number of FFGs increases (Node [10] and node [19])

```
# Probabilities associated with the FFGs

# AND

# Split between option in node [13] and node [21]

# C. Champod / 15.12.2013

# To inform the probabilities of the nodes of Ray Palmer BN "chapter6HeadHairV3"

## Match probabilities when the number of FFGs increases (Node [10] and node [19])

# for a group with a match probability of f

f <- 0.05

#probability of having at least one matching group with the total number of group = k

k <- 1

#you get the probability using 1 minus the probability of having no correspondance

1-dbinom(0,k,f)

dbinom(0,k,f)

# We can use these directly to either populate the BN manually, or when we simulate in R, to adjust direction the probabilities as a function of f.

## Split between 1-5/6-10/>10 in node [13] and node [21]

# Case 1 (1-5 & 1-10)

a <- round(runif(10000, min = 1, max = 10), 0) #simulate 10000 cases with between 1 and 10 fibres

b <- round(runif(10000, min = 1, max = 5), 0) #simulate 10000 cases with between 1 and 5 fibres

hist(a+b, breaks=c(0,5,10,15), include.lowest= T) # histogram of the sum

hist(a+b, breaks=c(0,5,10,15), include.lowest= T)$counts/10000 # relative frequencies
```

```
# Case 2 (6-10 & 1-10)

a <- round(runif(10000, min = 1, max = 10), 0) #simulate 10000 cases with between 1 and 10 fibres

b <- round(runif(10000, min = 6, max = 10), 0) #simulate 10000 cases with between 1 and 5 fibres

hist(a+b, breaks=c(0,5,10,20), include.lowest= T) # histogram of the sum

hist(a+b, breaks=c(0,5,10,20), include.lowest= T)$counts/10000 # relative frequencies
```

APPENDIX 5

Sensitivity Analysis on the Case Involving Head Hair

Ray Palmer & Christophe Champod

22 February 2015

Summary of sensitivity analysis

Bayesian Network file *chapter5headhairv10_net.net*

Version control

1. v3: Restarted from the previous *Rapport_2.pdf* based on the BN file *chapter5headhairv5_cc.net*. I have change how the parameters are allocated to ease things. Also all parameters have been updated based on the *chapter5_feb15.pdf*. Added a seed on each simulation run (set.seed(1234)). Rediscussed the parameters of the Dirichlet during the meeting on March 6, 2015.

2. v4: Made changes on plotting functions to have a line for LR=1. Also now you can add or remove the legends (with the cases) and change the names of simulations on the plots. Added a table on the PDF document with the LR corresponding to each outcome. Modifications made on the BN (now chapter5headhairv10_net.net) to have outcomes with 1-5 non-matching groups and >5 non matching groups. The simulations (S8) with the "ignorance" BN and play with the rarity has been removed (refer to v3 if needed).

3. v5: Based on the updated BN provided by Ray (now hapter5headhairv10_net.net) and the TransferNode_1.xls (e-mail dated 20.04.15). Also the table of LRs has been corrected (following message from Ray 22.04.15). The set of function is now in v9 because the short names from the cases where not properly assigned in the plots. The levels have also be reordered to have from Case-1 to Case-9.

4. v6: Adapted the set of functions (now v.10) to have the correct order of legend names. Changed the call for function (instead of source()) to allow cross platform usage (Mac and PC). Lower case modification in do.call lines 265 and 267.

5. v7: Adapted the plotting functions (now in version 11). Increased the number of simulations to 100000.

6. v8: Adapted the plotting function (now in version 12) to capture the fact that under Hd1, only half of the scenarios need to be presented.

```
GetProbaFFG <- function(f, range=c(2:5)){

res <- vector(mode="numeric", length = length(range))
```

```
for (i in 1:length(range)){

j <- range[i]

res[i] <- 1-dbinom(0,j,f)

}

res

}
```

You can then simply type the following commands in the Console. Please check that the relative proportion for respectively rare and frequent fibres are correct. They should match the values you will use for the Dirichlet distributions.

```
a <- 16/(643+16) #value for the frequent

b <- 2/(1401+2) #value for the rare

#to get the values for 2-5 FFGs

#frequent

c(mean(GetProbaFFG(a, range=c(2:5))),

1-mean(GetProbaFFG(a, range=c(2:5))))

#rare

c(mean(GetProbaFFG(b, range=c(2:5))),

1-mean(GetProbaFFG(b, range=c(2:5))))

#to get the values for >5 FFGs (max 20) FFGs

#frequent

c(mean(GetProbaFFG(a, range=c(6:20))),

1-mean(GetProbaFFG(a, range=c(6:20))))

#rare
```

c(mean(GetProbaFFG(b, range=c(6:20))),

1-mean(GetProbaFFG(b, range=c(6:20))))

Enter these values in BN directly. During the simulations later, that function will directly be called and used to update the CPTs.

For the record, the probabilistic split between 1-5/6-10/>10 states in node [14] and node [21] is obtained as shown in the R code below. The BN used here as been updated according to these values.

```
# Case 1 (1-5 & 1-10)

set.seed(123)

a <- round(runif(100000, min = 1, max = 10), 0)

#simulate 10000 cases with between 1 and 10 fibres

b <- round(runif(100000, min = 1, max = 5), 0)

#simulate 10000 cases with between 1 and 5 fibres

hist(a+b, breaks=c(0,5,10,15), include.lowest= TRUE)

# histogram of the sum

hist(a+b, breaks=c(0,5,10,15), include.lowest= TRUE)$counts/100000

# relative frequencies

# Case 2 (6-10 & 1-10)

set.seed(123)

a <- round(runif(100000, min = 1, max = 10), 0)

#simulate 10000 cases with between 1 and 10 fibres

b <- round(runif(100000, min = 6, max = 10), 0)

#simulate 10000 cases with between 1 and 5 fibres
```

hist(a+b, breaks=c(0,5,10,20), include.lowest= TRUE)

histogram of the sum

hist(a+b, breaks=c(0,5,10,20), include.lowest= TRUE)$counts/100000

relative frequencies

Case 3 (1-5 & 1)

set.seed(123)

a <- round(runif(100000, min = 1, max = 5), 0)

#simulate 10000 cases with between 1 and 5 fibres

b <- round(runif(100000, min = 1, max = 1), 0)

#simulate 10000 cases with between 1 and 1 fibres

hist(a+b, breaks=c(0,5,10,20), include.lowest= TRUE)

histogram of the sum

hist(a+b, breaks=c(0,5,10,20), include.lowest= TRUE)$counts/100000/2

relative frequencies (divide by 2 only when required to account for the 0.5/0.5 split between t(1-5) and **Required external files**

The have in that folder the two excel spreadsheets that are required later in R:

• List of cases.xlsx

(this is the state specification for the 9 cases that will be simulated)

• TransferNode_1.xlsx (this is the table of parameters that will be used to simulate probabilities associated with the transfer node). The other parameters are directly entered in the code.

• Ray Palmer PhD Functions v12.R (The set of functions developed for the simulations)

• The BN file named: chapter5headhairv10_net.net. Be careful, you need to allow all possibilities for the defence propositions in the initial BN. The file from Ray has been modified accordingly.

Commands to manually knit the document and prepare the PDF report

#to clean workspace

rm(list=ls())

#to lead the library

library(knitr)

#to carry out the simulations and produce .md file that will be used to produce the PDF report.

knit("RSimulations_HeadHairV8cc.Rmd")

#To generate the PDF (or DOCX) file invoking PANDOC with a system command:

system("pandoc -V geometry:margin=1in -o RSimulations_HeadHairV8cc.pdf RSimulations_HeadHairV8cc.md --highlight-All the figures will be placed in PDF in a folder called *figure*. When we run the script multiple times, it is wise to delete the previous PDF files from the folder in order to be sure that the graphs are updated as well.

R Code and libraries needed to carry out the simulations

There a set of library is required to run these simulations:

library(gtools) *# to allow import from XLS files*

library(RHugin) *# to allow the link with the Hugin Decision Engine*

library(rBeta2009) *# to allow calling the random generator for Dirichlet functions*

library(ggplot2) *# to be able to make more fancy plots*

library(gridExtra) *#needed to make multiple plots on one sheet*

library(gdata)

library(plyr) # *to use the function ddply for obtaining summaries in dataframes*

library(knitr) *#to use the reporting capabilities of knitr*

library(markdown) *#markdown process with knitr*

library(rmarkdown)

library(pander) *#to help with the printing of the tables*

library(formatR) # *to tidy the code if needed*

library(dplyr) *#for data manipulation*

Then we need to set the environment. We will also load the Excel spreadsheets. Keep in mind that you can adjust the XLSX files as required to change the parameters.

Here the parameters have been set according to the counts provided in the file *chapter5_feb15.pdf*. The file *TransferNode_1.xlsx* has been adapted accordingly as well.

opts_chunk$**set**(cache.path ="cache/")

opts_chunk$**set**(fig.path ="figure/")

opts_chunk$**set**(comment = NA) # *to remove double*

opts_chunk$**set**(dev = 'pdf')

opts_chunk$**set**(fig.width = 40, fig.height = 40) *#for large sheets with 11 graphs*

#Dirichlet parameters are as follows:

TransferParameters_1 <- **read.xls**("TransferNode_1.xlsx",sheet=1, header=FALSE)

CommonFibresPara=**c**(14,545) *#MLE = 2.4% = 14/(545+14)*

RareFibresPara=**c**(2,1401) # *MLE = 0.0014 = 2/(1401+2)*

HairFFGPara=**c**(2,2,499,501)

SizeHairFFGPara=**c**(46,6)

Specifications of the various cases:

Cases_1 <- **read.xls**("List of cases.xlsx",sheet=1, header=FALSE)

NumberOfSimulations=10000 *# Set the number of simulations.*

 # Once you are satisfied, we can increase it to 10000,

 # but it will take more time to generate the report and graphs

 # Select the outcomes that will be explored individually

SelectedOutcome1 <- 9

SelectedOutcome2 <- 10

SelectedOutcome3 <- 3

FontSize_1 <- 12 *#FontSize for plots with 11 subplots*

FontSize_2 <- 18 *#FontSize for specific case plots*

We load the required functions. They are available in the file “Ray Palmer PhD Functions v11.R” that will be called directly.

eval(**parse**("Ray Palmer PhD Functions v12.R", encoding="UTF-8"))

We load the relevant BN (it seems safe to do so before each run of simulations).

Headhair <- **read.rhd**("chapter5headhairv10_net.net",

type = "net", password = NULL, generate.tables)

Warning in read.rhd("chapter5headhairv10_net.net", type = "net", password

= NULL, : RHugin 7.7 introduced support for models: 'generate.tables' is

depricated

#to load the BN developed in Hugin. Must be a .net file

compile(Headhair) *# equivalent to the compile button in Hugin*

#plot(Headhair)

Simulations exploring the impact of variables based on current data

Simulations adding one simulated node in turn according to its specific Dirichlet parameters. The situation under *none* is with the default parameters in the Hugin original file.

set.seed(1234) *#We can set the seed to any number as long as we keep it the same for reproducible results.*

options(warn=-1) *# to remove the warning messages from display in R*

S6_none <- **RunMultipleSimulations4**(Headhair, NumbSim= 1, Cases=Cases_1)

S6_FFG <- **RunMultipleSimulations4**(Headhair, NumbSim=NumberOfSimulations,

HairFFGParameters=HairFFGPara,

Cases=Cases_1)

S6_Size <- **RunMultipleSimulations4**(Headhair, NumbSim=NumberOfSimulations,

SizeHairFFGParameters=SizeHairFFGPara,

Cases=Cases_1)

S6_Rarity <- **RunMultipleSimulations4**(Headhair, NumbSim=NumberOfSimulations,

CommonFibresParameters=CommonFibresPara,

RareFibresParameters=RareFibresPara,

Cases=Cases_1)

S6_Transfer <- **RunMultipleSimulations4**(Headhair, NumbSim=NumberOfSimulations,

TransferParameters=TransferParameters_1,

Cases=Cases_1)

S6_all <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara,

SizeHairFFGParameters=SizeHairFFGPara,

CommonFibresParameters=CommonFibresPara,

RareFibresParameters=RareFibresPara,

TransferParameters=TransferParameters_1,

Cases=Cases_1)

We can prepare a table with the results obtained with the BN as is with its current parameters:

Tcolnames <- **get.states**(Headhair, "Results_Hair")

T <- **as.data.frame**(S6_none$LR)

T <- **cbind**(T,S6_none$DefProp, S6_none$Case, S6_none$RarityFibre)

colnames(T) <- **c**(Tcolnames,"DefProp", "Case", "Frequency")

#to have the names of results for each outcome columns

#make sure we have factors

T$DefProp <- **as.factor**(T$DefProp) *# to have Hp1 and Hp2 as factors*

T$Frequency <- **as.factor**(T$Frequency) *#idem for RarityFibre*

T$Case <- **as.factor**(T$Case) *#idem for Case*

 # to adapt the levels names

levels(T$DefProp) <- **c**("Hd1", "Hd2")

levels(T$Frequency) <- **c**("Common", "Rare")

levels(T$Case) <- **paste**("Case_",**c**(5,4,3,2,1,9,8,7,6), sep="") *# previously we had c(1:9) which led to a # to adapt the legend to be shorter*

colnames(T) <- **c**(Tcolnames,"Defense's proposition",

"Case considered", "Frequency of fibres")

panderOptions('round', 2)

panderOptions('keep.trailing.zeros', TRUE)

set.caption("LRs obtained for each possible outcome according to the case considered, the choice of the **pander**(T,split.table = Inf)

Table 1: LRs obtained for each possible outcome according to the case considered, the choice of the defense proposition and the rarity of fibres

t(1-5)	t(6-10)	t(>10)	t(1-5)/1-5nM	t(6-10)/1-5nM	t(>10)/1-5nM	t(1-5)/>5nM	t(6-10)/>5nM	t(>10)/>5nM	Non matching FIBRES	No FIBRES at all	Defense's proposition	Case considered	Frequency of fibres
24.46	14.97	82.34	7.22	4.74	26.63	2.08	1.69	10.03	0.35	0.35	Hd1	Case_1	Common
30.13	30.53	83.19	8.66	9.05	27.96	2.25	2.64	11.5	0.1	0.1	Hd1	Case_2	Common
7.73	25.86	239.6	2.21	7.44	73.93	0.56	1.96	24.55	0.01	0.01	Hd1	Case_3	Common
30.13	30.53	83.19	8.66	9.05	27.96	2.25	2.64	11.5	0.1	0.1	Hd1	Case_4	Common
7.73	25.86	239.6	2.21	7.44	73.93	0.56	1.96	24.55	0.01	0.01	Hd1	Case_5	Common
1.34	1.17	1.81	1.09	1.05	1.26	1.02	1.01	1.1	0.99	0.99	Hd1	Case_6	Common
58.65	2.34	4.75	16.92	1.42	3.37	4.49	1.15	2.96	0.3	0.3	Hd1	Case_7	Common
1.34	1.17	1.81	1.09	1.05	1.26	1.02	1.01	1.1	0.99	0.99	Hd1	Case_8	Common
58.65	2.34	4.75	16.92	1.42	3.37	4.49	1.15	2.96	0.3	0.3	Hd1	Case_9	Common
2.86	11.66	44.91	2.34	4.37	18.76	1.43	1.65	7.74	0.39	0.39	Hd2	Case_1	Common
11.2	21.42	56.21	5.92	8.09	23.22	2.05	2.58	10.25	0.1	0.1	Hd2	Case_2	Common
0.13	11.03	50.43	0.13	5.23	21.93	0.13	1.7	8.3	0.03	0.03	Hd2	Case_3	Common
25.81	28.16	59.17	8.28	8.85	24.75	2.24	2.63	10.98	0.1	0.1	Hd2	Case_4	Common
6.62	23.85	170.4	2.12	7.28	65.44	0.56	1.95	23.44	0.01	0.01	Hd2	Case_5	Common
1.14	1.08	1.29	1.04	1.02	1.11	1.01	1	1.05	1	1	Hd2	Case_6	Common
50.23	2.16	3.38	16.2	1.39	2.98	4.45	1.14	2.83	0.3	0.3	Hd2	Case_7	Common
1.14	1.08	1.29	1.04	1.02	1.11	1.01	1	1.05	1	1	Hd2	Case_8	Common
50.23	2.16	3.38	16.2	1.39	2.98	4.45	1.14	2.83	0.3	0.3	Hd2	Case_9	Common
446.5	265.4	1446	125.5	74.92	408.7	33.84	20.54	112.7	0.35	0.35	Hd1	Case_1	Rare
555.8	556.2	1435	156	156.3	406.8	41.82	42.21	113.2	0.1	0.1	Hd1	Case_2	Rare
142.9	476.4	4295	40.09	133.7	1210	10.74	35.87	329.7	0.01	0.01	Hd1	Case_3	Rare
555.8	556.2	1435	156	156.3	406.8	41.82	42.21	113.2	0.1	0.1	Hd1	Case_4	Rare

t(1-5)	t(6-10)	t(>10)	t(1-5)/1-5nM	t(6-10)/1-5nM	t(>10)/1-5nM	t(1-5)/>5nM	t(6-10)/>5nM	t(>10)/>5nM	Non matching FIBRES	No FIBRES at all	Defense's proposition	Case considered	Frequency of fibres
142.9	476.4	4295	40.09	133.7	1210	10.74	35.87	329.7	0.01	0.01	Hd1	Case_5	Rare
7.34	4.17	15.33	2.77	1.89	5.05	1.47	1.23	2.11	0.99	0.99	Hd1	Case_6	Rare
1080	24.87	38.54	303.1	7.74	12.84	81.35	2.84	5.5	0.3	0.3	Hd1	Case_7	Rare
7.34	4.17	15.33	2.77	1.89	5.05	1.47	1.23	2.11	0.99	0.99	Hd1	Case_8	Rare
1080	24.87	38.54	303.1	7.74	12.84	81.35	2.84	5.5	0.3	0.3	Hd1	Case_9	Rare
3.14	43.05	120.8	3.1	30.55	95.94	2.94	14.75	54.72	0.39	0.39	Hd2	Case_1	Rare
16.98	62.25	174.2	15.78	48.51	131.3	12.45	26.51	69.46	0.1	0.1	Hd2	Case_2	Rare
0.13	19.16	111.4	0.13	17.28	94.25	0.13	12.61	59.92	0.03	0.03	Hd2	Case_3	Rare
133.2	215.1	175.8	82.67	108.3	134.5	33.88	37.77	72.76	0.1	0.1	Hd2	Case_4	Rare
34.26	184.2	526	21.25	92.62	400.3	8.7	32.1	211.9	0.01	0.01	Hd2	Case_5	Rare
1.76	1.61	1.88	1.47	1.31	1.67	1.19	1.11	1.36	1	1	Hd2	Case_6	Rare
258.9	9.62	4.72	160.7	5.36	4.25	65.9	2.55	3.54	0.3	0.3	Hd2	Case_7	Rare
1.76	1.61	1.88	1.47	1.31	1.67	1.19	1.11	1.36	1	1	Hd2	Case_8	Rare
258.9	9.62	4.72	160.7	5.36	4.25	65.9	2.55	3.54	0.3	0.3	Hd2	Case_9	Rare

We can prepare the plots for these results (here just two cases are illustrated below):

p_S6_none <- **PlotResults4_LR**(Headhair, S6_none, FontSize=FontSize_1, fatten_value=4)

do.call(grid.arrange,p_S6_none[[1]])

#dev.new() #needed only in R

do.call(grid.arrange,p_S6_none[[2]])

p_S6_all <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_1, minlog10LR=-2, maxlog10LR=6)

do.call(grid.arrange,p_S6_all[[1]])

Warning: Removed 1 rows containing non-finite values (stat_boxplot).

Warning: Removed 10 rows containing non-finite values (stat_boxplot).

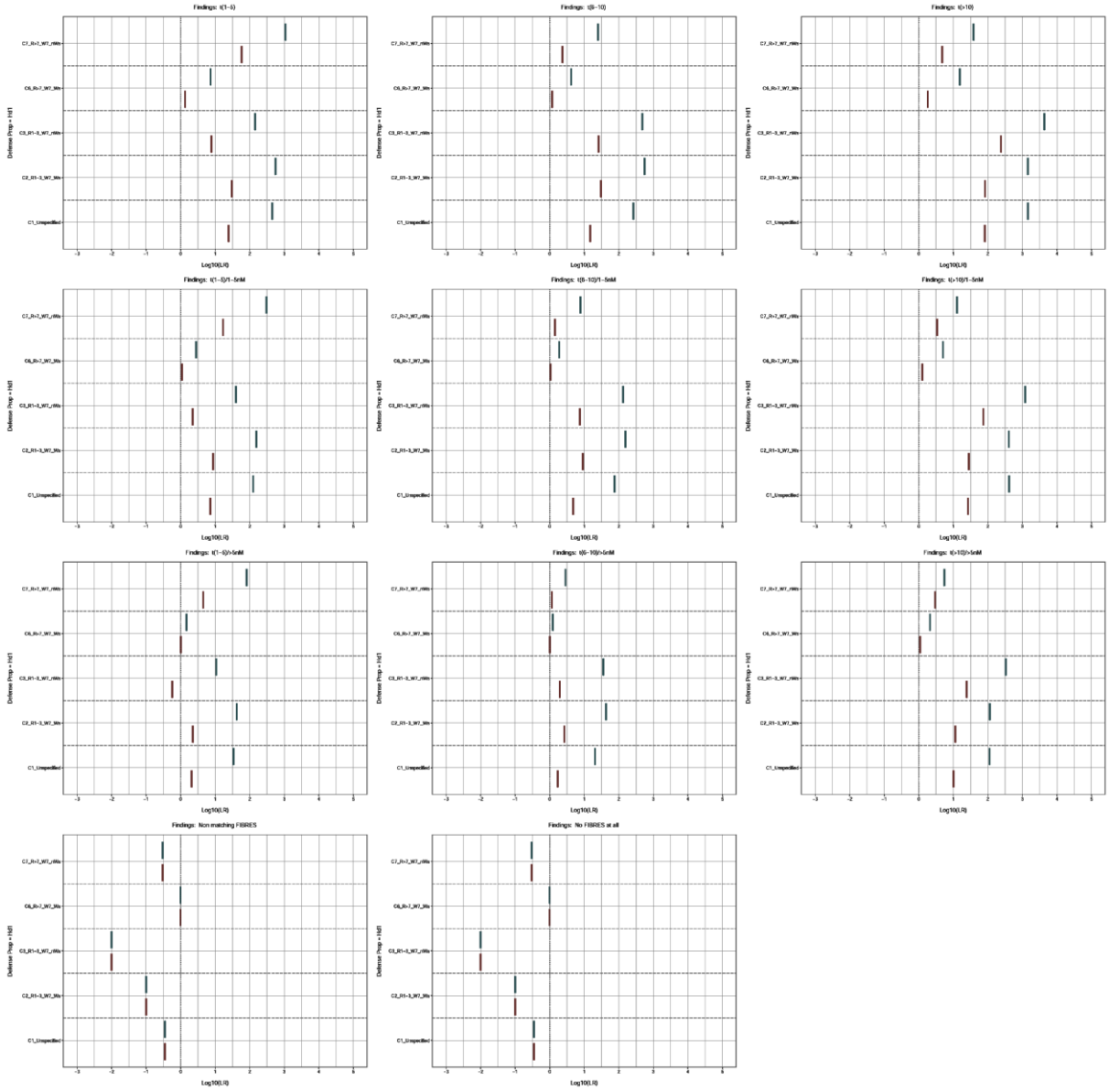

Figure 1: plot of chunk PlotS6_NO_parameters

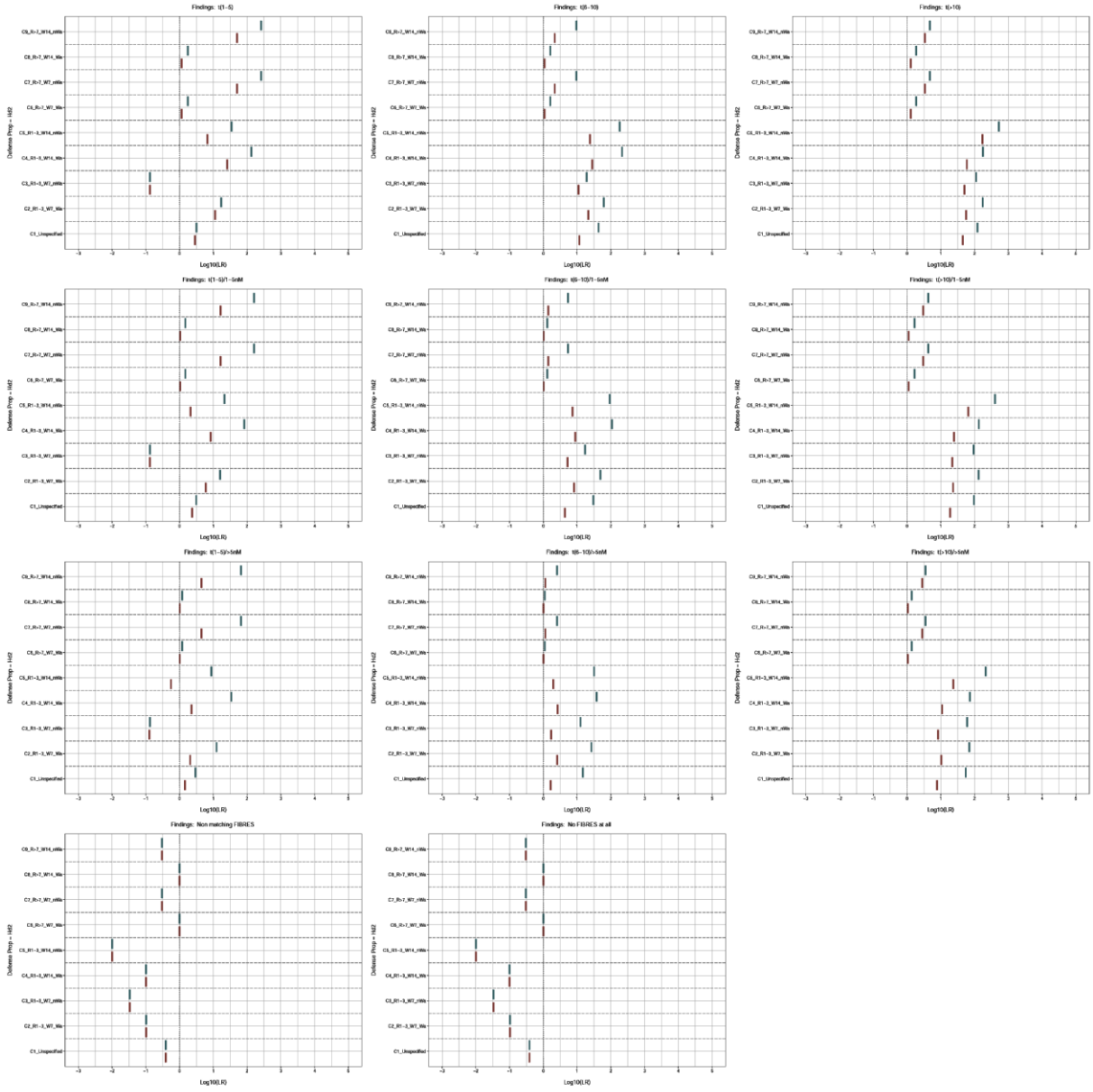

Figure 2: plot of chunk PlotS6_NO_parameters

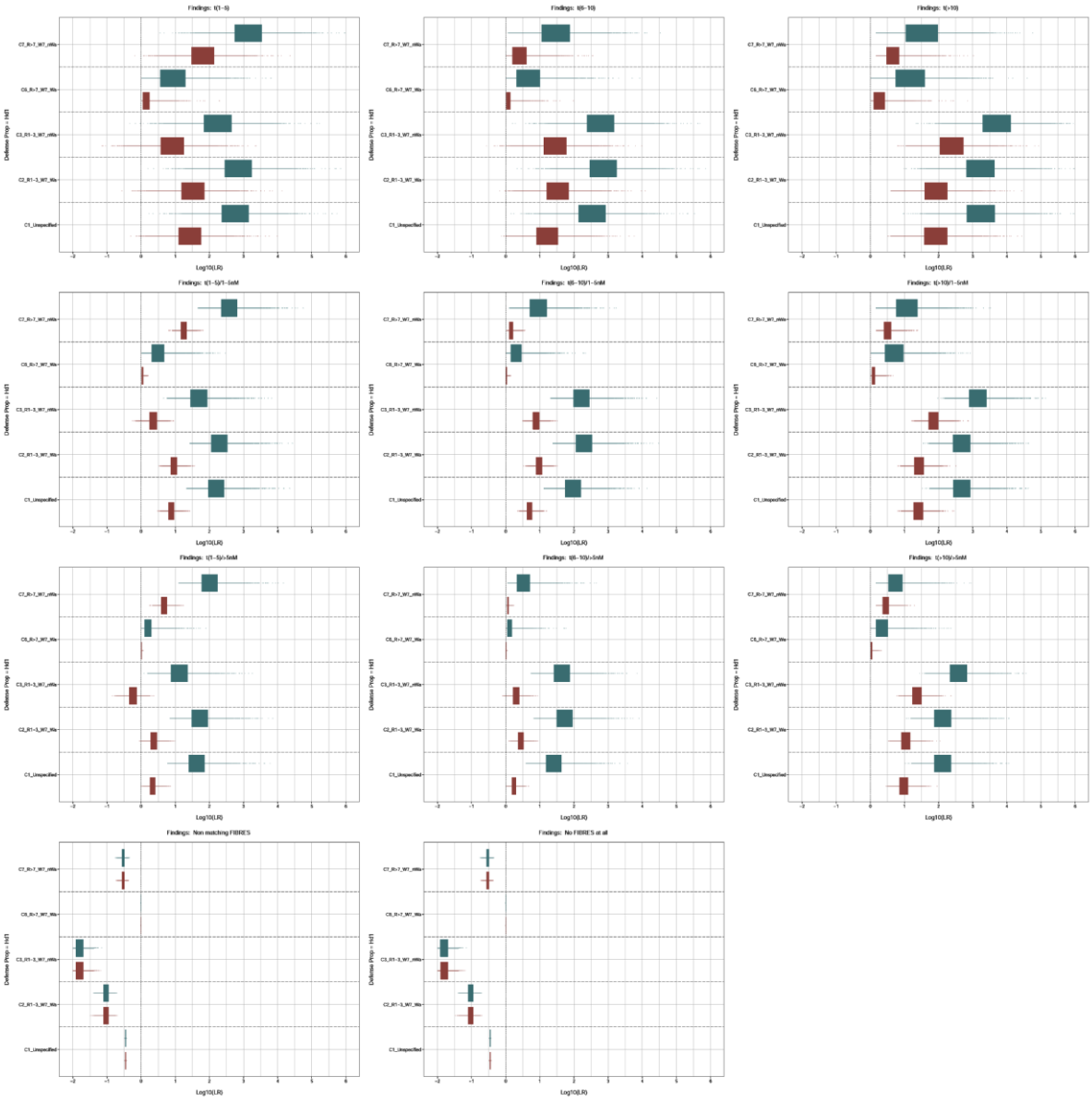

Figure 3: plot of chunk PlotS6_all_parameters

#dev.new() #needed only in R

do.call(grid.arrange,p_S6_all[[2]])

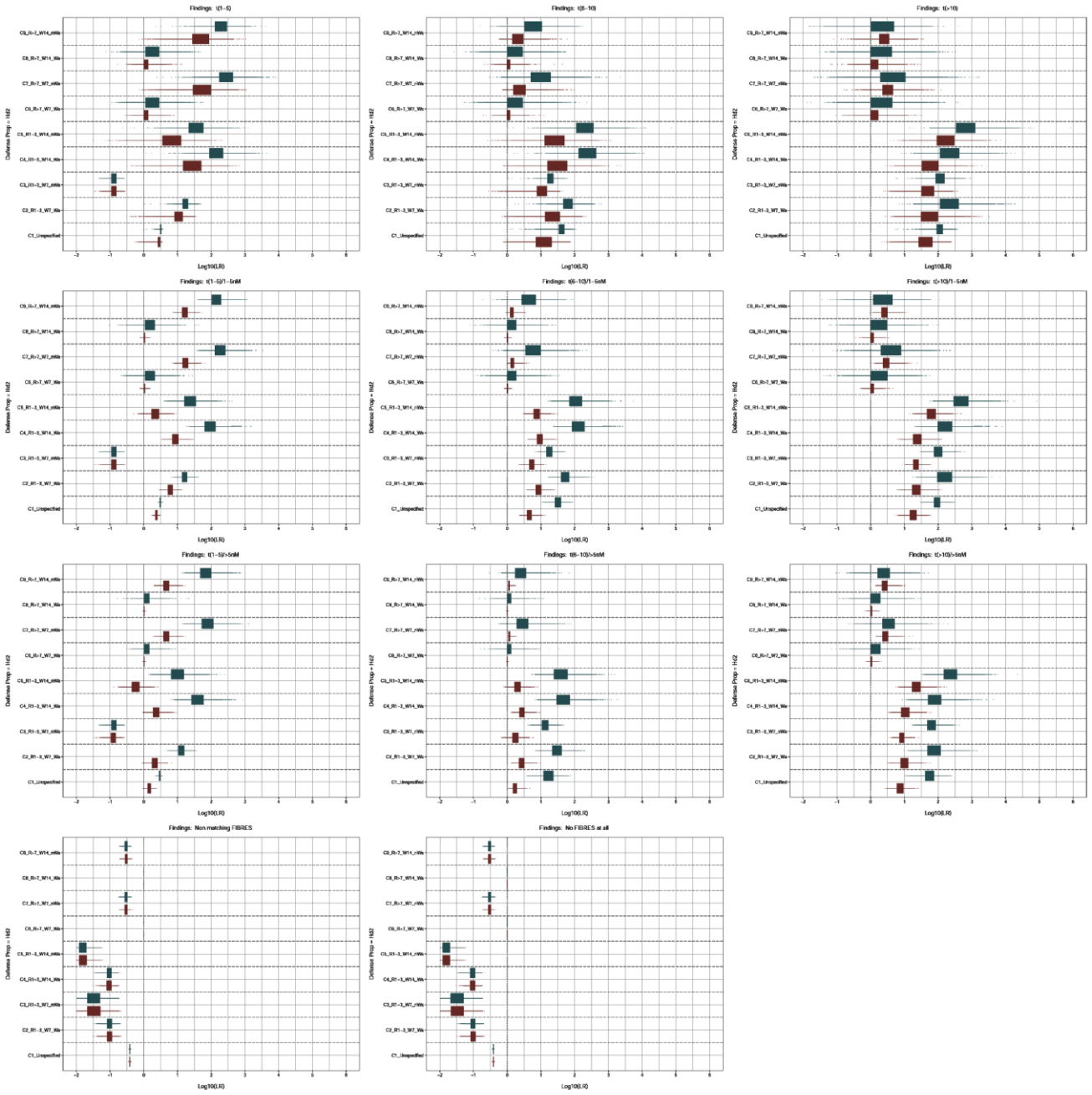

Figure 4: plot of chunk PlotS6_all_parameters

The dataframe that will summarize the results is obtained as follows:

ResultsSimulations6 <- **CompileResultsFromSetsOfSimulation**(Headhair,

DatasetsNames= **c**("S6_none","S6_FFG", "S6_Size",

"S6_Rarity", "S6_Transfer","S6_all"),

ChangedNames= **c**("No\nsimulations","FFG", "Size",

"Rarity", "Transfer","All nodes\ntogether"))

The data (IQR and median) associated with these results can be visualised as follows, first the effects on the interquadratile range (IQR) and then on the Median of the LR.

p1 <- **PlotResults4_SummaryStat_IQR**(Headhair, ResultsSimulations6, FontSize=FontSize_1)

do.call(grid.arrange,p1)

p2 <- **PlotResults4_SummaryStat_median**(Headhair, ResultsSimulations6, FontSize=FontSize_1)

do.call(grid.arrange,p2)

From the above analysis, it seems reasonable to invest in data in relation to FFG, transfer and Rarity (especially when the fibre is rare).

Simulations exploring the impact of acquiring more data on some variable

We can run a second set of simulation focused on variations (meaning pretenting more knowledge) on these parameters only, keeping the rest as it is. First we need to load the update the parameters.

XtimesMore = 10 *#set the amount of additional data in each node*

TransferParameters_2 <- **cbind**(TransferParameters_1[,1:8]*XtimesMore,TransferParameters_1[,9:16], TransferParameters_Then we run the simulations with the updated parameters.

set.seed(1234)

S7_Ini <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara,

SizeHairFFGParameters=SizeHairFFGPara,

CommonFibresParameters=CommonFibresPara,

RareFibresParameters=RareFibresPara,

TransferParameters=TransferParameters_1,

Cases=Cases_1)

#Initial state of uncertainty in the BN

#With the current state of knowledge

#and given the initial Dirichlet distributions

S7_F <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara*XtimesMore,

SizeHairFFGParameters=SizeHairFFGPara*XtimesMore,

 # X times more data on FFG

CommonFibresParameters=CommonFibresPara,

RareFibresParameters=RareFibresPara,

TransferParameters=TransferParameters_1,Cases=Cases_1)

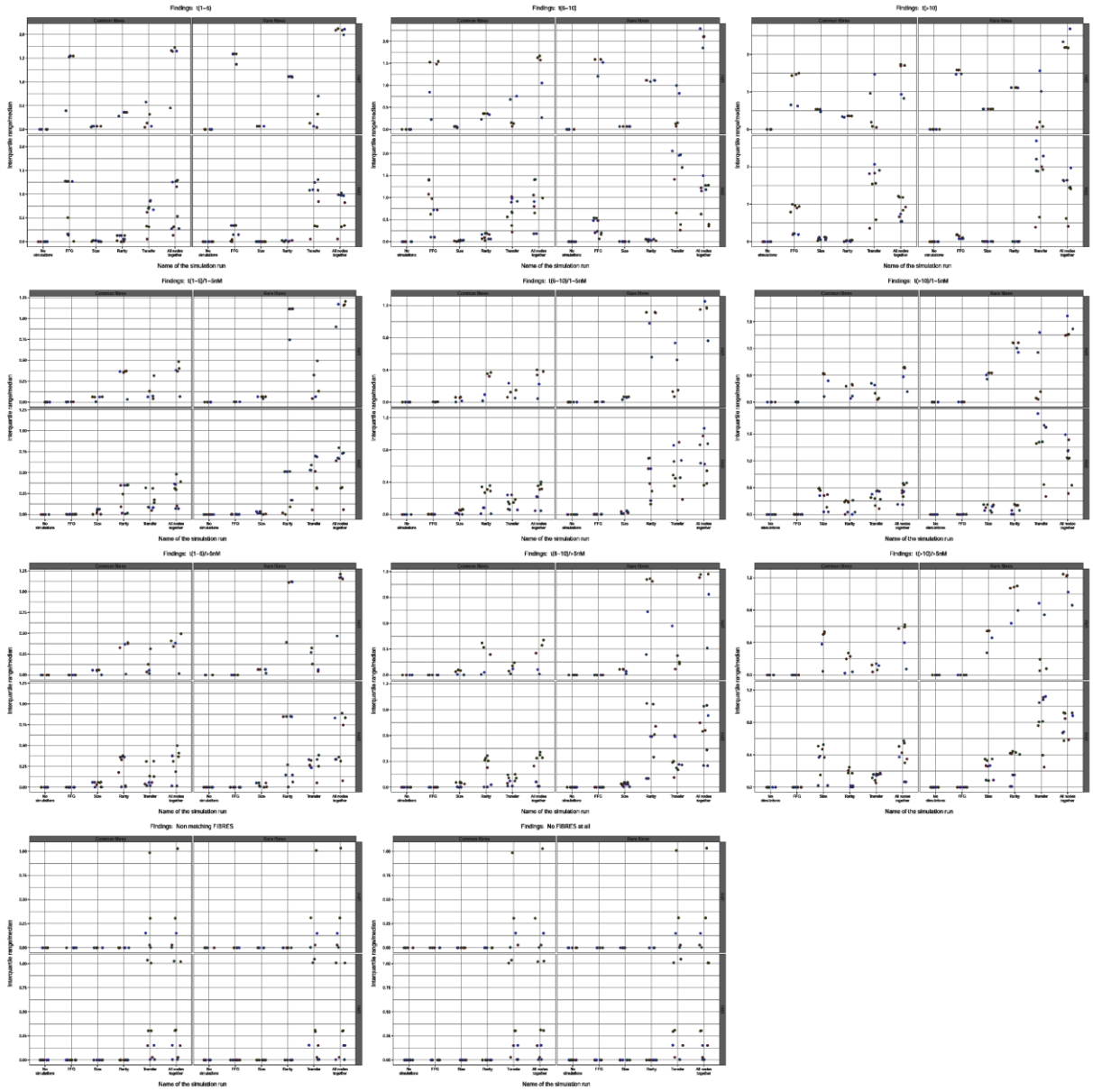

Figure 5: plot of chunk PlotSummaryIQRS6

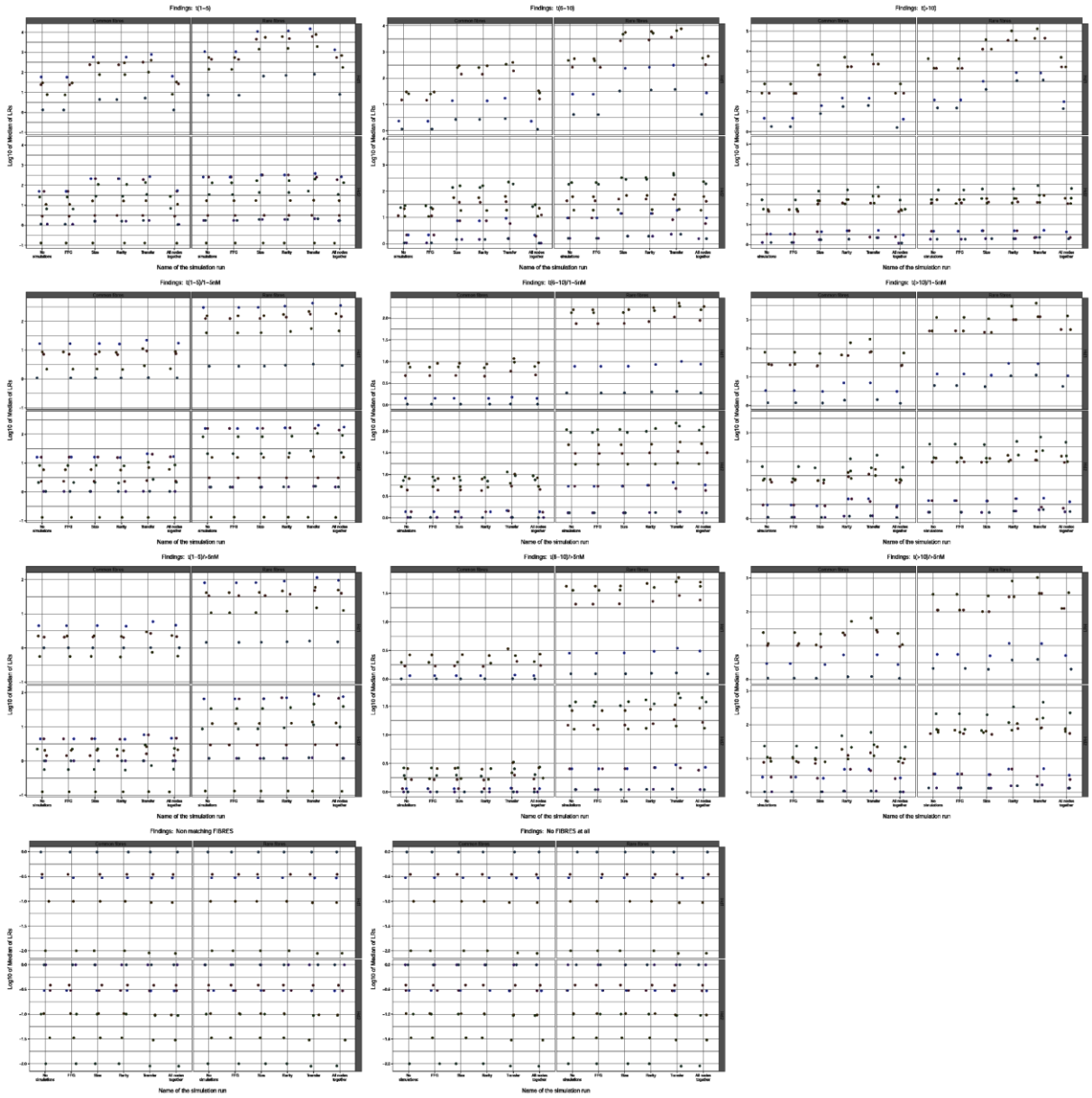

Figure 6: plot of chunk PlotSummaryMedianS6

S7_R <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara,

SizeHairFFGParameters=SizeHairFFGPara,

CommonFibresParameters=CommonFibresPara*XtimesMore,

 # X times more data on Rarity

RareFibresParameters=RareFibresPara*XtimesMore,

 # X times more data on Rarity

TransferParameters=TransferParameters_1,

Cases=Cases_1)

S7_T <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara,

SizeHairFFGParameters=SizeHairFFGPara,

CommonFibresParameters=CommonFibresPara,

RareFibresParameters=RareFibresPara,

TransferParameters=TransferParameters_2,

#X times more data on Transfer (hence _2)

Cases=Cases_1)

S7_F_R <- **RunMultipleSimulations4**(Headhair, NumbSim= NumberOfSimulations,

HairFFGParameters=HairFFGPara*XtimesMore,

SizeHairFFGParameters=SizeHairFFGPara*XtimesMore,

CommonFibresParameters=CommonFibresPara*XtimesMore,

RareFibresParameters=RareFibresPara*XtimesMore,

 # 10 times more data on Rarity and FFG

TransferParameters=TransferParameters_1,

```
Cases=Cases_1)
S7_F_T <- RunMultipleSimulations4(Headhair, NumbSim= NumberOfSimulations,
HairFFGParameters=HairFFGPara*XtimesMore,
SizeHairFFGParameters=SizeHairFFGPara*XtimesMore,
# X times more data on FFG and Transfer
CommonFibresParameters=CommonFibresPara,
RareFibresParameters=RareFibresPara,
TransferParameters=TransferParameters_2,
Cases=Cases_1)
S7_F_R_T <- RunMultipleSimulations4(Headhair, NumbSim= NumberOfSimulations,
HairFFGParameters=HairFFGPara*XtimesMore,
SizeHairFFGParameters=SizeHairFFGPara*XtimesMore,
CommonFibresParameters=CommonFibresPara*XtimesMore,
RareFibresParameters=RareFibresPara*XtimesMore,
TransferParameters=TransferParameters_2,
# 10 times more data on FFG, Rarity and Transfer
Cases=Cases_1)
```

The dataframe that will summarize the results is obtained as follows:

```
ResultsSimulations7 <- CompileResultsFromSetsOfSimulation(Headhair,
DatasetsNames= c("S7_Ini","S7_F", "S7_R", "S7_T","S7_F_R",
"S7_F_T","S7_F_R_T"),
```

ChangedNames= **c**("Initial\nstate","FFG", "Rarity", "Transfer","FFG and\nRarity", The data associated with these results can be visualised as follows, first the effects on the interquadratile range IQR and then on the Median of the LR

p3 <- **PlotResults4_SummaryStat_IQR**(Headhair, ResultsSimulations7, FontSize=FontSize_1)

do.call(grid.arrange,p3)

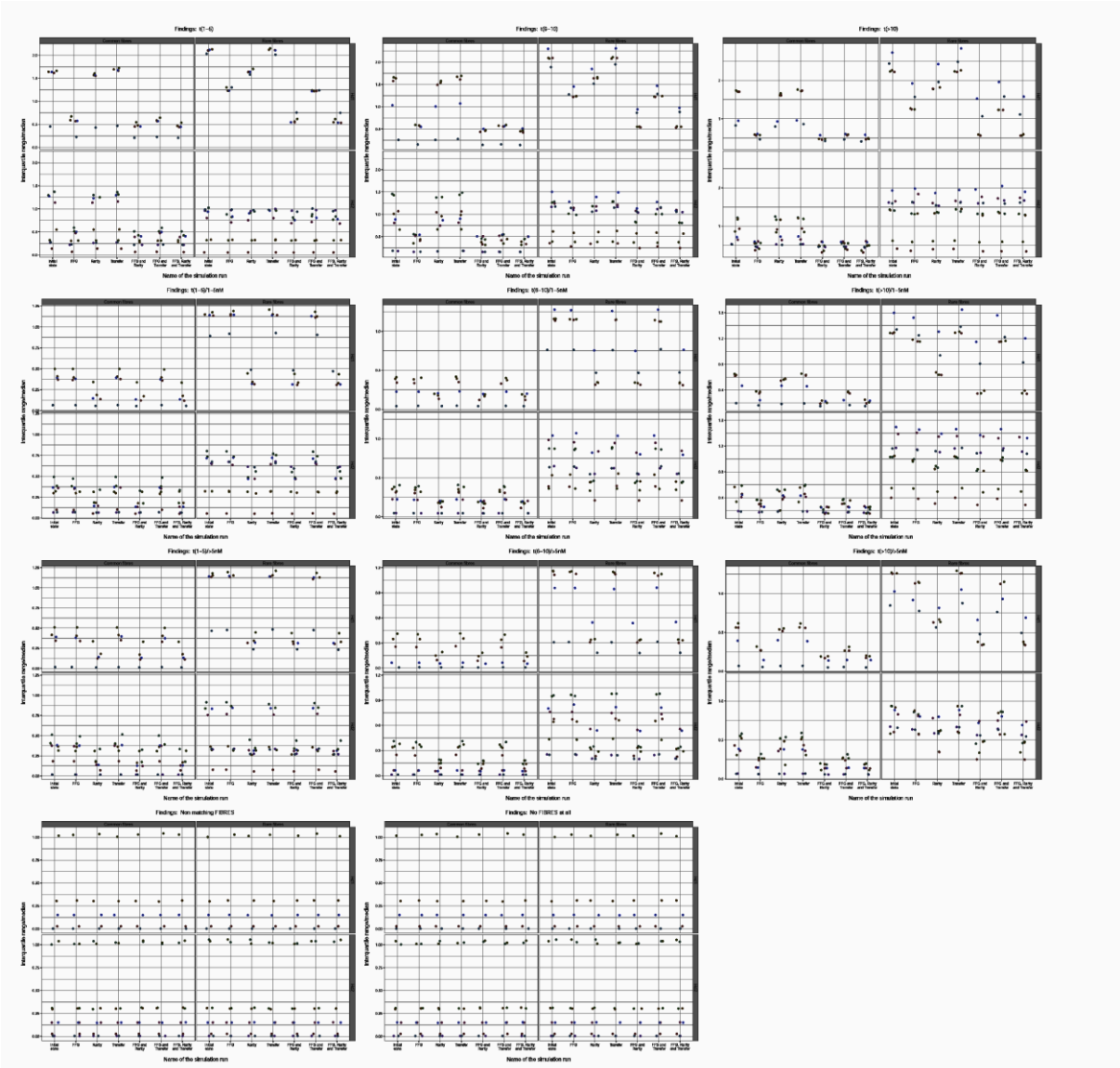

Figure 7: plot of chunk PlotSummaryIQRS7

We can plot the median, but it should show that it will not change much simply because the changes should have affected on the range of LRs obtained, hence the only IQR will show it.

p4 <- **PlotResults4_SummaryStat_median**(Headhair, ResultsSimulations7, FontSize=FontSize_1)

do.call(grid.arrange,p4)

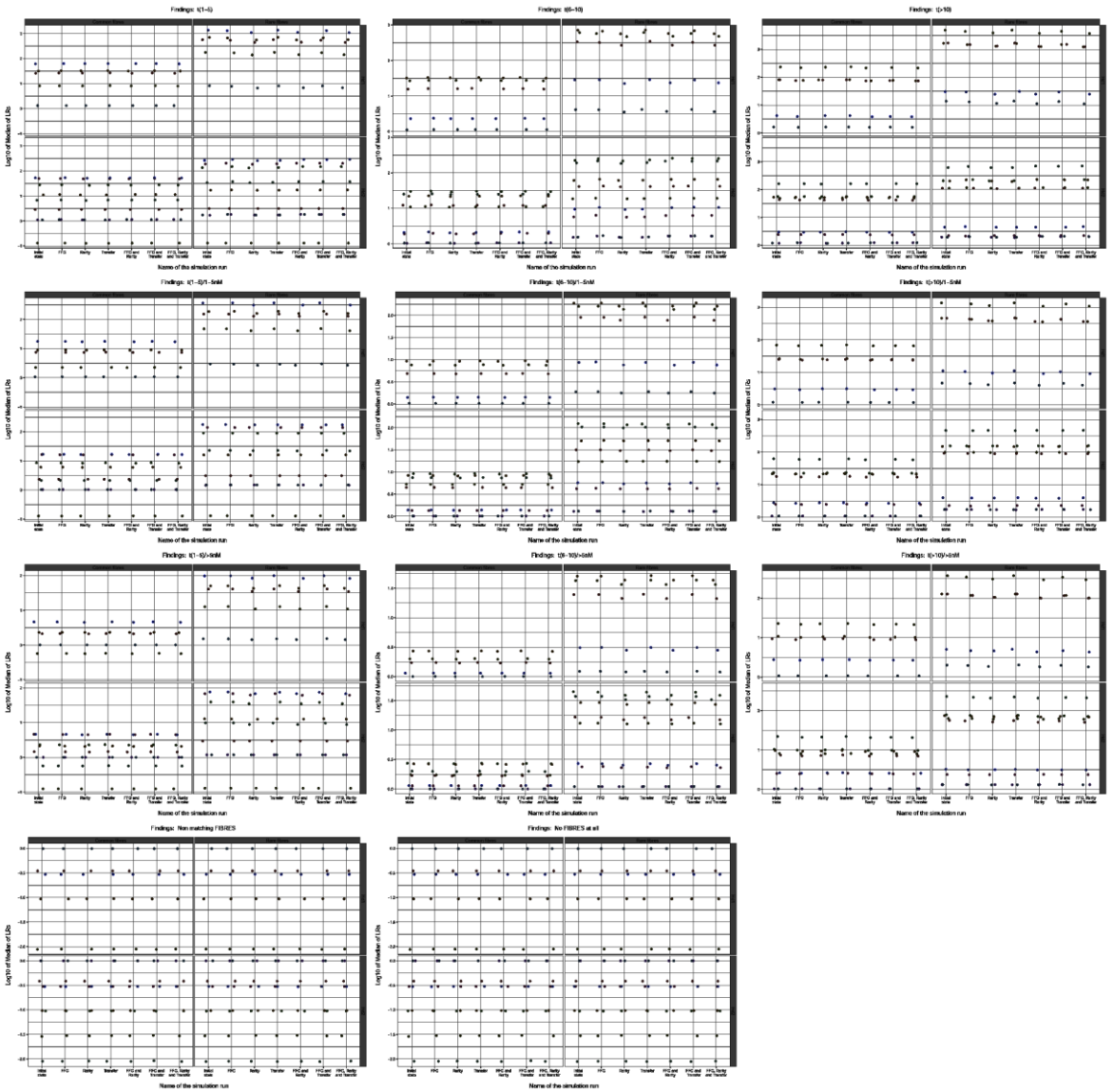

Figure 8: plot of chunk PlotSummaryMedianS7

It is a good move to increase our data (or knowledge) in relation to both FFG and Transfer. We can continue to simulate other possibilities but I leave that to you Ray using the above as a example

We can visualise the range of LR obtained with S7_F, S7_F_R_T and compare with the intitial situation using the following plotting commands. We can easily visualise the reduction of the range of the LRs. Investing on FFG is probably enough. The gain for investing on rarity and transfer data is modest, but may depend on the considered outcome.

```
#we prepare the results for plotting

SimulationName <- rep("Initial\nstate\n", nrow(S7_Ini[[1]]))

S7a_Ini <- S7_Ini

S7a_Ini$sim <- (SimulationName)

S7a_Ini <- as.data.frame(S7a_Ini)

SimulationName <- rep("More on\nFFG\n", nrow(S7_F[[1]]))

S7a_F <- S7_F

S7a_F$sim <- (SimulationName)

S7a_F <- as.data.frame(S7a_F)

SimulationName <- rep("More on\nTransfer\n", nrow(S7_T[[1]]))

S7a_T <- S7_T

S7a_T$sim <- (SimulationName)

S7a_T <- as.data.frame(S7a_T)

SimulationName <- rep("More on\nRarity\n", nrow(S7_R[[1]]))

S7a_R <- S7_R

S7a_R$sim <- (SimulationName)

S7a_R <- as.data.frame(S7a_R)

SimulationName <- rep("More on\nFFG, Rarity\nand Transfer\n", nrow(S7_F_R_T[[1]]))

S7a_F_R_T <- S7_F_R_T

S7a_F_R_T$sim <- (SimulationName)

S7a_F_R_T <- as.data.frame(S7a_F_R_T)
```

ResultsS7 <- **rbind**(S7a_Ini, S7a_T, S7a_R, S7a_F, S7a_F_R_T) *# join the results for plotting*

pResultsS7 <- **PlotResults_Simu**(Headhair, ResultsS7, FontSize=FontSize_1, minlog10LR=-1, maxlog10LR=5)

do.call(grid.arrange,pResultsS7[[1]])

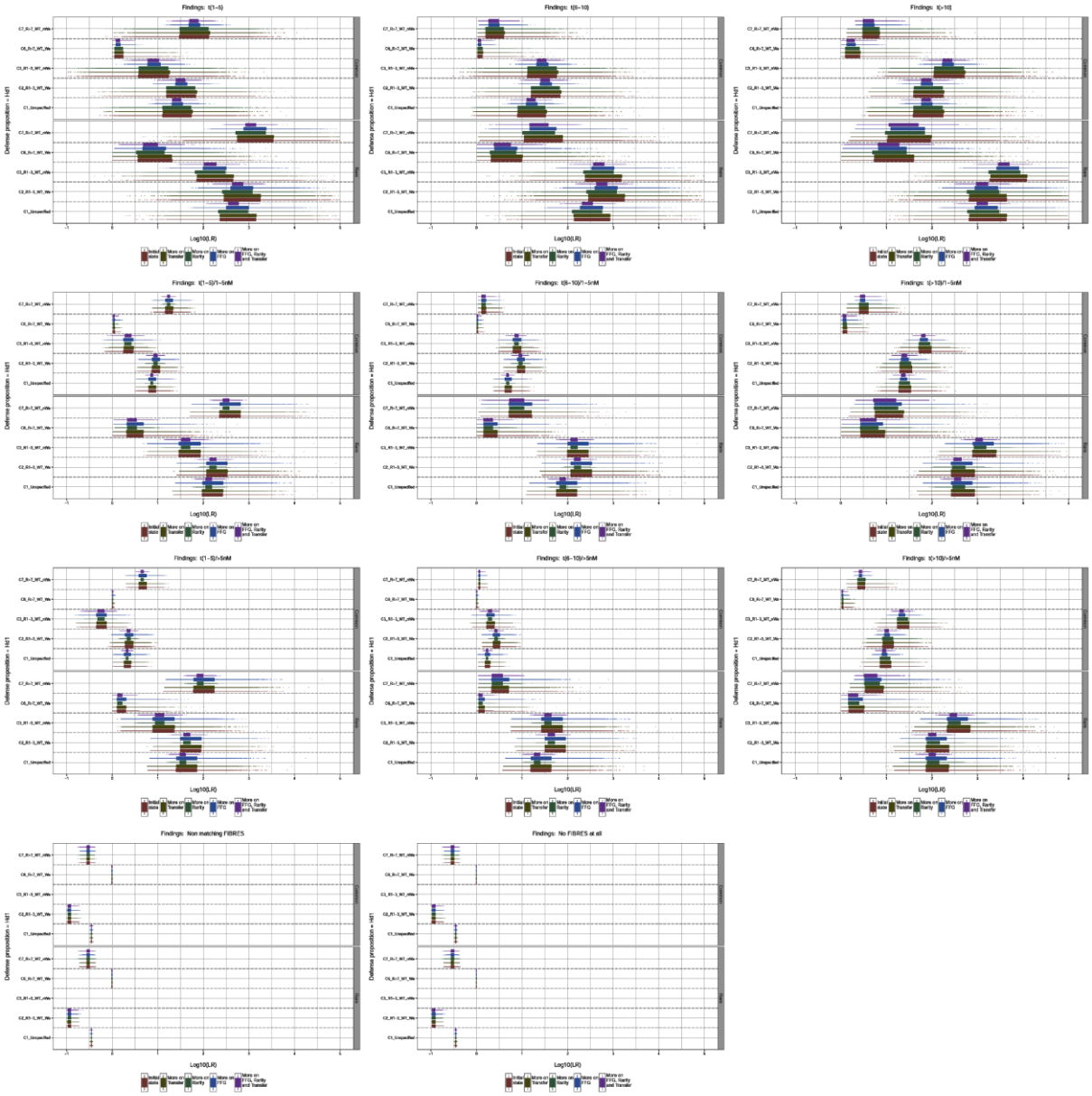

Figure 9: plot of chunk PlotImprovement_F_R_T

Plots for individual outcomes

First we need to set new plotting options to generate adequate PDF files.

#Adapt the size of figures to individual outcomes

opts_chunk$**set**(dev = 'pdf')

opts_chunk$**set**(fig.width = 25, fig.height = 15)

#Will apply to all next chuncks

Then we can plot them.

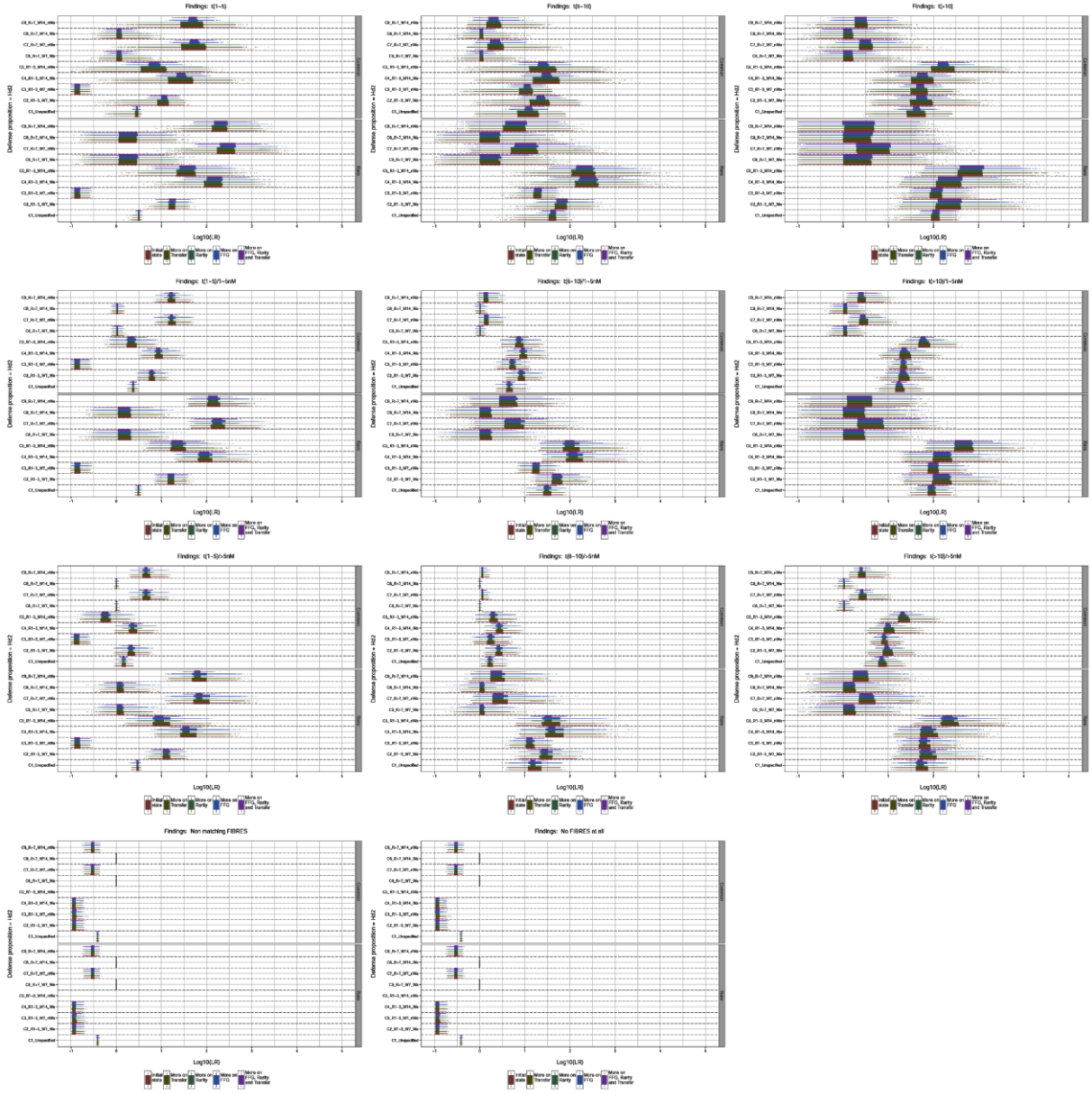

Figure 10: plot of chunk PlotImprovement_F_R_T

 # we can focus on some outcomes (hence we change the fontsize and LR scale if necessary)

p_S6_none1 <- **PlotResults4_LR**(Headhair, S6_none, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=4,fatten_**do.call**(grid.arrange,p_S6_none1[[1]][SelectedOutcome1])

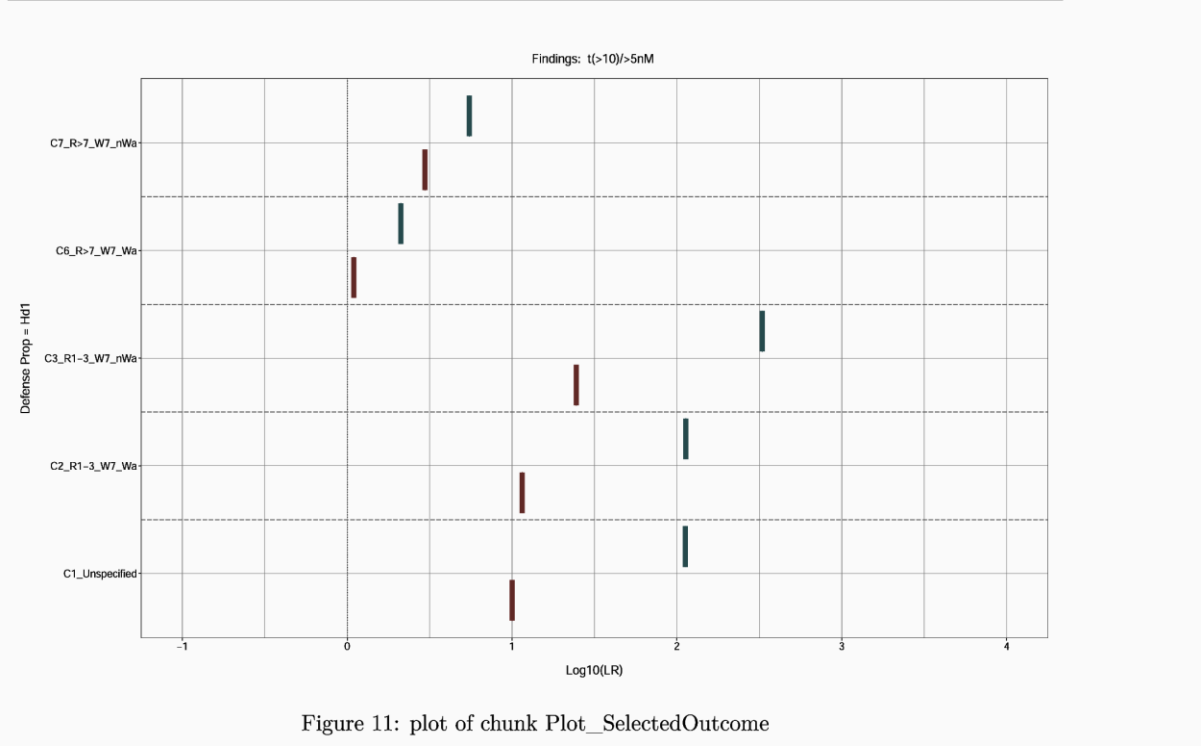

Figure 11: plot of chunk Plot_SelectedOutcome

do.call(grid.arrange,p_S6_none1[[2]][SelectedOutcome1])

p_S6_none2 <- **PlotResults4_LR**(Headhair, S6_none, FontSize=FontSize_2, minlog10LR=-2, maxlog10LR=0.3,fatten_**do.call**(grid.arrange,p_S6_none2[[1]][SelectedOutcome2])

do.call(grid.arrange,p_S6_none2[[2]][SelectedOutcome2])

p_S6_none3 <- **PlotResults4_LR**(Headhair, S6_none, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=4,fatten_**do.call**(grid.arrange,p_S6_none3[[1]][SelectedOutcome3])

do.call(grid.arrange,p_S6_none3[[2]][SelectedOutcome3])

p_S6_all1 <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=6)

do.call(grid.arrange,p_S6_all1[[1]][SelectedOutcome1])

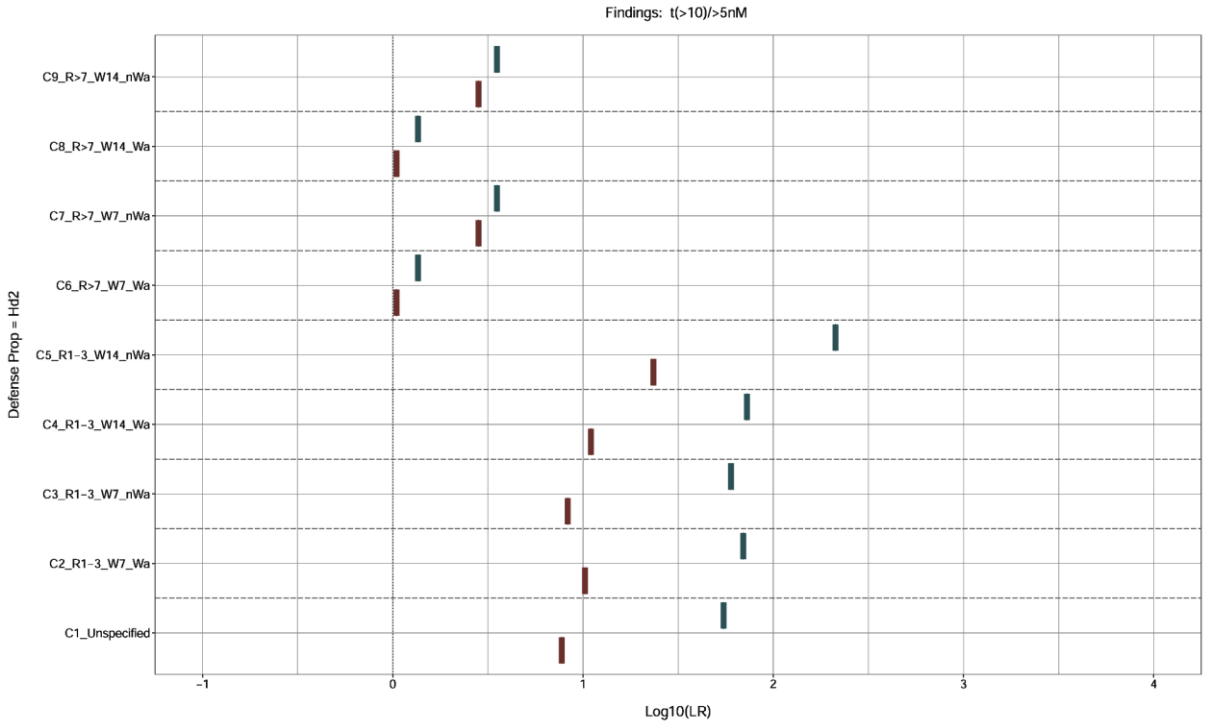

Figure 12: plot of chunk Plot_SelectedOutcome

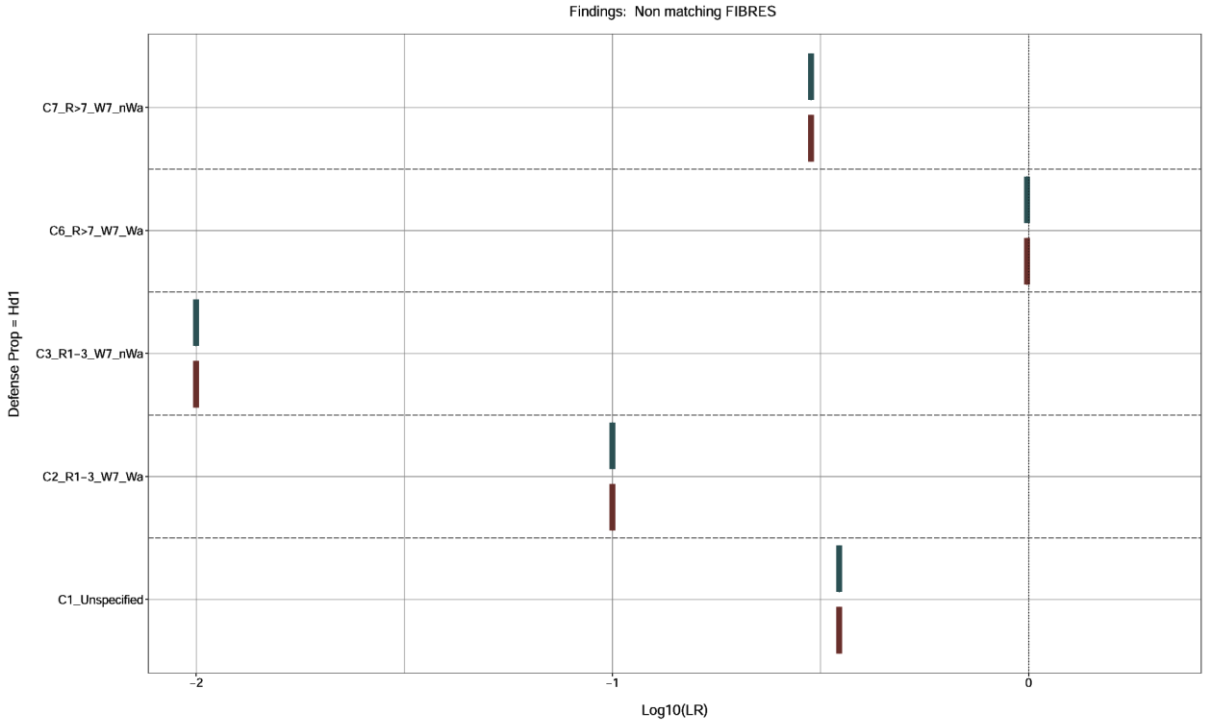

Figure 13: plot of chunk Plot_SelectedOutcome

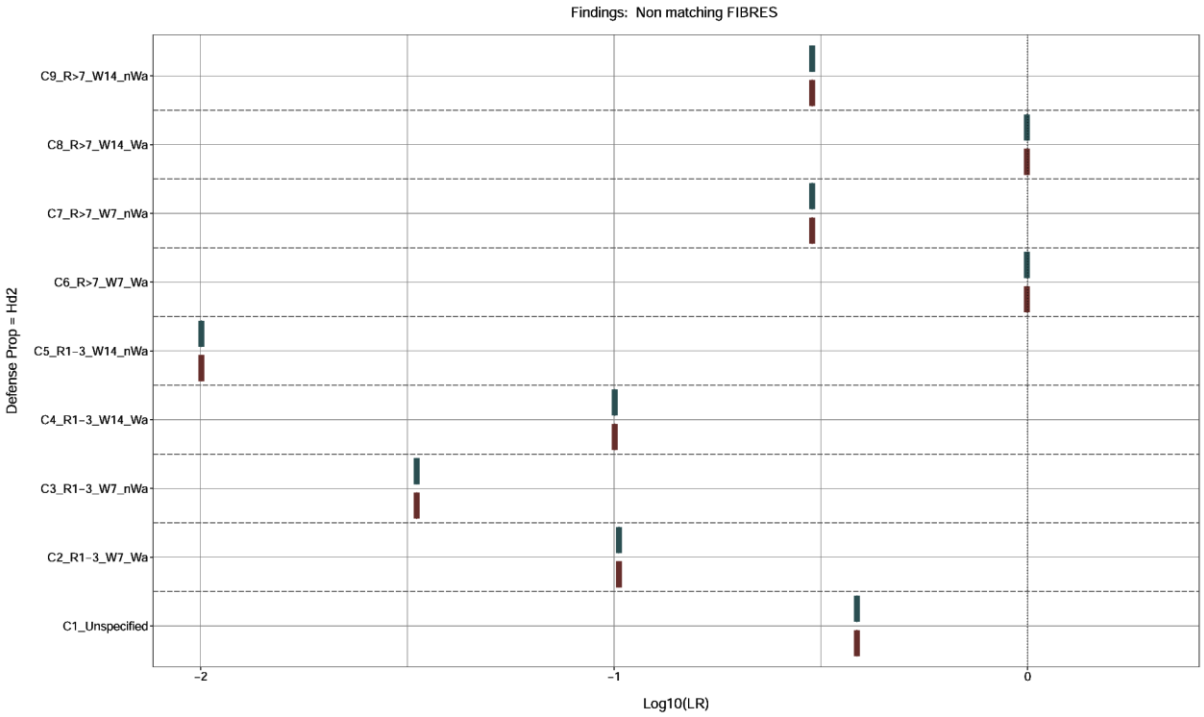

Figure 14: plot of chunk Plot_SelectedOutcome

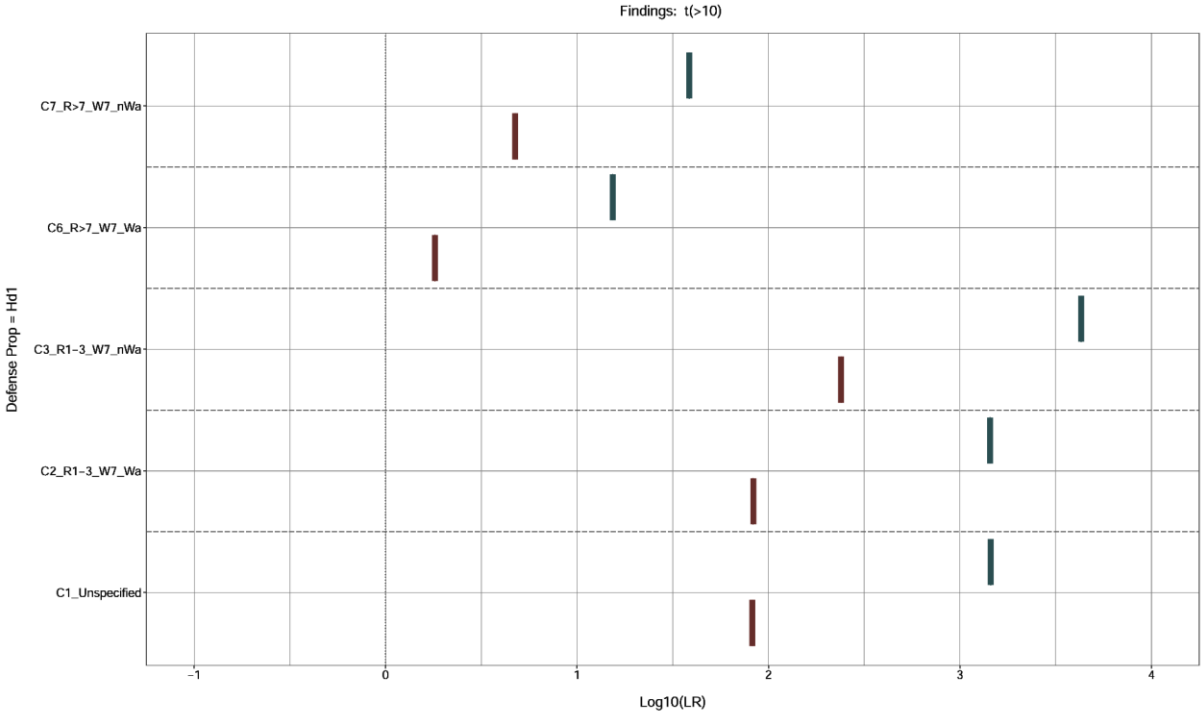

Figure 15: plot of chunk Plot_SelectedOutcome

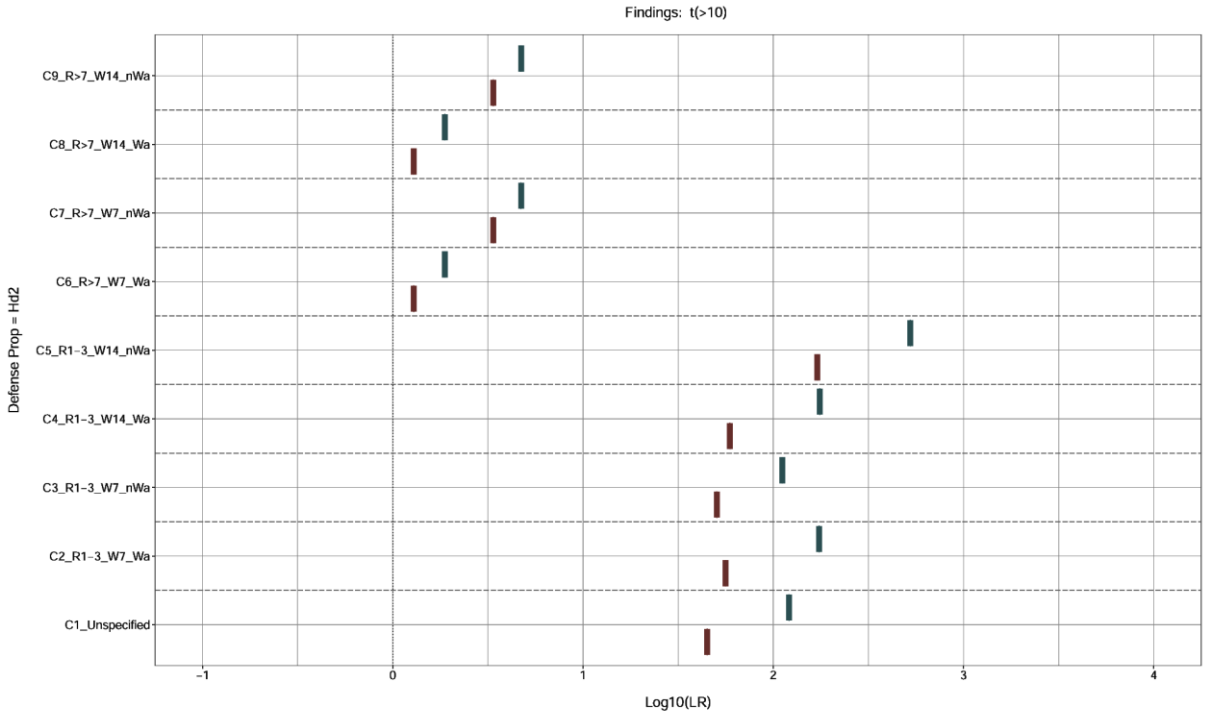

Figure 16: plot of chunk Plot_SelectedOutcome

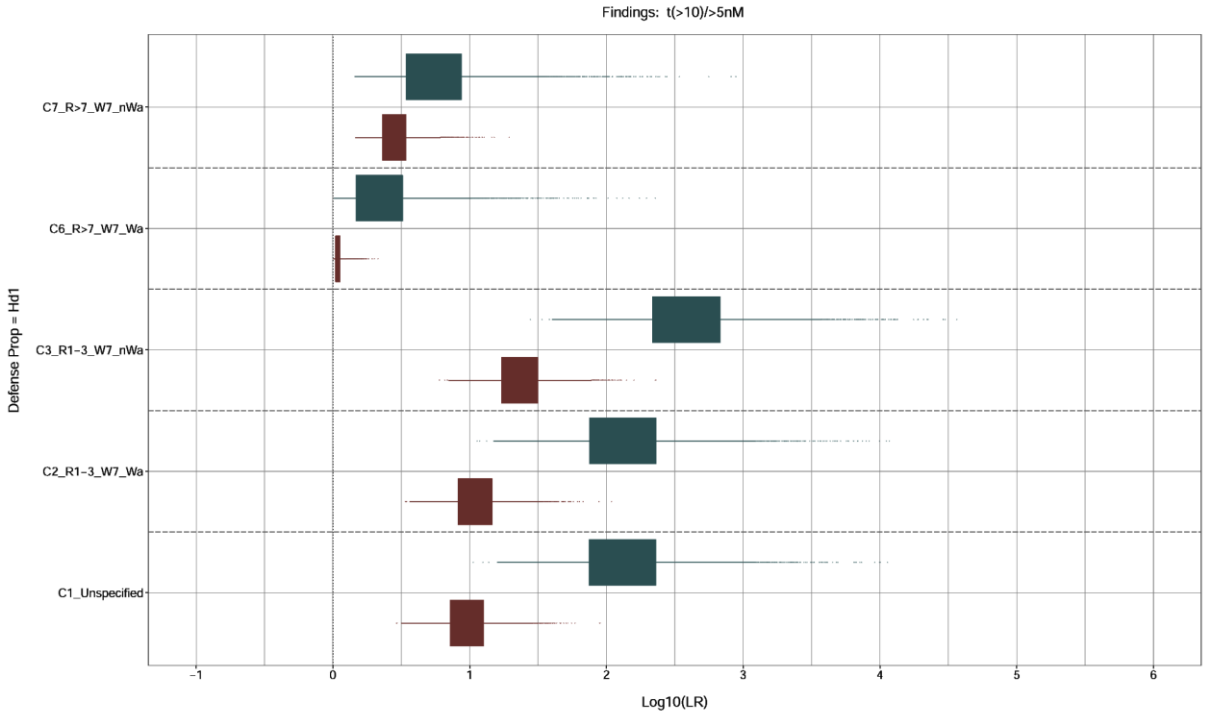

Figure 17: plot of chunk Plot_SelectedOutcome

do.call(grid.arrange,p_S6_all1[[2]][SelectedOutcome1])

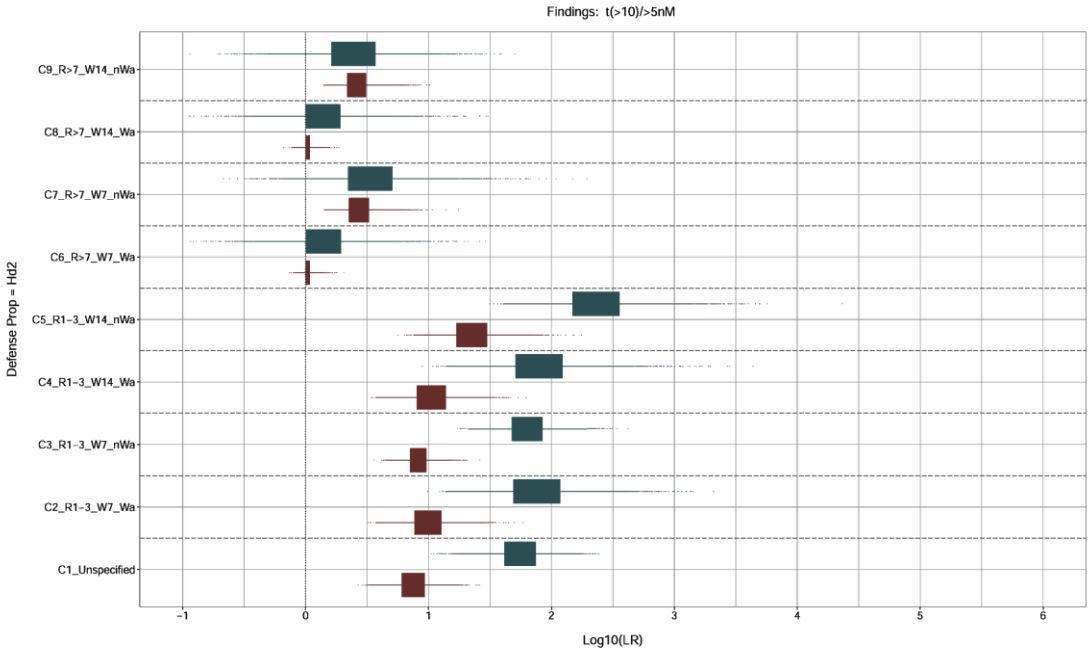

Figure 18: plot of chunk Plot_SelectedOutcome

p_S6_all2 <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_2, minlog10LR=-3, maxlog10LR=0.3)

do.call(grid.arrange,p_S6_all2[[1]][SelectedOutcome2])

Warning: Removed 302 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,p_S6_all2[[2]][SelectedOutcome2])

Warning: Removed 327 rows containing non-finite values (stat_boxplot).

p_S6_all3 <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=6)

do.call(grid.arrange,p_S6_all3[[1]][SelectedOutcome3])

Warning: Removed 10 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,p_S6_all3[[2]][SelectedOutcome3])

Warning: Removed 178 rows containing non-finite values (stat_boxplot).

p_S6_all2 <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_2, minlog10LR=-3, maxlog10LR=0.3)

do.call(grid.arrange,p_S6_all2[[1]][SelectedOutcome2])

Warning: Removed 302 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,p_S6_all2[[2]][SelectedOutcome2])

Warning: Removed 327 rows containing non-finite values (stat_boxplot).

p_S6_all3 <- **PlotResults4_LR**(Headhair, S6_all, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=6)

do.call(grid.arrange,p_S6_all3[[1]][SelectedOutcome3])

Warning: Removed 10 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,p_S6_all3[[2]][SelectedOutcome3])

Warning: Removed 178 rows containing non-finite values (stat_boxplot).

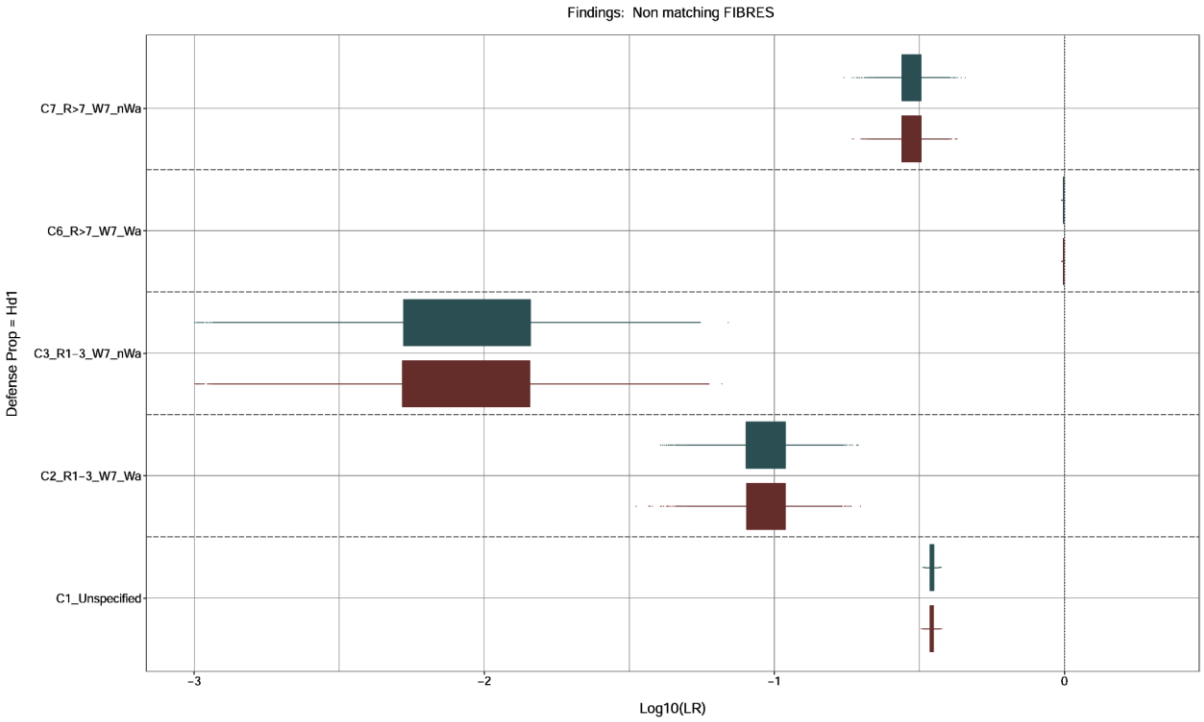

Figure 19: plot of chunk Plot_SelectedOutcome

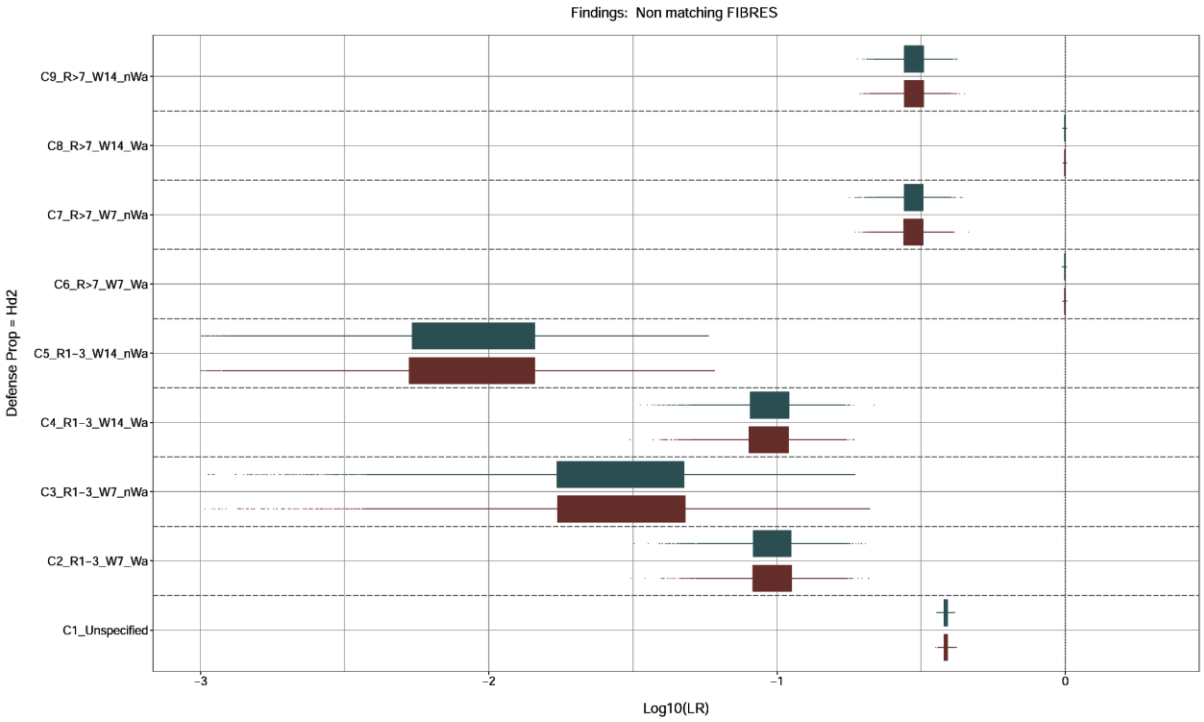

Figure 20: plot of chunk Plot_SelectedOutcome

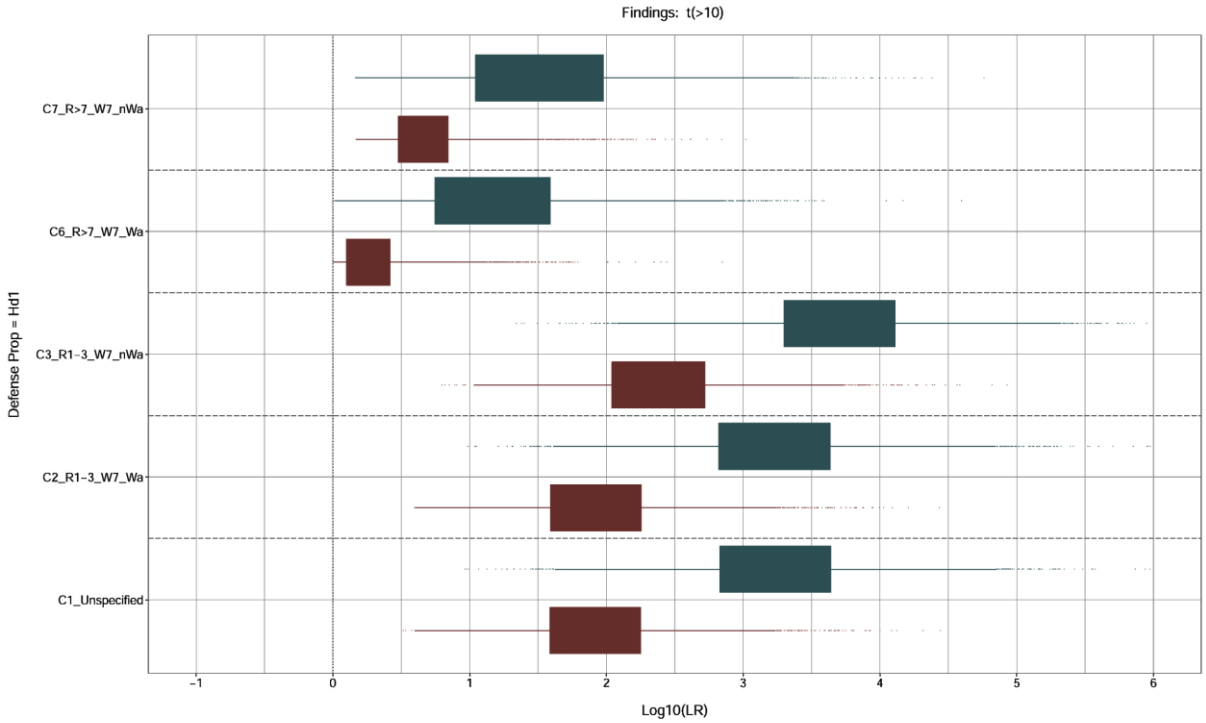

Figure 21: plot of chunk Plot_SelectedOutcome

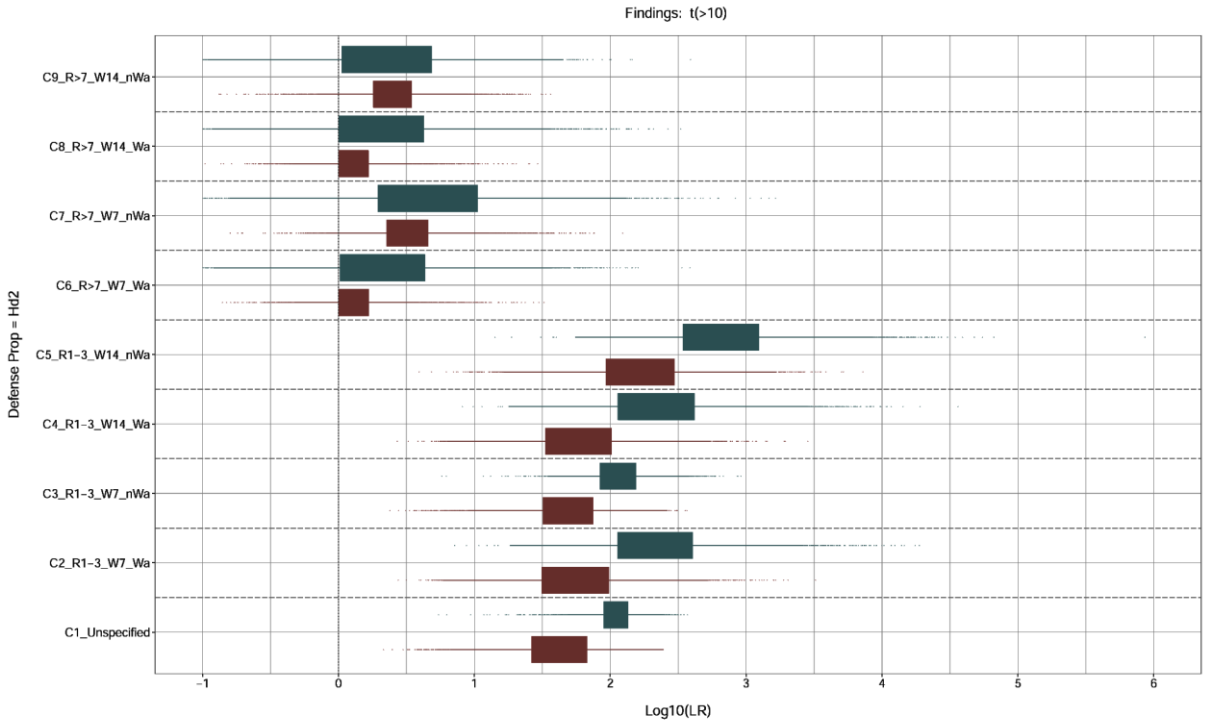

Figure 22: plot of chunk Plot_SelectedOutcome

p1.1 <- **PlotResults4_SummaryStat_IQR**(Headhair, ResultsSimulations6, FontSize=FontSize_2, DotSize=5, show_**do.call**(grid.arrange,p1.1[SelectedOutcome1])

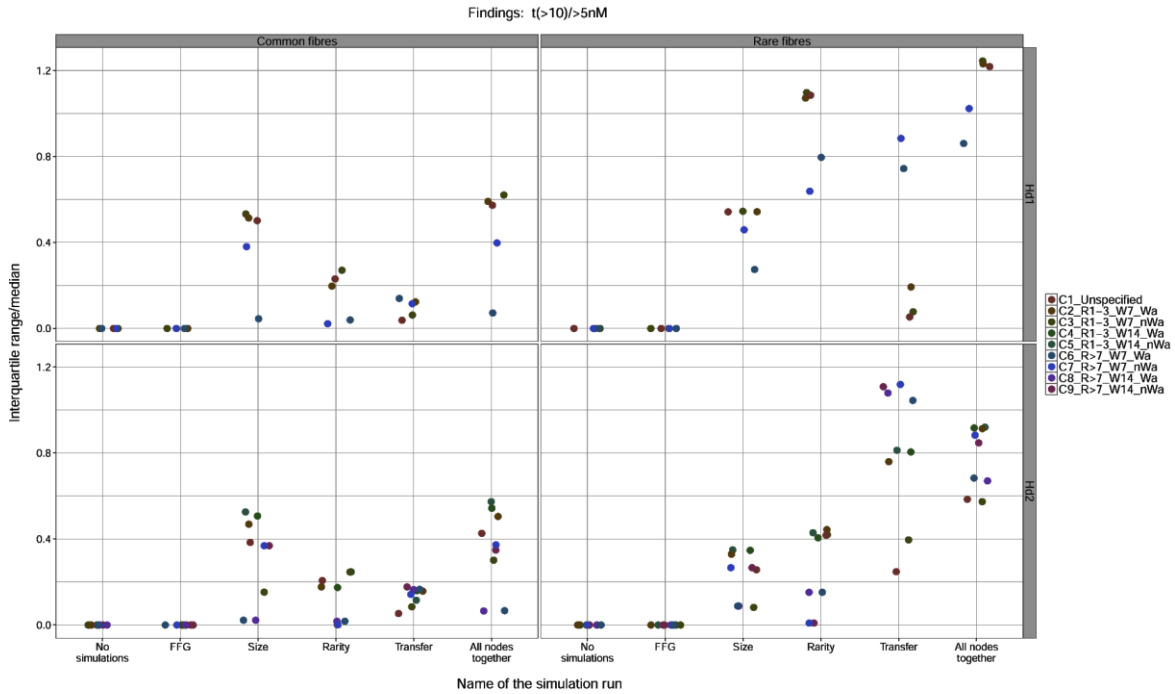

Figure 23: plot of chunk Plot_SelectedOutcome

do.call(grid.arrange,p1.1[SelectedOutcome2])

do.call(grid.arrange,p1.1[SelectedOutcome3])

p2.1 <- **PlotResults4_SummaryStat_median**(Headhair, ResultsSimulations6, FontSize=FontSize_2, DotSize=5, show_**do.call**(grid.arrange,p2.1[SelectedOutcome1])

do.call(grid.arrange,p2.1[SelectedOutcome2])

do.call(grid.arrange,p2.1[SelectedOutcome3])

p3.1 <- **PlotResults4_SummaryStat_IQR**(Headhair, ResultsSimulations7, FontSize=FontSize_2, DotSize=5, show_**do.call**(grid.arrange,p3.1[SelectedOutcome1])

do.call(grid.arrange,p3.1[SelectedOutcome2])

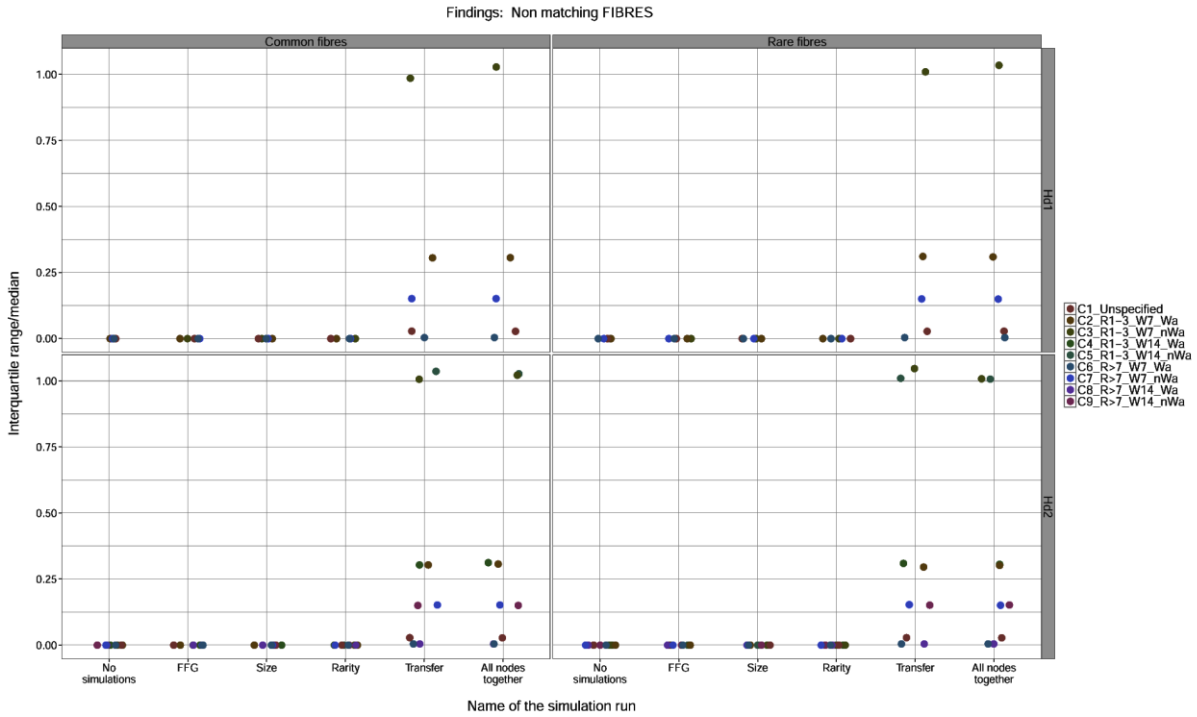

Figure 24: plot of chunk Plot_SelectedOutcome

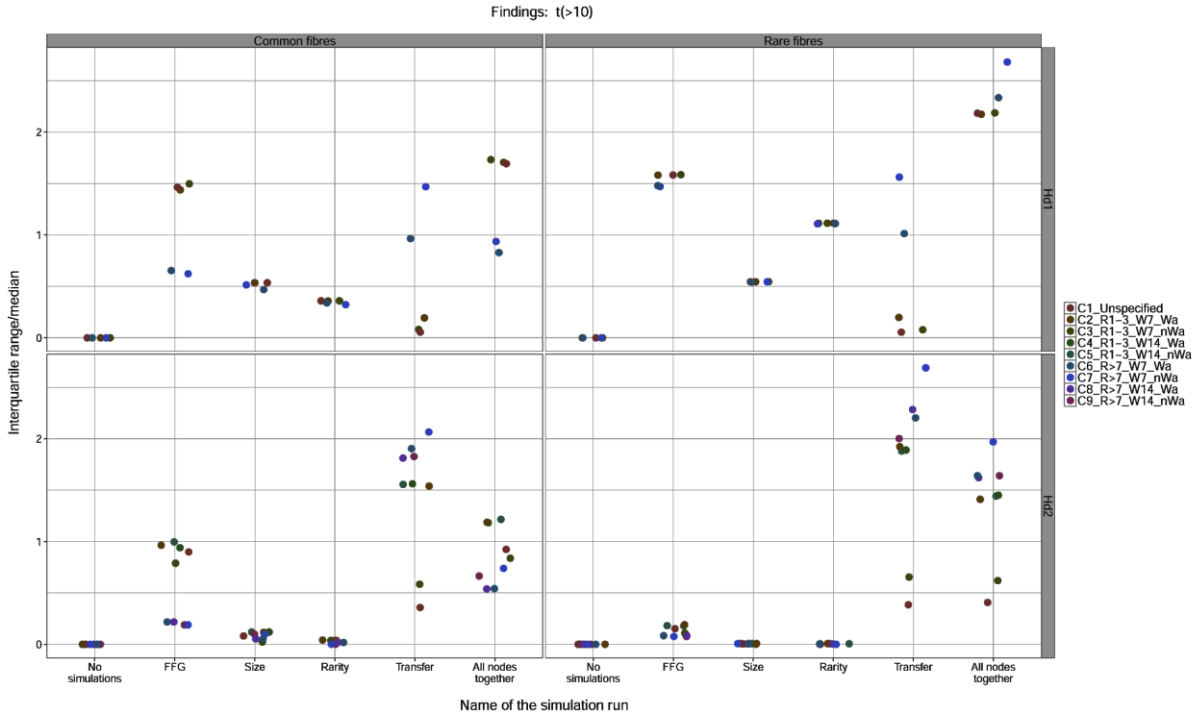

Figure 25: plot of chunk Plot_SelectedOutcome

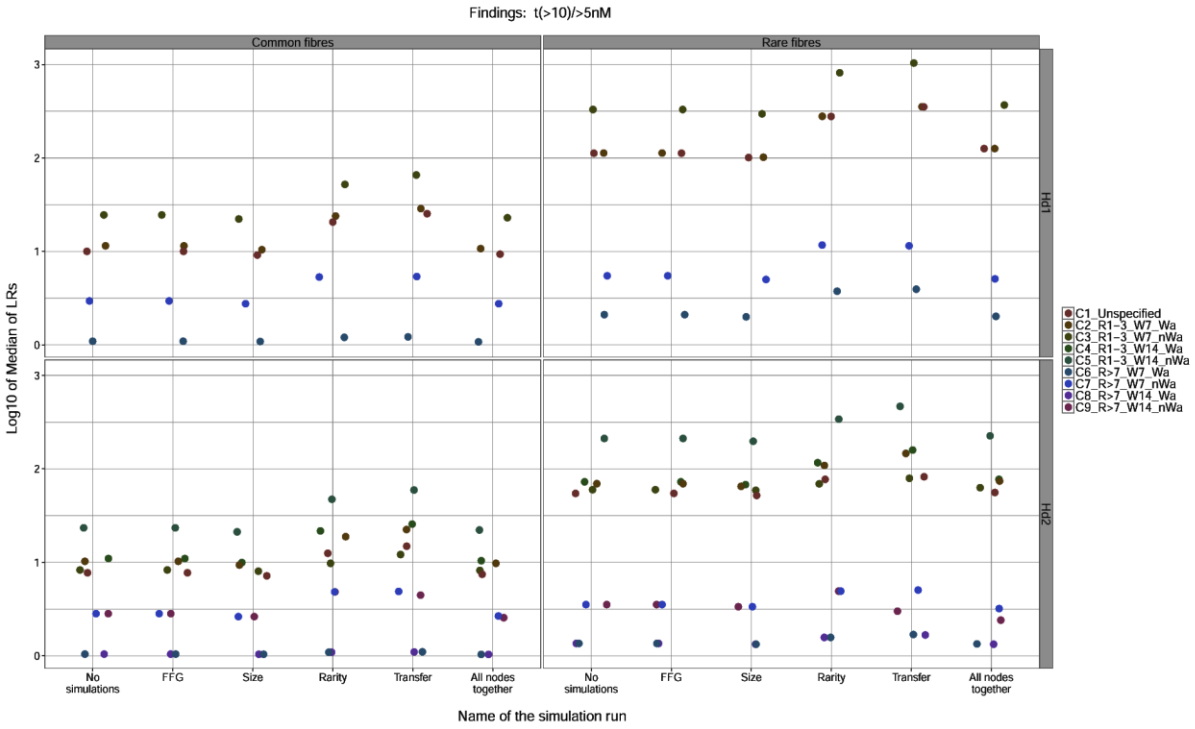

Figure 26: plot of chunk Plot_SelectedOutcome

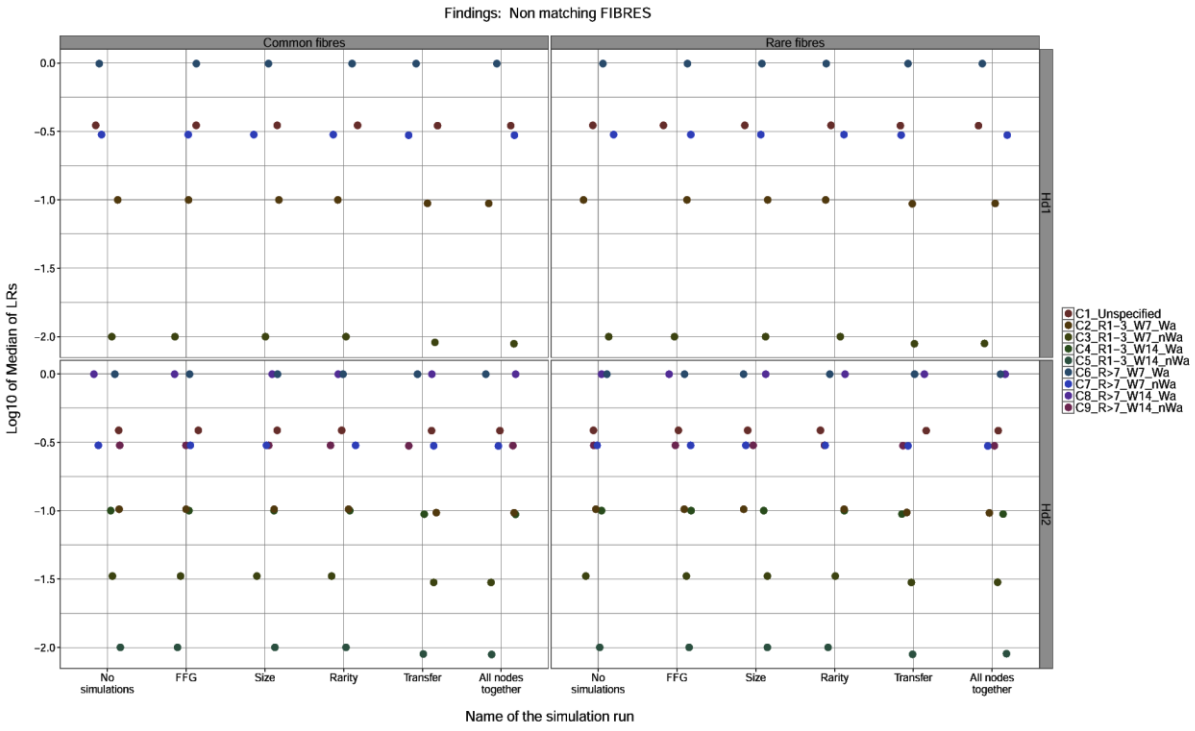

Figure 27: plot of chunk Plot_SelectedOutcome

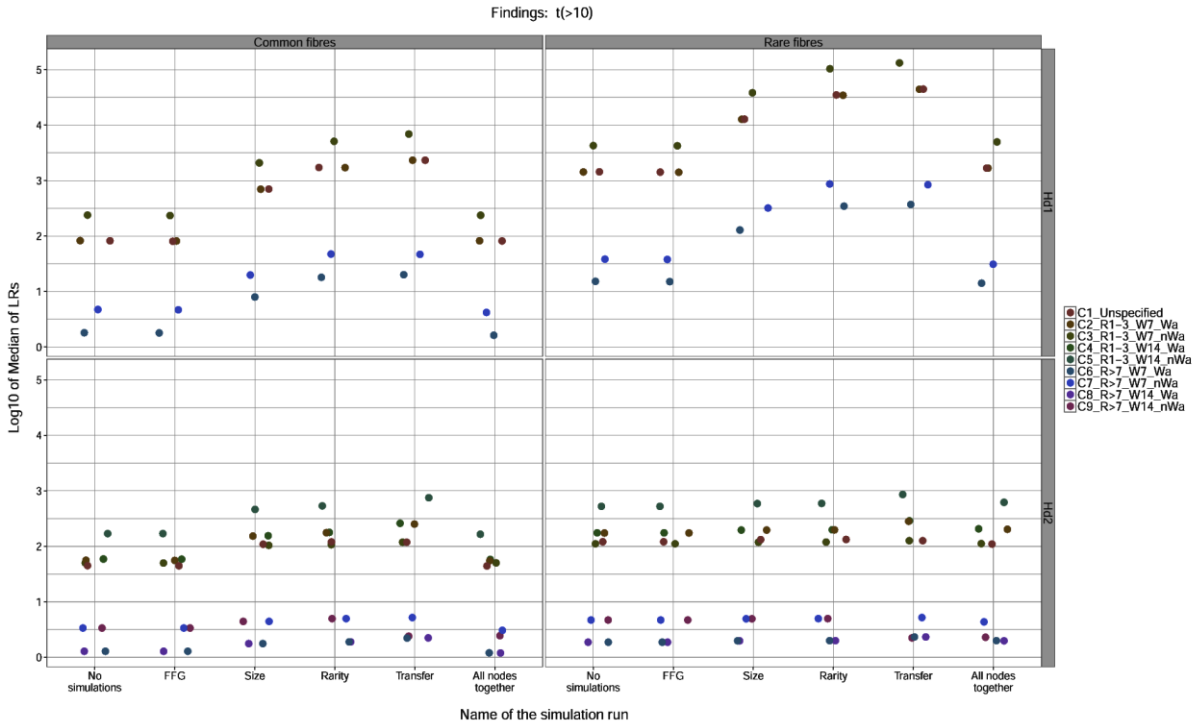

Figure 28: plot of chunk Plot_SelectedOutcome

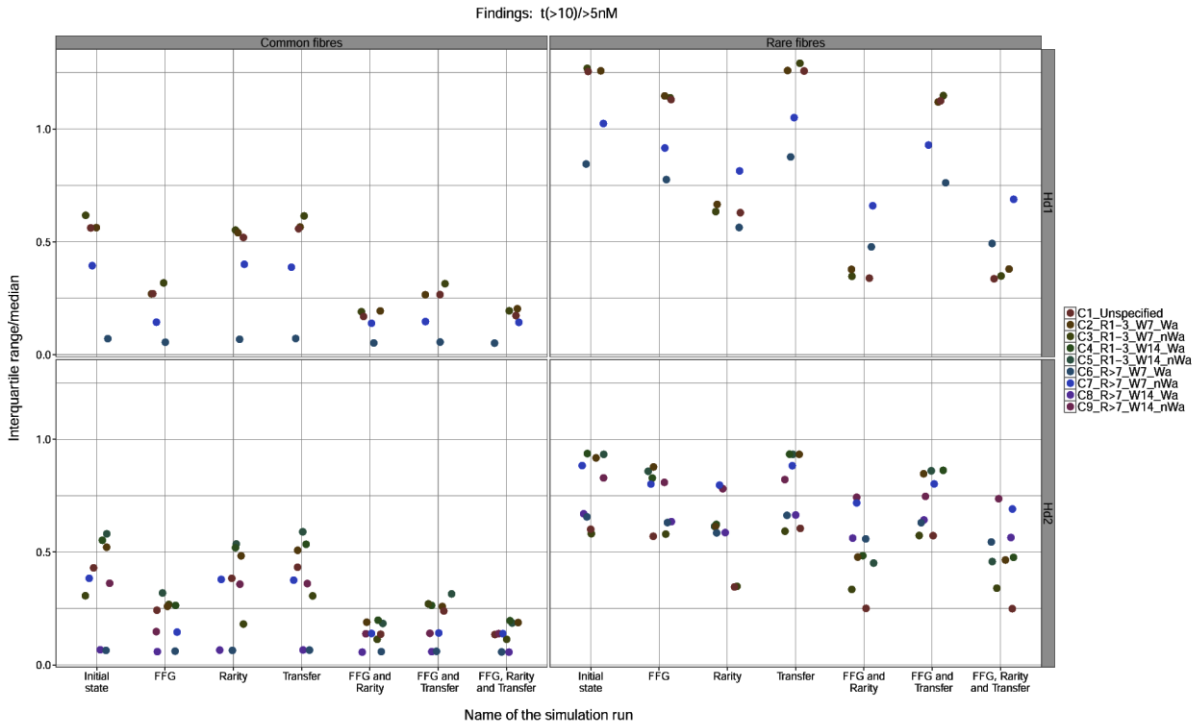

Figure 29: plot of chunk Plot_SelectedOutcome

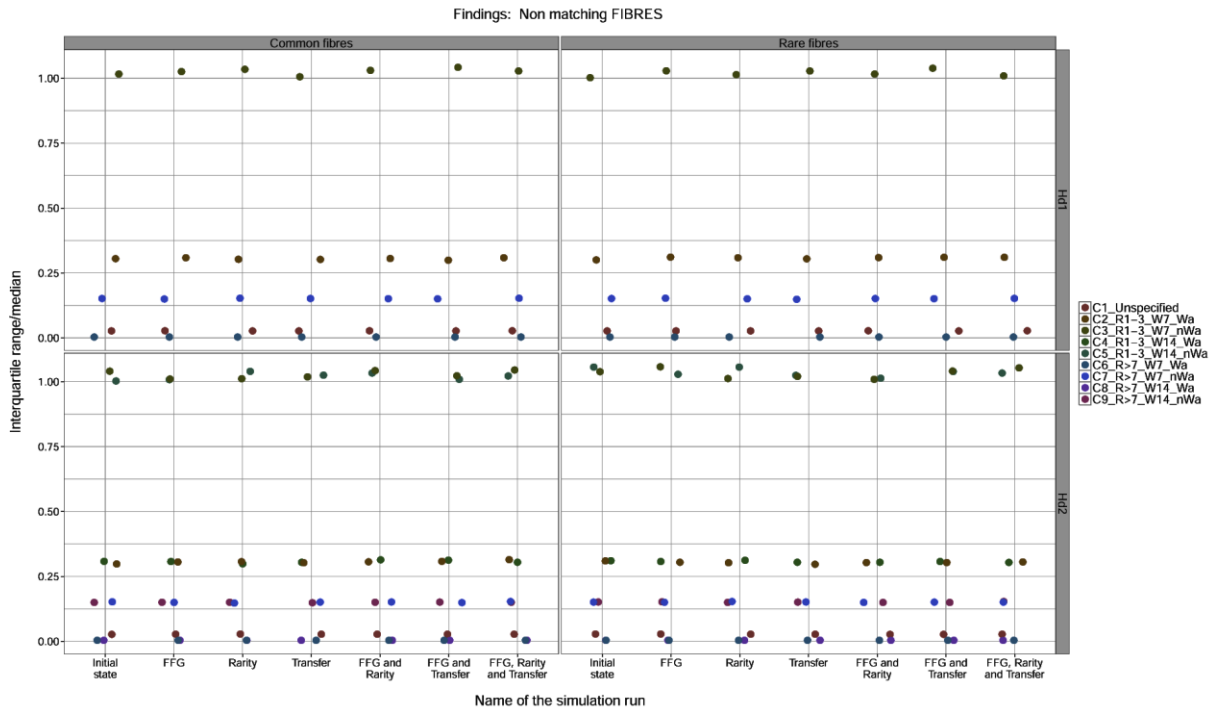

Figure 30: plot of chunk Plot_SelectedOutcome

do.call(grid.arrange,p3.1[SelectedOutcome3])

p4.1 <- **PlotResults4_SummaryStat_median**(Headhair, ResultsSimulations7, FontSize=FontSize_2, DotSize=5, show_**do.call**(grid.arrange,p4.1[SelectedOutcome1])

do.call(grid.arrange,p4.1[SelectedOutcome2])

do.call(grid.arrange,p4.1[SelectedOutcome3])

pResultsS7.1 <- **PlotResults_Simu**(Headhair, ResultsS7, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=6,
do.call(grid.arrange,pResultsS7.1[[1]][SelectedOutcome1])

do.call(grid.arrange,pResultsS7.1[[2]][SelectedOutcome1])

Warning: Removed 7 rows containing non-finite values (stat_boxplot).

pResultsS7.2 <- **PlotResults_Simu**(Headhair, ResultsS7, FontSize=FontSize_2, minlog10LR=-4, maxlog10LR=1,
do.call(grid.arrange,pResultsS7.2[[1]][SelectedOutcome2])

Warning: Removed 3 rows containing non-finite values (stat_boxplot).

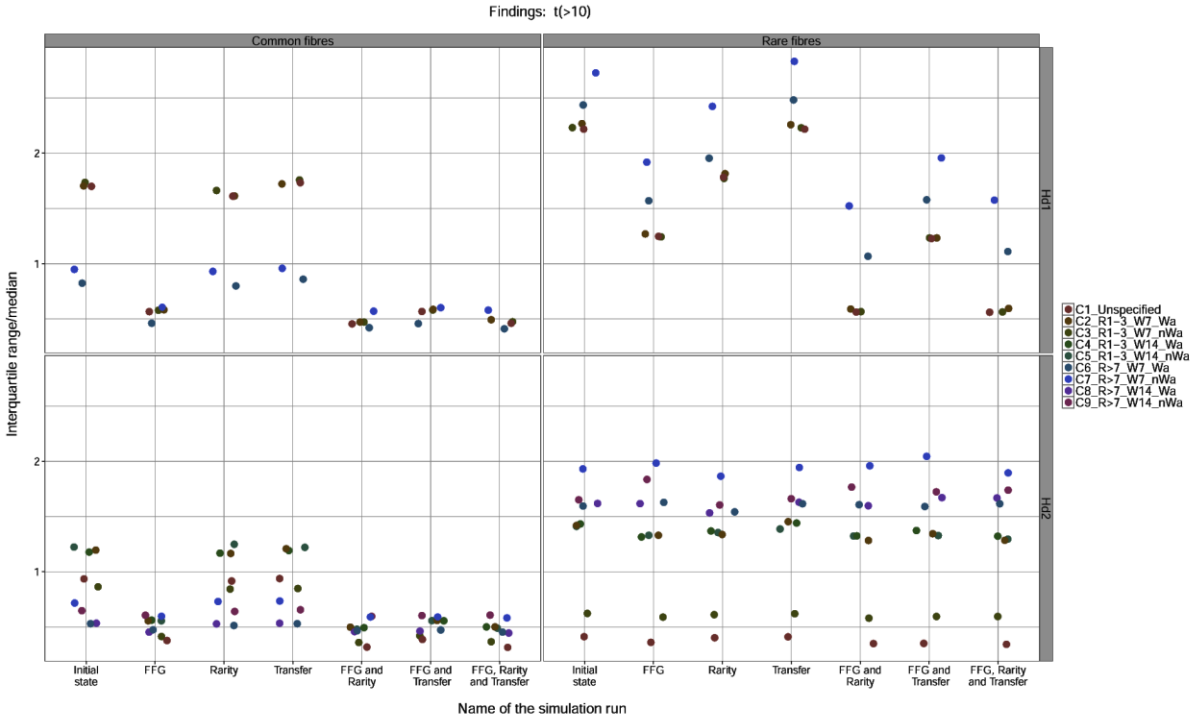

Figure 31: plot of chunk Plot_SelectedOutcome

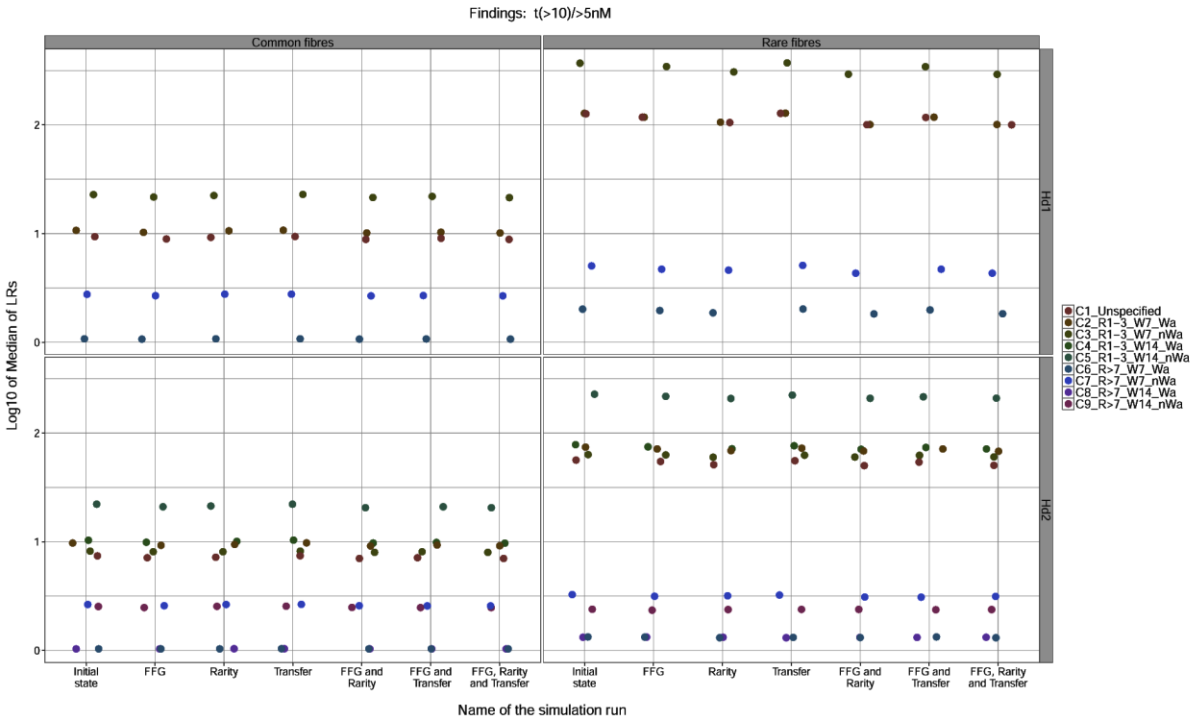

Figure 32: plot of chunk Plot_SelectedOutcome

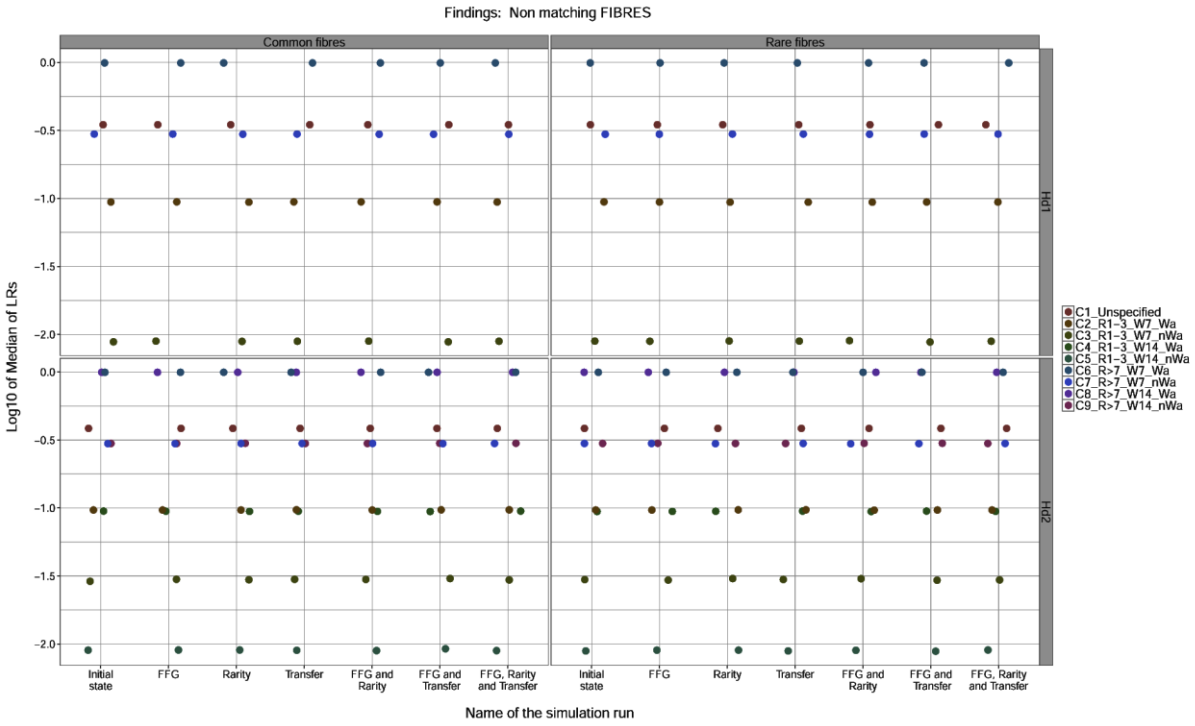

Figure 33: plot of chunk Plot_SelectedOutcome

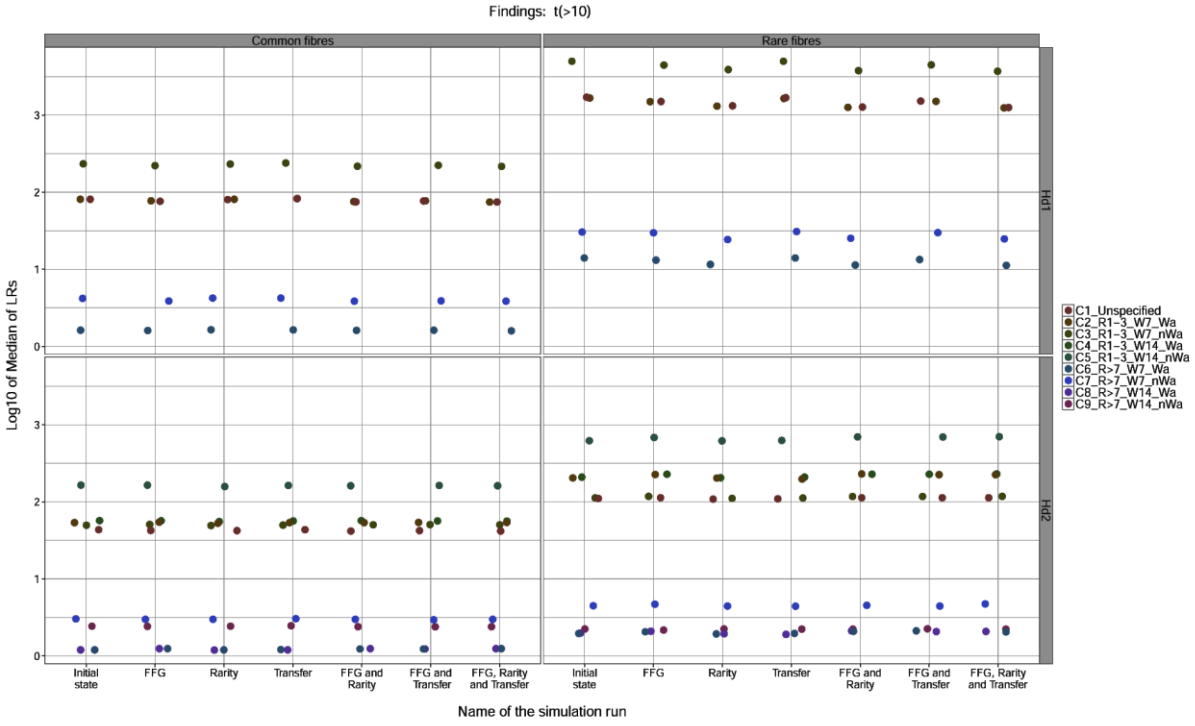

Figure 34: plot of chunk Plot_SelectedOutcome

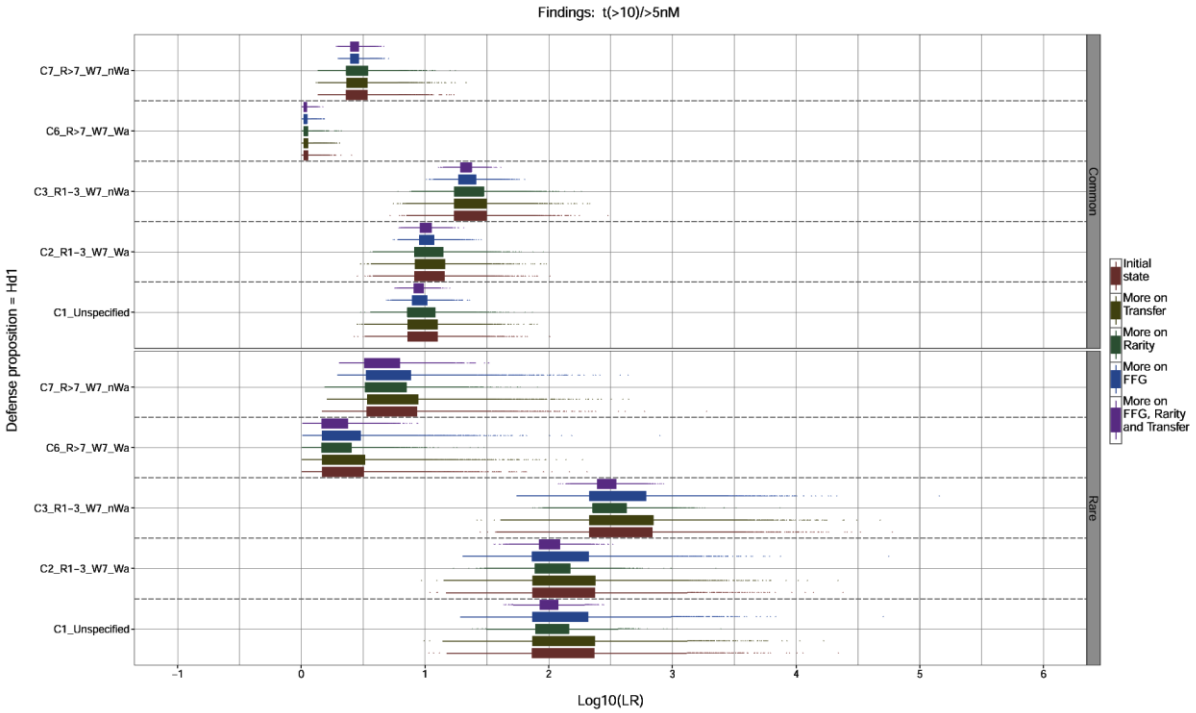

Figure 35: plot of chunk Plot_SelectedOutcome

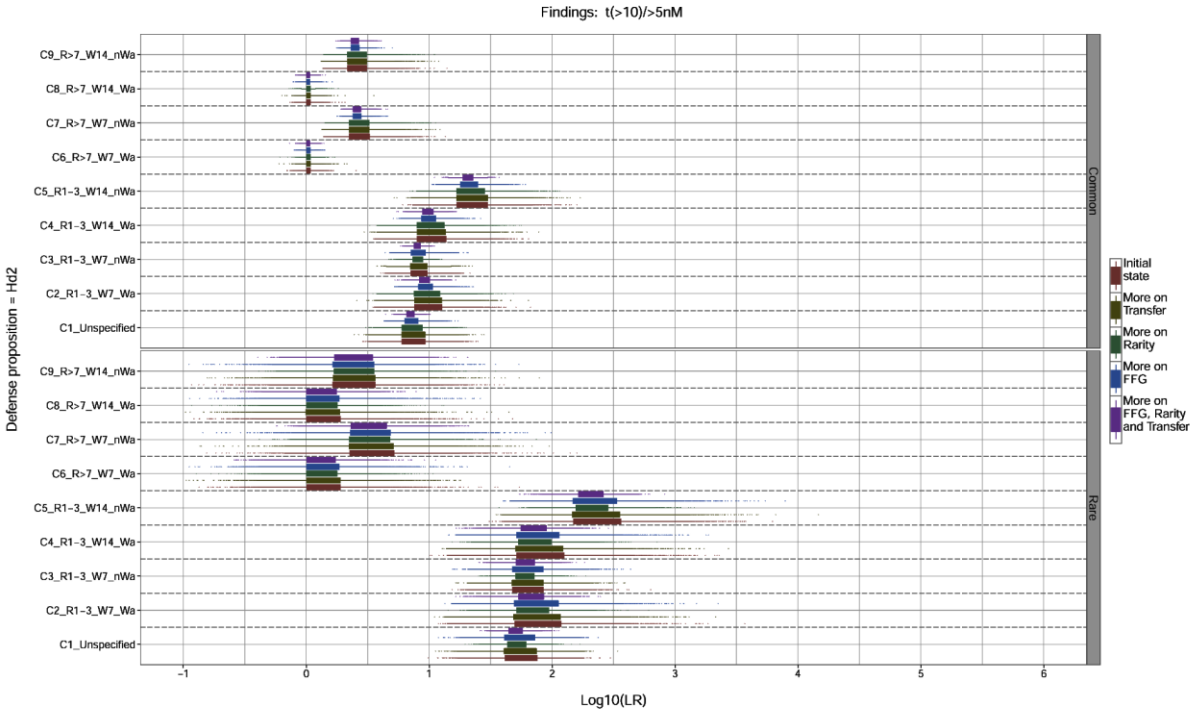

Figure 36: plot of chunk Plot_SelectedOutcome

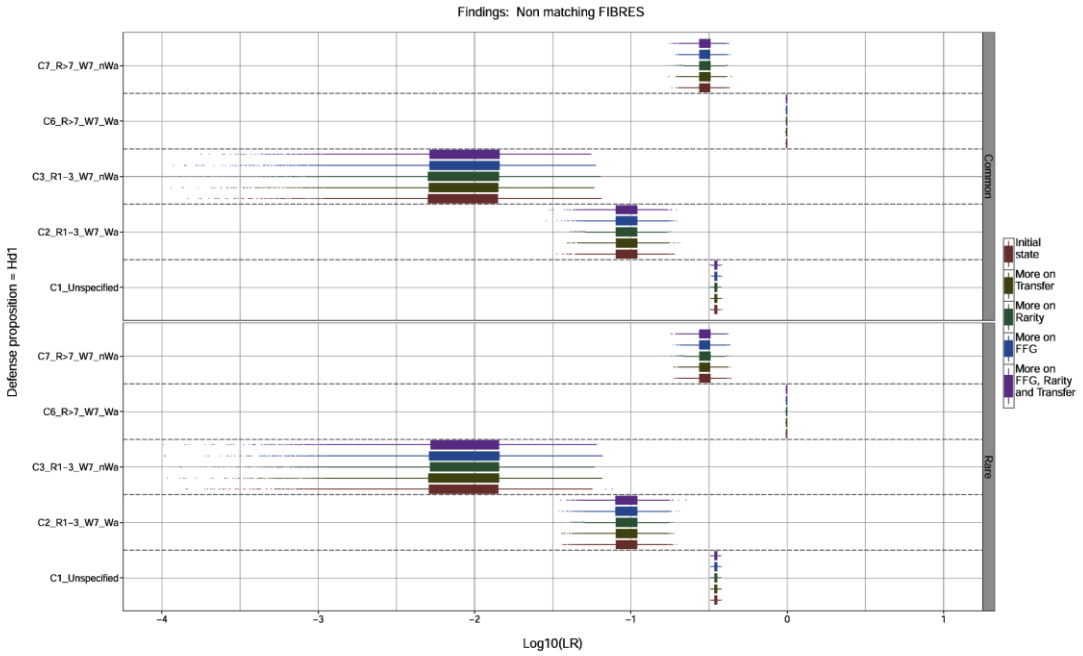

Figure 37: plot of chunk Plot_SelectedOutcome

Warning: Removed 7 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,pResultsS7.2[[2]][SelectedOutcome2])

Warning: Removed 11 rows containing non-finite values (stat_boxplot).

Warning: Removed 8 rows containing non-finite values (stat_boxplot).

pResultsS7.3 <- **PlotResults_Simu**(Headhair, ResultsS7, FontSize=FontSize_2, minlog10LR=-1, maxlog10LR=6,
do.call(grid.arrange,pResultsS7.3[[1]][SelectedOutcome3])

Warning: Removed 22 rows containing non-finite values (stat_boxplot).

do.call(grid.arrange,pResultsS7.3[[2]][SelectedOutcome3])

Warning: Removed 12 rows containing non-finite values (stat_boxplot).

Warning: Removed 753 rows containing non-finite values (stat_boxplot).

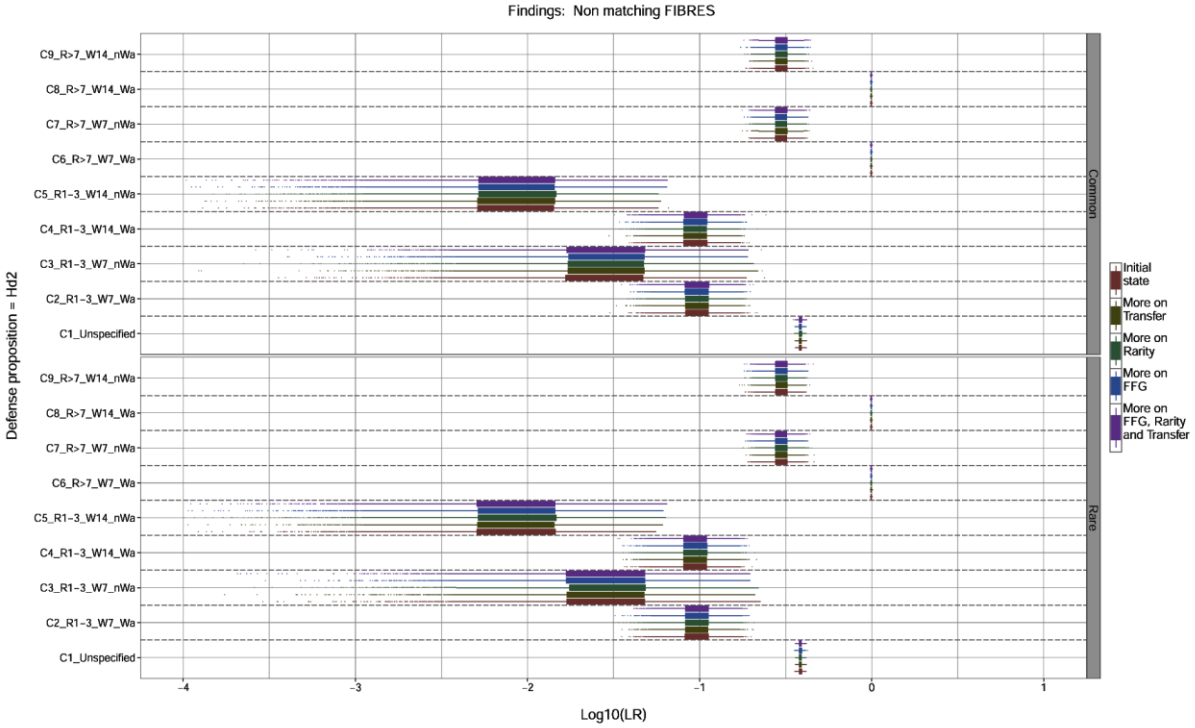

Figure 38: plot of chunk Plot_SelectedOutcome

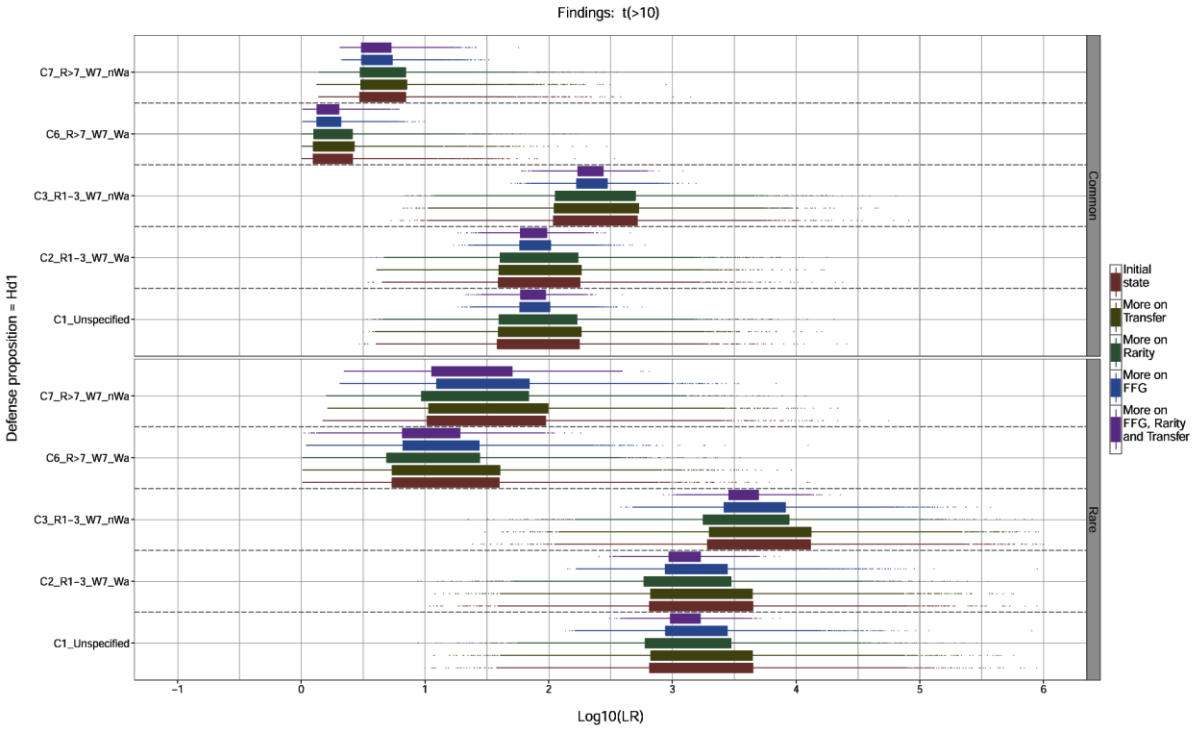

Figure 39: plot of chunk Plot_SelectedOutcome

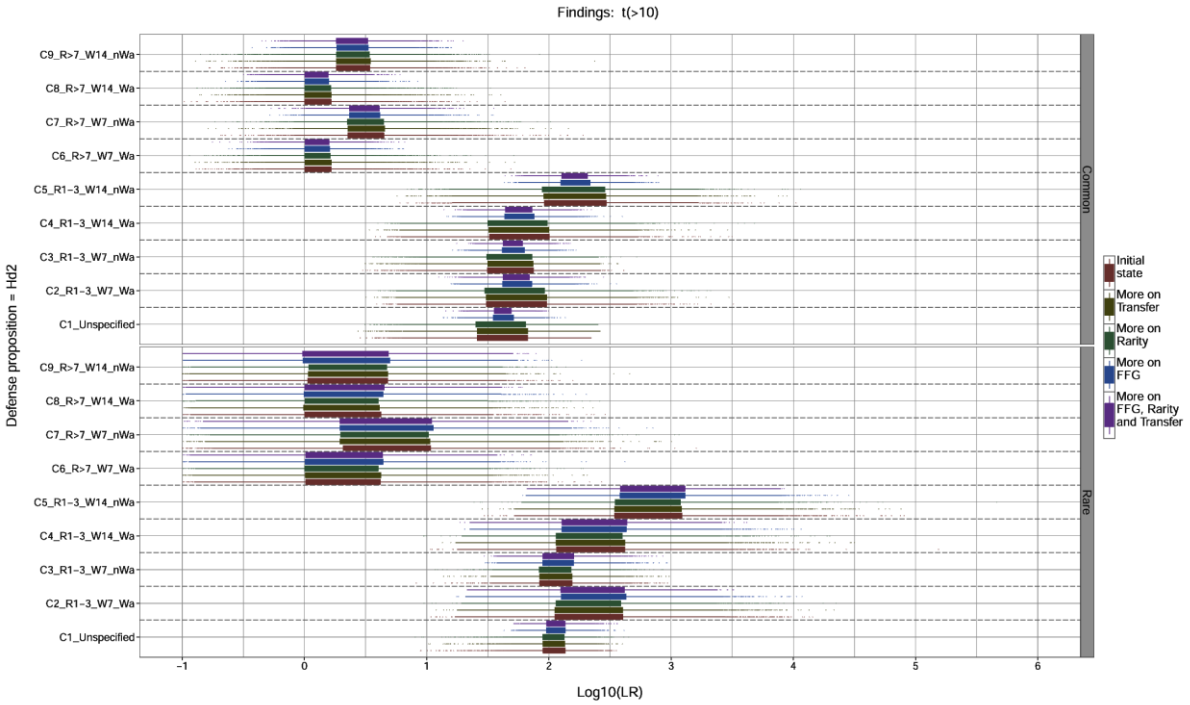

Figure 40: plot of chunk Plot_SelectedOutcome

APPENDIX 6

Transfer data (counts) used to inform MLE's contained in 'TransferNode1.xls' called by sensitivity analysis R script

Transfer Data (Counts) under Hp							
Washed		Not Washed		Washed		Not Washed	
1-3 Days		7 Days		1-3 Days		7 Days	
7 Days	14 Days	7 Days	14 Days	7 Days	14 Days	7 Days	14 Days
38	38	2	2	111	111	2	2
65	65	2	2	56	56	4	4
65	65	4	4	18	18	126	126
19	19	1000	1000	3	3	56	56
Transfer Data (Counts) under Hd1							
Washed		Not Washed		Washed		Not Washed	
1-3 Days		7 Days		1-3 Days		7 Days	
7 Days	14 Days	7 Days	14 Days	7 Days	14 Days	7 Days	14 Days
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1
Transfer Data (Counts) under Hd2							
Washed		Not Washed		Washed		Not Washed	
1-3 Days		7 Days		1-3 Days		7 Days	
7 Days	14 Days	7 Days	14 Days	7 Days	14 Days	7 Days	14 Days
2	2	2	2	2	2	2	2
6	2	2	2	4	2	2	2
21	3	3	3	126	3	3	3
975	997	997	997	56	997	997	997

APPENDIX 7

Set of functions called by sensitivity analysis R script

##Sets of functions developed for Ray Palmer's thesis

 # C. Champod

#19.03.2014: Developement of the function SimulateLR_Headhair4 allowing to deal with all cases (requires initially the external file "cases.xlsx")

#21.03.2014: Development of the function SummaryStatisticsResults allowing to compute summary statistics for results from the function SimulateLR_Headhair4

 # v7: 23.03.2014: Development of the functions PlotResults4_SummaryStat_IQR and PlotResults4_SummaryStat_median

 # The initial master file for the earlier development is Ray Palmer PhD Functions v6.R

 # v8: 3.04.2015: Added line at LR=1 on graphs, plus possibilities to add legends and change font sizes.

 # v9: 3.05.2015: Added a correction to have the appropriate relationship with the case number. The assignment of new levels was incorrect. The plotting function have been changed to allow to have ordered cases from 1 to 9.

 # v10: 14.05.2015: Added a sorting function to sort the legends in plots.

 # v11: 16.11.2015: Added separator lines to distinguish cases in plots,

 # Change the names of cases to be more explicit.

 # Change the greylevels in the strips.

 # Add a fatten_value to beef up the median indicators on boxplots

 # Add the title of the Findings in the graph titles

#v12: 14.01.2016: Removed redundant cases under Hd1, leaving only 1, 2,3,6 and 7

#This function is already in the RMD file, but recalled here

```
#GetProbaFFG <- function(f, range=c(2:5)){
#  res <- vector(mode="numeric", length = length(range))
#  for (i in 1:length(range)){
#    j <- range[i]
#    res[i] <- 1-dbinom(0,j,f)
#  }
#  res
#}


SimulateLR_Headhair4 <- function(BN, DefenceProposition=2,
NumberOfSimulations="NA", HairFFGParameters="NA",
SizeHairFFGParameters="NA", CommonFibresParameters="NA",
RareFibresParameters="NA", Rarity="Rare fibres", TransferParameters="NA",
Cases="NA") {


  # Simulation fo the random dirichlet distributions according to the parameters
provided as input. Included as the cases that will instantiate the BN.

  # We just need to handle the cases where no parameters are provided in the form
c(x,x), hence we dont want to update this variable (see below when we invoke the
set.table function) We will introduce a condition to update the table, only if the
parameters have been specified. Otherwisem they are by default set to "NA" which
is a logical vector and not a numeric vector. That allow to run the function without
any variation on the parameters using directly the parameters set in the Hugin .net
file. It will allow to run simulations increasing the number of variables to be
incorporated into the simulations.
```

```
  if(sum(is(CommonFibresParameters)==c("numeric",
"vector"))+sum(is(RareFibresParameters)==c("numeric", "vector"))==4){ # case with
c(x,x) and c (x,x)

    RandomCommon <- rdirichlet(NumberOfSimulations, CommonFibresParameters)

    RandomRare <- rdirichlet(NumberOfSimulations, RareFibresParameters)

  }

  else { # case with "NA"

    RandomCommon <- rdirichlet(NumberOfSimulations, c(1,1)) # this value will not
be used further, but it allow to assign something

    RandomRare <- rdirichlet(NumberOfSimulations, c(1,1))

  }


  if(sum(is(HairFFGParameters)==c("numeric", "vector"))==2){

    RandomHairFFG <- rdirichlet(NumberOfSimulations, HairFFGParameters)
#simulated dirichlet according to the chosen parameters for the node "Hair_FFGs"

  }

  else {

    RandomHairFFG <- rdirichlet(NumberOfSimulations, c(1,1,1,1))

  }


  if(sum(is(SizeHairFFGParameters)==c("numeric", "vector"))==2){

    RandomSizeFFG <- rdirichlet(NumberOfSimulations, SizeHairFFGParameters)

  }
```

```
  else {
    RandomSizeFFG <- rdirichlet(NumberOfSimulations, c(1,1))
  }

  ChoiceOfPropositions <- get.states(BN,"Prop") # to get the states number corresponding the the choices set in the call of the function, for the defence we can choose between [2] and [3].

  #Definition of the output variables for this function (the *9 comes from the number of cases considered with the loop using k)

  NumberOfState <- length(get.states(BN,"Results_Hair")) # number of states in the targetNode
  SimuLR <- matrix(0, nrow= NumberOfSimulations*9, ncol= NumberOfState) #matrix of results
  MPUsed <- matrix(0, nrow= NumberOfSimulations*9, ncol=1) #matrix with the frequency used
  CaseUsed <- matrix(0, nrow= NumberOfSimulations*9, ncol=1) #matrix with the frequency used

  #to keep a trace of the Rarity and Defense propositions, they will remain constant throughout as they are part of the call of the function
  #We use the function RunMultipleSimulations4 to cover all options for Rarity and DefenceProp
```

```
  RarityUsed <- matrix(Rarity, nrow= NumberOfSimulations*9, ncol=1) #matrix with the Rarity used

  PropUsed <- matrix(ChoiceOfPropositions[DefenceProposition], nrow= NumberOfSimulations*9, ncol=1) #matrix with the defense proposition used


  #Specification of the _table that will be updated with simulated parameters


  Hair_FFGs_table <- get.table(BN, "Hair_FFGs")

  RMP_FFG_table <- get.table(BN, "Hair_FFG_matching_Mask")

  SizeHair_FFGs_table <- get.table(BN, "SizeFFG_Hair")

  Transfer_Head_table <- get.table(BN,"Transfer_Head")

  TimeRecovery_table <- get.table(BN,"TimeRecovery")

  TimeWear_table <- get.table(BN,"TimeWear")

  Washed_table <- get.table(BN,"Washed")


  #Start of the simulations


  for (i in 1:NumberOfSimulations){


    #NumberOfSimulations: keep in mind that the total number of simulations will be that value x 9 (for each case considered)


    initialize.domain(BN) # to initiatilize the BN
```

```
   #Dealing with the match probability- We update the parameters regardless of the case handled (rare fibres or common fibres)

   mp1 <- RandomCommon[i] #Match probability for "common fibres"

   mp2 <- RandomRare[i] #Match probability for  "rare fibres"

      #Assign in the RMP as a function of the vector of log10_match_probabilities (beware the factors in front!)

   RMP_FFG_table$Freq[3] <- mp2

   RMP_FFG_table$Freq[4] <- 1-mp2


   #to get the values for 2-5 FFGs and >5 FFGs (max 20) FFGs, it calls the function GetProbaFFG and use the mean value

   mp2b <- mean(GetProbaFFG(mp2, range=c(2:5)))

   mp2c <- mean(GetProbaFFG(mp2, range=c(6:20)))


   # assign in the table accordingly

   RMP_FFG_table$Freq[5] <- mp2b

   RMP_FFG_table$Freq[6] <- 1-mp2b

   RMP_FFG_table$Freq[7] <- mp2c

   RMP_FFG_table$Freq[8] <- 1-mp2c


   #Idem for the "Common" fibres
```

```
    RMP_FFG_table$Freq[11] <- mp1

    RMP_FFG_table$Freq[12] <- 1-mp1


    #to get the values for 2-5 FFGs and >5 FFGs (max 20) FFGs, it calls the function GetProbaFFG and use the mean value

    mp1b <- mean(GetProbaFFG(mp1, range=c(2:5)))

    mp1c <- mean(GetProbaFFG(mp1, range=c(6:20)))


    RMP_FFG_table$Freq[13] <- mp1b

    RMP_FFG_table$Freq[14] <- 1-mp1b

    RMP_FFG_table$Freq[15] <- mp1c

    RMP_FFG_table$Freq[16] <- 1-mp1c


    # the two RMP vectors in the call start with c(x,x),an object with "numeric" "vector" attributes. If only one is specified with c(x,x) then nothing will be updated


    if(sum(is(CommonFibresParameters)==c("numeric", "vector"))+sum(is(CommonFibresParameters)==c("numeric", "vector"))==4){

      set.table(BN, "Hair_FFG_matching_Mask", RMP_FFG_table) #update the table according to the new parameters

    }

    # no else, because if the condition is not met, we change nothing in the table
```

```
    #Dealing with the FFGs

    Hair_FFGs_table$Freq[1:4] <- RandomHairFFG[i,] # assign to the table the data from the Dirichlet

    if(sum(is(HairFFGParameters)==c("numeric", "vector"))==2){   #all vector in the call starting with c(x,x) is an object with "numeric" "vector" attributes

      set.table(BN, "Hair_FFGs", Hair_FFGs_table) #update of the table ""Hair_FFGs" #update the table according to the new parameters

    }


    #Dealing with the size of FFGS

    SizeHair_FFGs_table$Freq[1] <- RandomSizeFFG[i]

    SizeHair_FFGs_table$Freq[2] <- 1-RandomSizeFFG[i]


    if(sum(is(SizeHairFFGParameters)==c("numeric", "vector"))==2){   #all vector in the call starting with c(x,x) is an object with "numeric" "vector" attributes

      set.table(BN, "SizeFFG_Hair", SizeHair_FFGs_table)  #update of the table ""Hair_FFGs" #update the table according to the new parameters

    }


#Dealing with the transfer probabilities

    # we will simulate according to Dirichlet with parameters obtained from as.vector(t(TransferParameters_1[j]))

    # j will range from 1 to 24 to cover all the columns of the CPT
```

```
   # Compared to previously, we will simulate from the Dirichlet on the fly in the loop at each itteration [i] and not intially before the loop as for the other nodes

   # in R, the CPT is made of 96 lines corresponding to the 4*24. All parameters are grouped by 4


   for (j in 1:24){

     b <- j*4 #upper end

     a <- b-3 #lower end


     if(sum(TransferParameters_1[j])==1){ # if in the parameter matrix we have (1,0,0)

       Values <- t(TransferParameters_1[j])

     }

     else{Values <- rdirichlet(1,as.vector(t(TransferParameters_1[j])))}

     Transfer_Head_table$Freq[a:b]<- Values #generate on the fly according to the specified Dirichlet distribution

   }


   if(sum(is(TransferParameters)==c("data.frame", "list", "oldClass", "vector"))==4){ #all vector in the call starting with c(x,x) is an object with "data.frame" "list" "oldClass"   "vector" attributes

     set.table(BN, "Transfer_Head", Transfer_Head_table)  #update of the table "Transfer_Head" #update the table according to the new parameters

   } #otherwise we don't update the parameters (when the call is "NA")
```

```
# Now we can simulate one scenario


#We can set the finding for "Rarity"
if (Rarity=="Rare fibres") {
  set.finding(BN,"Rarity", "Rare fibres") #set Rarity to "Rare Fibres"
}

if (Rarity=="Common fibres") {
  set.finding(BN,"Rarity", "Common fibres") #set Rarity to "Common Fibres"
}
# To get the frequency actually used after the above set finding
set.finding(BN,"Hair_FFGs", "1 FFG") #pretend that there is only one group in the background
propagate(BN)
mp3 <- get.belief(BN, "Hair_FFG_matching_Mask")[1] # Get the frequency used, given on position 1 for matching fibres (one group)



#Dealing with the choice of cases (k in 1:9 in total as per file "List of cases.xlsx")


for (k in 1:9){
  CaseNumber <- k+2 #to start with the appropriate columns in cases (V1 and V2 being reserved for the names)
```

```
TimeRecovery_table$Freq[1:2]<- Cases[1:2,CaseNumber]

TimeWear_table$Freq[1:2]<- Cases[3:4,CaseNumber]

Washed_table$Freq[1:2]<- Cases[5:6,CaseNumber]


if(sum(is(Cases)==c("data.frame", "list", "oldClass", "vector"))==4){   #all vector in the call starting with c(x,x) is an object with "data.frame" "list"       "oldClass" "vector" attributes

  set.table(BN, "TimeRecovery", TimeRecovery_table)  #update of the table

  set.table(BN, "TimeWear", TimeWear_table)

  set.table(BN, "Washed", Washed_table)

} # Otherwise the tables will bot be changed and will remain as set in the BN


initialize.domain(BN) # to initialize the BN for each itterations


#We can set the finding for "Rarity" again and moving with Hp and Hp


if (Rarity=="Rare fibres") {

  set.finding(BN,"Rarity", "Rare fibres") #set Rarity to "Rare Fibres"

}


if (Rarity=="Common fibres") {

  set.finding(BN,"Rarity", "Common fibres") #set Rarity to "Common Fibres"

}
```

set.finding(BN,"Hp_Hd", "Hp") #set Hp = true

propagate(BN)

Prob_Results_Hair_Hp <- get.belief(BN, "Results_Hair")

#Defense proposition

set.finding(BN,"Hp_Hd", "Hd") #set Hd = true

#Dealing with the choice of the defense proposition, beware the BN need to have both defense possibilities available (1 and 1, so we can set findings - otherwise with 1,0 the system will not allow setting findings)

set.finding(BN,"Prop", ChoiceOfPropositions[DefenceProposition]) #set Hd corresponding to either [2] or [3]

 # We can now propagate the BN

propagate(BN)

Prob_Results_Hair_Hd <- get.belief(BN, "Results_Hair")

rownumber_for_results <- ((9*i)-9)+k # to set the rownumber of the results matrix at the appropriate number given i and k

SimuLR[rownumber_for_results,] <- Prob_Results_Hair_Hp/Prob_Results_Hair_Hd

MPUsed[rownumber_for_results,] <- mp3

```
    CaseName <- as.vector(Cases[,2])

    CaseName <- paste(CaseName[Cases[, CaseNumber]>0], collapse="--") #will
create a text value explaining the chosen states

    CaseUsed[rownumber_for_results,] <- CaseName

   }


 }

 SimuLR <- list(LR=SimuLR, MP1=MPUsed, DefProp=PropUsed,
RarityFibre=RarityUsed, Case=CaseUsed)

 SimuLR # output of the function

}


RunMultipleSimulations4 <- function (BN, NumbSim=1000,
HairFFGParameters="NA", SizeHairFFGParameters="NA",
CommonFibresParameters="NA", RareFibresParameters="NA",
TransferParameters="NA", Cases="NA") {


 Results <- list()

 sim1 <- SimulateLR_Headhair4(BN, NumberOfSimulations= NumbSim,
DefenceProposition=2, HairFFGParameters= HairFFGParameters,
SizeHairFFGParameters= SizeHairFFGParameters, CommonFibresParameters=
CommonFibresParameters, RareFibresParameters= RareFibresParameters,
TransferParameters=TransferParameters, Cases=Cases, Rarity="Common fibres")

 sim2 <- SimulateLR_Headhair4(BN, NumberOfSimulations= NumbSim,
DefenceProposition=3, HairFFGParameters= HairFFGParameters,
SizeHairFFGParameters= SizeHairFFGParameters, CommonFibresParameters=
```

```
CommonFibresParameters, RareFibresParameters= RareFibresParameters,
TransferParameters=TransferParameters, Cases=Cases, Rarity="Common fibres")

  sim3 <- SimulateLR_Headhair4(BN, NumberOfSimulations= NumbSim,
DefenceProposition=2, HairFFGParameters= HairFFGParameters,
SizeHairFFGParameters= SizeHairFFGParameters, CommonFibresParameters=
CommonFibresParameters, RareFibresParameters= RareFibresParameters,
TransferParameters=TransferParameters, Cases=Cases, Rarity="Rare fibres")

  sim4 <- SimulateLR_Headhair4(BN, NumberOfSimulations= NumbSim,
DefenceProposition=3, HairFFGParameters= HairFFGParameters,
SizeHairFFGParameters= SizeHairFFGParameters, CommonFibresParameters=
CommonFibresParameters, RareFibresParameters= RareFibresParameters,
TransferParameters=TransferParameters, Cases=Cases, Rarity="Rare fibres")


  Results <- mapply(rbind, sim1, sim2, sim3, sim4,SIMPLIFY=FALSE) #to
concatenate the outputs but keeping the list format

  Results

}


SummaryStatisticsResults <- function(BN, Data) {

  #Preparation of the data

  DataforSummary <- data.frame(Data$LR, Data$DefProp, Data$RarityFibre,
Data$MP, Data$Case)

  names(DataforSummary) <- c(get.states(BN,"Results_Hair"),"DefProp",
"RarityFibre", "Frequency","Case")

  DataforSummary$DefProp <- as.factor(DataforSummary$DefProp) # to have Hp1
and Hp2 as factors
```

```
  DataforSummary$RarityFibre <- as.factor(DataforSummary$RarityFibre) #idem for
RarityFibre

  DataforSummary$Case <- as.factor(DataforSummary$Case) #idem for Case

  levels(DataforSummary$DefProp) <- c("Hd1", "Hd2") # to adapt the legend to be
shorter

  #levels(DataforSummary$Case) <- paste("Case_",c(5,4,3,2,1,9,8,7,6),sep="") # to
adapt the legend to be shorter

  levels(DataforSummary$Case) <-  c("C5_R1-3_W14_nWa","C4_R1-
3_W14_Wa","C3_R1-3_W7_nWa",
                                    "C2_R1-3_W7_Wa","C1_Unspecified","C9_R>7_W14_nWa",
                                    "C8_R>7_W14_Wa","C7_R>7_W7_nWa","C6_R>7_W7_Wa")


  # to adapt the legend to be coded names as in "List of cases.xlsx"

  Results <- list() # we will create on object in the list per outcome


  for (i in 1:11){

    DataforSummary_per_outcome <- data.frame(DataforSummary[,i],
DataforSummary$DefProp, DataforSummary$RarityFibre,
DataforSummary$Frequency, DataforSummary$Case)

    names(DataforSummary_per_outcome) <- c("LR","DefProp", "RarityFibre",
"Frequency", "Case")

      temp1 <- ddply(DataforSummary_per_outcome, c("DefProp",
"RarityFibre","Case"), function(x) summary(x[,1])) #require the ply library

    temp2 <- ddply(DataforSummary_per_outcome, c("DefProp",
"RarityFibre","Case"), function(x) IQR(x[,1])) # to get IQR, will be given in temp2$V1
```

```
    names(temp2) <- names(temp2) <- c("DefProp", "RarityFibre", "Case", "IQR" )

    temp <- cbind(temp1,temp2$IQR)

    names(temp) <- c("DefProp", "RarityFibre", "Case", "Min.", "1st Qu.", "Median",
"Mean", "3rd Qu.", "Max.", "IQR" )


    Results[[i]] <- temp


  }


  return(Results)

}


CompileResultsFromSetsOfSimulation <- function (BN, DatasetsNames,
ChangedNames=DatasetsNames) {


  nbObjects <- length(DatasetsNames)

  Res1 <- get(DatasetsNames[1], envir = parent.env(environment())) #to obtain the
content of the object corresponding to DatasetsNames[i] in the global env.

  Results <- SummaryStatisticsResults(BN, Res1) # to get the first structure

  SimulationName <- rep(ChangedNames[1],nrow(Results[[1]])) # to add a column
with the simulation name (so we can sort them)


  # We put the name of the results as a additional column (to be used as a factor
later)
```

```
  for (j in 1:11){
    Results[[j]] <-cbind(Results[[j]], SimulationName)
  }

  for (i in 2:nbObjects){
    Res2 <- get(DatasetsNames[i], envir = parent.env(environment())) #to obtain the content of the object corresponding to DatasetsNames[i] in the global env.
    IndividualResults2 <- SummaryStatisticsResults(BN, Res2)Â # to get the first structure
    SimulationName <- rep(ChangedNames[i],nrow(IndividualResults2[[1]]))
    for (j in 1:11){
      IndividualResults2[[j]] <-cbind(IndividualResults2[[j]], SimulationName)
    }
    Results <- mapply(rbind, Results, IndividualResults2, SIMPLIFY=FALSE)
  }
  Results
}

PlotResults4_LR <- function(BN, Data, FontSize=7, minlog10LR=-3, maxlog10LR=5, fatten_value=0) {
  DataforPlot <- data.frame(Data$LR, Data$DefProp, Data$RarityFibre, Data$MP, Data$Case)
  names(DataforPlot) <- c(get.states(BN,"Results_Hair"),"DefProp", "RarityFibre", "Frequency","Case")
```

```
  Names <- names(DataforPlot)

  DataforPlot$DefProp <- as.factor(DataforPlot$DefProp) # to have Hp1 and Hp2 as
factors

  DataforPlot$RarityFibre <- as.factor(DataforPlot$RarityFibre) #idem for RarityFibre

  DataforPlot$Case <- as.factor(DataforPlot$Case) #idem for Case

  levels(DataforPlot$DefProp) <- c("Hd1", "Hd2") # to adapt the legend to be shorter

  #levels(DataforPlot$Case) <- paste("Case_",c(5,4,3,2,1,9,8,7,6),sep="") # to adapt
the legend to be shorter

  levels(DataforPlot$Case) <-  c("C5_R1-3_W14_nWa","C4_R1-3_W14_Wa","C3_R1-
3_W7_nWa",
                                 "C2_R1-3_W7_Wa","C1_Unspecified","C9_R>7_W14_nWa",
                                 "C8_R>7_W14_Wa","C7_R>7_W7_nWa","C6_R>7_W7_Wa")


  theme_set(theme_bw(24))

  p1 <- list() #Hd1

  p2 <- list() #Hd2


  for (i in 1:11){

    dataPlot <- data.frame(DataforPlot[,i], DataforPlot$DefProp,
DataforPlot$RarityFibre, DataforPlot$Frequency, DataforPlot$Case)

    names(dataPlot) <- c("LR","DefProp", "RarityFibre", "Frequency", "Case")

    dataPlot <- dataPlot[dataPlot$DefProp=="Hd1",]

    #Now we can select the cases of interest
```

```
    dataPlot <- subset(dataPlot, Case %in% c("C3_R1-3_W7_nWa", "C2_R1-3_W7_Wa","C1_Unspecified","C7_R>7_W7_nWa","C6_R>7_W7_Wa"))

    #Drop unused levels

    dataPlot$Case <- droplevels(dataPlot$Case)

    p1[[i]] <- ggplot(aes(y = log10(LR), x = reorder(Case), fill = RarityFibre, color = RarityFibre), data = dataPlot) + geom_boxplot(outlier.size=0.5, outlier.colour = NULL, show_guide = FALSE, position=position_dodge(1), fatten=fatten_value) # FALSE to remove the legend, color is dealing with the colour of borders of boxplots and outliers

    p1[[i]] <- p1[[i]] + geom_hline(xintercept = 0, size=0.5, linetype=3)

    p1[[i]] <- p1[[i]] + coord_flip() #to put LR on horizontal axis

    p1[[i]] <- p1[[i]] + scale_y_continuous(name="\nLog10(LR)", limits = c(minlog10LR, maxlog10LR), breaks = minlog10LR:maxlog10LR) # specify range and ticks on yaxis

    p1[[i]] <- p1[[i]] + scale_x_discrete(name="Defense Prop = Hd1\n")

    p1[[i]] <- p1[[i]] + ggtitle(paste("Findings: ",names(DataforPlot)[i],"\n"))

    p1[[i]] <- p1[[i]] + theme(axis.text=element_text(size=FontSize),

                               axis.title=element_text(size=FontSize+3),

                               plot.title=element_text(size=FontSize+3))

    #add seperation lines (less needed under Hd1)

    p1[[i]] <- p1[[i]] + geom_vline(xintercept=c(1.5,2.5,3.5,4.5),linetype = "longdash",colour="grey")

  }


  for (i in 1:11){
```

```
    dataPlot <- data.frame(DataforPlot[,i], DataforPlot$DefProp,
DataforPlot$RarityFibre, DataforPlot$Frequency, DataforPlot$Case)

    names(dataPlot) <- c("LR","DefProp", "RarityFibre", "Frequency", "Case")

    dataPlot <- dataPlot[dataPlot$DefProp=="Hd2",]

    p2[[i]] <- ggplot(aes(y = log10(LR), x = reorder(Case), fill = RarityFibre, color =
RarityFibre), data = dataPlot) + geom_boxplot(outlier.size=0.5, outlier.colour =
NULL, show_guide = FALSE, position=position_dodge(1), fatten=fatten_value) #
FALSE to remove the legend, color is dealing with the colour of borders of boxplots
and outliers

    p2[[i]] <- p2[[i]] + geom_hline(xintercept = 0, size=0.5, linetype=3)

    p2[[i]] <- p2[[i]] + coord_flip() #to put LR on horizontal axis

    p2[[i]] <- p2[[i]] + scale_y_continuous(name="\nLog10(LR)", limits =
c(minlog10LR, maxlog10LR), breaks = minlog10LR:maxlog10LR) # specify range
and ticks on yaxis

    p2[[i]] <- p2[[i]] + scale_x_discrete(name="Defense Prop = Hd2\n")

    p2[[i]] <- p2[[i]] + ggtitle(paste("Findings: ",names(DataforPlot)[i],"\n"))

    p2[[i]] <- p2[[i]] + theme(axis.text=element_text(size=FontSize),

                               axis.title=element_text(size=FontSize+3),

                               plot.title=element_text(size=FontSize+3))

    p2[[i]] <- p2[[i]] + geom_vline(xintercept=c(1.5,2.5,3.5,4.5,5.5,6.5,7.5,8.5),linetype =
"longdash",colour="grey")

  }

  return(list(p1,p2))

}
```

```
PlotResults4_SummaryStat_median <- function(BN, DataSummary, FontSize=7,
DotSize=3, show_guide = FALSE) {

  theme_set(theme_bw(24))

  Names_outcome <- get.states(BN,"Results_Hair")

  p1 <- list()

  for (i in 1:11){ #for each outcome

    dataPlot <- DataSummary[[i]]

    #Remove cases that are not needed under Hd1

    dataPlot <- filter(dataPlot, !(DefProp== "Hd1" & Case %in% c("C4_R1-
3_W14_Wa","C5_R1-3_W14_nWa","C8_R>7_W14_Wa","C9_R>7_W14_nWa")))


    p1[[i]] <- ggplot(aes(y = log10(Median), x = SimulationName, color=reorder(Case)),
data = dataPlot)

    p1[[i]] <- p1[[i]] + geom_jitter(size= DotSize, show_guide = show_guide, position =
position_jitter(w = 0.2, h = 0))

    p1[[i]] <- p1[[i]] + scale_y_continuous(name="Log10 of Median of LRs\n") #
specify the name on yaxis

    p1[[i]] <- p1[[i]] + scale_x_discrete(name="\nName of the simulation run")

    p1[[i]] <- p1[[i]] + ggtitle(paste("Findings: ",Names_outcome[i],"\n"))

    p1[[i]] <- p1[[i]] + theme(axis.text=element_text(size=FontSize-2),

                               axis.title=element_text(size=FontSize+3),

                               plot.title=element_text(size=FontSize+3),

                               legend.title=element_blank(),

                               legend.text=element_text(size=FontSize))
```

```
   p1[[i]] <- p1[[i]] + facet_grid(DefProp ~ RarityFibre)+ theme(strip.text.x =
element_text(size = FontSize),
                                                    strip.text.y = element_text(size = FontSize),
                                                    strip.background = element_rect(colour =
"#707070", fill = "#f3f3f3"))
  }
  return(p1)
}


PlotResults4_SummaryStat_IQR <- function(BN, DataSummary, FontSize=7,
DotSize=3, show_guide = FALSE) {
  theme_set(theme_bw(24))
  Names_outcome <- get.states(BN,"Results_Hair")
  p1 <- list()
  for (i in 1:11){ #for each outcome
    dataPlot <- DataSummary[[i]]
    #Remove cases that are not needed under Hd1
    dataPlot <- filter(dataPlot, !(DefProp== "Hd1" & Case %in% c("C4_R1-
3_W14_Wa","C5_R1-3_W14_nWa","C8_R>7_W14_Wa","C9_R>7_W14_nWa")))
       p1[[i]] <- ggplot(aes(y = IQR/Median, x = SimulationName, color=reorder(Case)),
data = dataPlot)
    p1[[i]] <- p1[[i]] + geom_jitter(size= DotSize, show_guide = show_guide, position =
position_jitter(w = 0.2, h = 0))
```

```
   p1[[i]] <- p1[[i]] + scale_y_continuous(name="Interquartile range/median\n") # specify the name on yaxis

   p1[[i]] <- p1[[i]] + scale_x_discrete(name="\nName of the simulation run")

   p1[[i]] <- p1[[i]] + ggtitle(paste("Findings: ",Names_outcome[i],"\n"))

   p1[[i]] <- p1[[i]] + theme(axis.text=element_text(size=FontSize-2),

                              axis.title=element_text(size=FontSize+3),

                              plot.title=element_text(size=FontSize+3),

                              legend.title=element_blank(),

                              legend.text=element_text(size=FontSize))

   p1[[i]] <- p1[[i]] + facet_grid(DefProp ~ RarityFibre)+ theme(strip.text.x = element_text(size = FontSize),

                                                                 strip.text.y = element_text(size = FontSize),

                                                                 strip.background = element_rect(colour = "#707070", fill = "#f3f3f3"))

  }

  return(p1)

}

PlotResults_Simu <- function(BN, Data, FontSize=7, minlog10LR=-3, maxlog10LR=5, LegendPosition="bottom") {

  DataforPlot <- Data

  names(DataforPlot) <- c(get.states(BN,"Results_Hair"),"Frequency", "DefProp", "RarityFibre","Case","sim")

  Names <- names(DataforPlot)

  DataforPlot$DefProp <- as.factor(DataforPlot$DefProp) # to have Hd as factors
```

```
  DataforPlot$RarityFibre <- as.factor(DataforPlot$RarityFibre) #idem for RarityFibre

  DataforPlot$Case <- as.factor(DataforPlot$Case) #idem for Zone

  DataforPlot$sim <- as.factor(DataforPlot$sim) #idem for sim

  levels(DataforPlot$DefProp) <- c("Hd1", "Hd2") # to adapt the legend to be shorter

  #levels(DataforPlot$Case) <- paste("Case_",c(5,4,3,2,1,9,8,7,6),sep="") # to adapt the legend to be shorter

  levels(DataforPlot$Case) <-  c("C5_R1-3_W14_nWa","C4_R1-3_W14_Wa","C3_R1-3_W7_nWa",
                                 "C2_R1-3_W7_Wa","C1_Unspecified","C9_R>7_W14_nWa",
                                 "C8_R>7_W14_Wa","C7_R>7_W7_nWa","C6_R>7_W7_Wa")

  levels(DataforPlot$RarityFibre) <- c("Common", "Rare") # to adapt the legend to be shorter

  theme_set(theme_bw(24))

  p1 <- list() #Hd1

  p2 <- list() #Hd2


  for (i in 1:11){

    dataPlot <- data.frame(DataforPlot[,i], DataforPlot$DefProp, DataforPlot$RarityFibre, DataforPlot$Frequency, DataforPlot$Case, DataforPlot$sim)

    names(dataPlot) <- c("LR","DefProp", "RarityFibre","Frequency", "Case", "sim")

    dataPlot <- dataPlot[dataPlot$DefProp=="Hd1",]

    #Now we can select the cases of interest
```

```
    dataPlot <- subset(dataPlot, Case %in% c("C3_R1-3_W7_nWa", "C2_R1-3_W7_Wa","C1_Unspecified","C7_R>7_W7_nWa","C6_R>7_W7_Wa"))

    #Drop unused levels

    dataPlot$Case <- droplevels(dataPlot$Case)


    p1[[i]] <- ggplot(aes(y = log10(LR), x = reorder(Case), fill = sim, color = sim), data = dataPlot) + geom_boxplot(outlier.size=0.5, outlier.colour = NULL, show_guide = TRUE, position=position_dodge(1)) # FALSE to remove the legend, color is dealing with the colour of borders of boxplots and outliers

    p1[[i]] <- p1[[i]] + coord_flip() #to put LR on horizontal axis

    p1[[i]] <- p1[[i]] + facet_grid(RarityFibre~., scales="free", space="free")

    p1[[i]] <- p1[[i]] + scale_y_continuous(name="\nLog10(LR)", limits = c(minlog10LR, maxlog10LR), breaks = minlog10LR:maxlog10LR) # specify range and ticks on yaxis

    p1[[i]] <- p1[[i]] + scale_x_discrete(name="Defense proposition = Hd1\n")

    p1[[i]] <- p1[[i]] + ggtitle(paste("Findings: ",names(DataforPlot)[i],"\n"))

    p1[[i]] <- p1[[i]] + theme(axis.text=element_text(size=FontSize-2),
                               axis.title=element_text(size=FontSize+3),
                               plot.title=element_text(size=FontSize+3),
                               legend.title=element_blank(),
                               legend.text=element_text(size=FontSize),
                               legend.position = LegendPosition,
                               strip.text.y = element_text(size = FontSize),
```

```
                    strip.background = element_rect(colour = "#707070", fill =
"#f3f3f3"))

   #add seperation lines (less needed under Hd1)

   p1[[i]] <- p1[[i]] + geom_vline(xintercept=c(1.5,2.5,3.5,4.5),linetype =
"longdash",colour="grey")

  }

  for (i in 1:11){

   dataPlot <- data.frame(DataforPlot[,i], DataforPlot$DefProp,
DataforPlot$RarityFibre, DataforPlot$Frequency, DataforPlot$Case,
DataforPlot$sim)

   names(dataPlot) <- c("LR","DefProp", "RarityFibre","Frequency", "Case", "sim")

   dataPlot <- dataPlot[dataPlot$DefProp=="Hd2",]

   p2[[i]] <- ggplot(aes(y = log10(LR), x = reorder(Case), fill = sim, color = sim), data =
dataPlot) + geom_boxplot(outlier.size=0.5, outlier.colour = NULL, show_guide =
TRUE, position=position_dodge(1)) # FALSE to remove the legend, color is dealing
with the colour of borders of boxplots and outliers

   p2[[i]] <- p2[[i]] + coord_flip() #to put LR on horizontal axis

   p2[[i]] <- p2[[i]] + facet_grid(RarityFibre~., scales="free", space="free")

   p2[[i]] <- p2[[i]] + scale_y_continuous(name="\nLog10(LR)", limits =
c(minlog10LR, maxlog10LR), breaks = minlog10LR:maxlog10LR) # specify range
and ticks on yaxis

   p2[[i]] <- p2[[i]] + scale_x_discrete(name="Defense proposition = Hd2\n")

   p2[[i]] <- p2[[i]] + ggtitle(paste("Findings: ",names(DataforPlot)[i],"\n"))

   p2[[i]] <- p2[[i]] + theme(axis.text=element_text(size=FontSize-2),

                    axis.title=element_text(size=FontSize+3),
```

```
                    plot.title=element_text(size=FontSize+3),

                    legend.title=element_blank(),

                    legend.text=element_text(size=FontSize),

                    legend.position = LegendPosition,

                    strip.text.y = element_text(size = FontSize),

                    strip.background = element_rect(colour = "#707070", fill =
"#f3f3f3"))

   p2[[i]] <- p2[[i]] + geom_vline(xintercept=c(1.5,2.5,3.5,4.5,5.5,6.5,7.5,8.5),linetype =
"longdash",colour="grey")

  }

  return(list(p1,p2))
```