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# A graphical model based on performance shaping factors for assessing human reliability

Subeer Rangra, Mohamed Sallak, Walter Schön and Frédéric Vanderhaegen

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## Abstract

Human reliability assessment (HRA) is an aspect of risk analysis concerned with identifying, analyzing and quantifying the causes, contributions and occurrence of human failures. Applications of existing HRA methods are often domain-specific, and difficult to implement even for experts. Also, due to the lack of empirical data, managing uncertainty is important, if not essential. In view of such limitations, we propose a new and comprehensive HRA methodology acronymed 'PRELUDE' (Performance shaping factor based human REliability assessment using vaLUation-based systEms). It is a quantitative and qualitative HRA methodology, applied to railway operations. The qualitative part characterizes a safety critical situation using Performance Shaping Factors (PSFs). The PSFs are identified from domain specific human factors and PSF-based studies. The quantitative proposition is a framework of a graphical model (Valuation-based System) and belief functions theory. Appropriate representation and handling of all types of uncertainties, and combination of conflicting expert opinions is considered in this framework. To aid in the choice of appropriate combination method, combined expert data is discussed and compared using quantitative metrics. PRELUDE allows quantifying a human failure event given an operational context. Sensitivity analysis is used to establish a priority ranking among the PSFs. Finally, application on a railway accident scenario describes usage and applicability of our proposition.

## Index Terms

human reliability analysis, performance shaping factors, human factors, railway accident, valuation-based Systems, belief functions theory

## ACRONYMS

<b>ATHEANA</b>	A Technique for Human Error Analysis
<b>AWS</b>	Automatic Warning Systems
<b>BBN</b>	Bayesian Belief Networks
<b>BFT</b>	Belief Functions Theory
<b>BPA</b>	Basic Probability Assignments
<b>CPT</b>	Conditional Probability Tables
<b>CREAM</b>	Cognitive Reliability and Error Analysis Method
<b>EC</b>	Error Contexts
<b>EN</b>	Evidential Network
<b>EUAR</b>	European Union Agency for Railways

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35	<b>FTA</b>	Fault Tree Analysis
36	<b>GTT</b>	Generic Task Type
37	<b>HEP</b>	Human Error Probability
38	<b>HEART</b>	Human Error Assessment and Reduction Technique
39	<b>HERA</b>	Human Event Repository and Analysis
40	<b>HFE</b>	Human Failure Event
41	<b>HFTC</b>	Human Failure Type Context
42	<b>HMI</b>	Human Machine Interface
43	<b>HRA</b>	Human Reliability Analysis
44	<b>HSI</b>	Human System Interface
45	<b>HuPeROI</b>	Human Performance Railway Operational Index
46	<b>MERMOS</b>	Méthode d'Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté (French for
47		Assessment Method for the Performance of Safety Operation)
48	<b>NARA</b>	Nuclear Action Reliability Assessment
49	<b>PRA</b>	Probabilistic Risk Assessment
50	<b>PRELUDE</b>	Performance shaping factor based human reliability assessment using valuation-based systems
51	<b>PIF</b>	Performance Influencing Factors
52	<b>PRELUDE</b>	Performance shaping factor based human REliability assessment using vaLUation-baseD sys-
53		tEms
54	<b>PSF</b>	Performance Shaping Factor
55	<b>RARA</b>	Rail Action Reliability Assessment
56	<b>SPAR-H</b>	Standardized Plant Analysis Risk Model – Human reliability analysis
57	<b>THERP</b>	Technique for Human Error Rate Prediction
58	<b>TRACEr</b>	The technique for the retrospective and predictive analysis of cognitive errors
59	<b>VBS</b>	Valuation-Based Systems
60	<b>VN</b>	Valuation Networks

61

## 62 1 INTRODUCTION

63 **H**UMAN reliability Analysis (HRA) methods have been proposed to systematically incorporate human as part  
64 of a PRA (Probabilistic Risk Assessment) activity [1] [2]. Over the years, research and industrial usage has  
65 driven various changes in HRA methods and underlying techniques. These changes are often categorized into  
66 generations, the ‘first’ – HEART, THERP, SPAR-H, etc. and the ‘second’ – ATHEANA, MERMOS, CREAM, etc.  
67 The first generation methods have been developed with features broadly to THERP such as task analysis, nominal  
68 probabilities for human failures, and adjustment to consider different conditions, etc. The second generation aimed  
69 for a lesser focus on individual errors, and higher on determining the factors and conditions around said errors,  
70 i.e. ‘intrinsically unsafe situation’, and other emphasized cognitive model-based methods aiming for a complete  
71 capture of human performance [3]. Nevertheless, this classification is often not sufficient and a clear identification  
72 of desired and valid techniques is not straightforward [4] [5].

73 There are varied interpretations and propositions to the problem of human error [6]. For example, contrary  
74 to technical component reliability, human reliability is not static but evolves dynamically [7]. A prediction of  
75 human reliability should in that case include models which predict human actions by modeling the act of merging  
76 knowledge gained by a human in a situation [8]. The management thereof focuses on adjustable human-machine  
77 cooperation [9], supporting a human in reasoning/decision-making, and system resilience [10]. However, generally  
78 in the context of HRA, human reliability is often analyzed and defined in terms of the causes of human behavioral  
79 or functional dysfunction [4]. These causes are often characterized as Performance Shaping Factor (PSF). In  
80 most HRA methods, PSFs (or a variant thereof) are used to identify contributors to human errors and to provide  
81 a basis for quantifying those contributors systematically [11]. More specifically, PSFs allow the consideration of  
82 human’s own characteristics along with the context and environment which affect the performance in a negative or

83 positive manner [12]. First generation HRA methods employed PSFs as 'modification factors' to expected human  
84 performance (for HRA – nominal human error probabilities). Most second generation methods also agree that  
85 PSFs are an integral part of the modeling and characterization of errors and play an important role in the process  
86 of human reliability assessment. In general, various recent HRA models, and similar works (viz. Good Practices,  
87 SPAR-H, CREAM, 9-Factor Model, etc.) analyzed in [13] reach a similar conclusion in terms of the need of PSFs  
88 for HRA. The PSFs can then also be viewed as contributing factors that affect an operator's performance, which in  
89 turn leads to an accident/incident. In [14], it is concluded that 18 PSFs were responsible for more than 80% of the  
90 railway accidents they analyzed. A follow-up study [15] with additional data concluded that 12 PSFs, account for  
91 more than 90% of the accidents and incidents. This dual nature of PSFs in characterizing accident safety critical  
92 contexts (frequentist) and accounting for human and situational aspects (shaping human performance in general)  
93 make them an ideal candidate for risk-based decision making.

94 In the second generation of methods the focus was diverted from individual errors to cognitive aspects and  
95 the determination of factors (PSFs or PSF-like) in combination lead to an intrinsically unsafe situation [16]. Data  
96 on identification of contextual information itself can present challenges of uncertainty in the model [17]. Such  
97 a situation can be defined by one or more PSFs [18]. In ATHEANA, Error-forcing context (EFC) is defined as  
98 "... particular combinations of PSFs and plant conditions creating an environment in which unsafe actions are  
99 more likely to occur." EFC aims to present the experts potential interactions among the set of factors that are  
100 significantly different than the usual influence of individual factors. More recently in [19], ECs (Error Contexts)  
101 are derived from empirical data, they are defined as "certain combinations of PSFs those are more likely to produce  
102 human errors than the individual PSFs acting alone." It is further argued in [20] that such a collection of PSFs aids  
103 the experts in the elicitation process. This collection of PSFs as particular sets, characterizing a particular context  
104 or situation is also stated to be easier for usage [19], [21] [22]. In [23], EFCs are appreciate for providing HEP  
105 estimates based on realistic causes and an invaluable input for second generation methods.

106 For the quantification of rare events such as human failures managing uncertainty in data is an important and  
107 challenging task [24] [25] [17]. As remarked in [6]: "lack of data is probably the single most important factor  
108 impeding the development of human reliability indices." Rather recently, this issue was also recognized in the  
109 SPAR-H guide [26]. Some key aspects of quantifying such rate events in a PRA are: evaluation, propagation,  
110 combination and adequate representation [27]. Thus, towards the objectives of an accurate representation and  
111 subsequent evaluation, it is frequently classified by its source. The one originating from natural randomness is  
112 called aleatory and the other originating from a lack of information is termed epistemic. Aleatory is independent  
113 of the analyst's knowledge of the system and is inherent in nature, therefore is sometimes also called irreducible.  
114 Epistemic uncertainty on the other hand can be reduced by improving the model of the system under analysis.  
115 The interest in this classification is to mainly understand what is reducible and what is not. This classification is  
116 often used in the domain of risk analysis [28] [29]. Apart from traditional way of using classical probability theory  
117 [30], there are some alternative ways to represent both types of uncertainties, such as Fuzzy sets and theory [17],  
118 imprecise (interval) probability, possibility, belief function theory, etc. [25] [31]. Further, as concluded in [28]  
119 only the probability bound (latter two) approaches provide an easy interpretation in a practical decision-making  
120 context. The author further argues to "make these alternative approaches operational in a practical decision-making  
121 context, the probability bounds need to be highlighted, not the underlying theories."

122 When working with a lack of empirical data, concepts such as expert elicitation, conditional data, prior prob-  
123 abilities and combination thereof can be employed. Probabilistic graphical modeling frameworks are particularly  
124 easy to use in interaction with domain experts and are more expressive than traditional approaches [32]. Using  
125 expert systems for quantitative HRA can be helpful to improve the transparency and repeatability of assessments  
126 [33]. The usage of Bayesian network in the domain of reliability [34], and particularly HRA has seen significant  
127 growth in recent years [35] [36]. For HRA applications, this variable of interest is a specific failure event (e.g.  
128 an HFE: Human Failure Event) or a generic failure event, or system level inference such as an accident. The  
129 intermediate nodes or parent nodes (parent and child for multi-level BBN) are generally PSFs [36]. The objective  
130 is to compute probability of the occurrence of HFE (e.g. HFE in state true). To do that, once the variables and their  
131 states (or values) are identified, formal conditional relations need to be defined. These relations aim to define the

132 PSFs influencing human performance towards a certain task/function or failure thereof (HFE). Towards this task,  
 133 data-informed approaches to 'build' PSF-HFE relations have also seen recent popularity. In BBNs with discrete  
 134 state nodes, these relations are represented as Conditional Probability Distributions of each child node's state for  
 135 each possible combination of the parents' states and defined using CPTs (Conditional Probability Tables) [36].  
 136 The CPTs formally define these relations, and can vary within the interval  $[0, 1]$ . The exact values thereof can  
 137 define a strong or a weak influence among variables. This data can come from empirical sources as presented in  
 138 [19]. In domains where empirical databases of human failures are rare or are not suitable for formally building  
 139 such relations, expert opinion remains a common and acceptable source [37] [38] [36], and rail transport is not  
 140 an exception. Such frameworks, thus, not only provide an expressive reasoning framework, but also allow for the  
 141 possibility to employ expert and empirical data towards HRA objectives.

142 For a domain like railway, experts can be elicited for data on conditional elements, i.e. failure(s) and factor(s)  
 143 (HFEs and PSFs). In [38] this relational data represents the interpretation of multiple experts' estimates as specific  
 144 probability values on the set of specific states of HFEs and PSFs. In ATHEANA's expert elicitation process  
 145 [20] the HFEs are 'unsafe actions' (UAs), which can be a collection of HFEs. The information, thus desired  
 146 from an expert, is subjective probability on conditional elements of human performance. Generally, in such cases  
 147 multiple experts are consulted, methods to combine expert judgments are thus needed. Some use a group consensus  
 148 approach (a behavioral approach) towards quantifying human actions and treating uncertainty [20]. However, for  
 149 quantitative applications it is generally agreed that mathematical approaches for aggregating expert opinions yield  
 150 more accurate results than behavioral approaches [39]. In [38], such a formal aggregation (hereafter referred as  
 151 combination) of expert estimated probabilities using a Bayesian approach is presented. This combination accounts  
 152 for difference in an expert's belief (what present work hereafter refers to as conflict) and inherent variability in  
 153 HEP estimates. However, in such data combination approaches, it is often required to ensure expert estimates are  
 154 modeled as independent. As concluded in [36], when employing BBN-based or similar approaches, combination  
 155 of data taken from experts needs more work.

156 Despite the high share of human errors in rail accidents [40] [41] [42] domain specific methods of risk  
 157 assessment, considering human factors, towards an operational railway context are very few and rather limited.  
 158 In some cases, error probability of every human action is assigned a fixed value of  $10^{-3}$  [43] [44]. It is said  
 159 to be a hypothetical value representing a generic estimation of HEP, and the assignment is referred to as "...  
 160 a non-written agreement." in industrial railway applications [45]. Furthermore, with increasing complexity of  
 161 systems, such as rail transportation, notions of system-of-systems call for systematic methods to address human  
 162 factors and safety issues [46]. Nevertheless, some relevant works in the railway domain are discussed here. A  
 163 context related HRA model for rail systems is proposed in [44]. They also identified and discussed PSFs and their  
 164 importance to characterize a context. In [47] a qualitative analysis approach has been proposed to account for  
 165 certification requirements. Here, the authors argue for the applicability of a PSF-based model in safety analysis  
 166 of human-barrier interaction. The work in [48] presents a rail industry specific HRA method called Rail Action  
 167 Reliability Assessment (RARA). It is developed adapting the concepts from the HEART approach [49], such as  
 168 GTTs, Error Producing Condition, etc. Recently in [50], a PRA of a high-speed railway line, using a Markovian-  
 169 Bayesian network model was proposed. They considered a driver's state as one of the six possible values, three of  
 170 which were accident states (minor, moderate and severe), the other three distracted, attentive and alert represented  
 171 states of driver's attention. This, from perspective of PSFs, are considered as levels (or values) of a single PSF (i.e.  
 172 attention). To support the quantification of human performance for risk assessment objectives, Human Performance  
 173 Railway Operational Index (HuPeROI), a HRA model, which accounts for PSFs' influence is proposed in [51]. In  
 174 this approach, expert opinion is needed for PSF measurement, weighing factors and relations for quantification.  
 175 Further, in [52] after an extensive discussion of specific HRA methods, the author concludes that very few of  
 176 the analyzed methods were established on the concept of PSFs, while only one (RARA - Rail Action Reliability  
 177 Assessment) can be argued to be a complete methodology. Moreover, there are very few works dedicated to  
 178 quantitative assessment of HRA. Irrespective of the approach employed HRA can help in managing and containing  
 179 the increasing share of human error in transportation accidents. A recent survey by the EUAR's (European Union  
 180 Agency for Railways; old ERA – European Railway Agency) Human Factors Network [53] and amendments to

181 CSM regulation (Common Safety Methods) [54] concur, where, firstly, human factors are recognized to be “main  
 182 contributors to the systematic failures and systematic faults” and owing to the absence of HRA methods used, call  
 183 for “a need of information exchange on criteria for risks related to human errors and their assessment.”

184 Table 1 shows a comparison of a few well-known HRA methodologies. Most HRA methods have commonal-  
 185 ities such as qualitative and quantitative components. Most of the methods do not integrate empirical data in the  
 186 quantitative part. This lack of data is managed by either using data from other models, or by eliciting experts,  
 187 or both. Furthermore, the data obtained from experts is combined, by either using weights/ratings or reaching a  
 188 consensus. Thus, conflict or lack of knowledge of experts is considered implicitly in the model, explicitly when  
 189 eliciting the experts. However, as discussed previously (section 1), most of them do not explicitly consider all  
 190 types of uncertainty. Some recent works (last column of Table 1) have managed this issue by: (i). Using graphical  
 191 models (BBNs) and (ii). Alternative uncertainty theories such as fuzzy theory. Nevertheless, validation, even for  
 192 industrial scale models remains a challenge and the domain specific nature of HRA models limit it further.

193 Thus, the present work focuses on the needs of railway domain. It is also, inspired by the concurrent HRA  
 194 practices, and aims to address some issues of the HRA methods as resumed in Table 1. The original contributions  
 195 of the present work are as follows:

- 196 • Guidelines on identification of PSF (rail-specific) and HFE, from human functions and accident analysis  
 197 reports (most HRA methods provide this step, but are domain-specific in nature, *column 2, Table 1*).
- 198 • A quantitative framework of human reliability using a graphical model, which is easy to use by the experts  
 199 (most use expert elicitation, however, it is not necessarily conditional, or lacks an explicit consideration of  
 200 conflict or uncertainty in model, *column 3, Table 1*).
- 201 • In the absence of data for the rail domain, expert data can be used, thus a combination and uncertainty  
 202 management aspect is needed. Here, a formal combination and transformation approach is proposed, to  
 203 deal with conditional expert data which can work with particularly conflicting opinions and uncertainty  
 204 (this work makes a distinction between aleatory and epistemic nature of the uncertainties explicitly in the  
 205 model and results, contrary to most other complete methodologies *column 4, Table 1*).
- 206 • The VBS/BFT framework allowing for imprecision of data in modeling and quantification as imprecise  
 207 probability intervals (this work makes a distinction between aleatory or epistemic nature of the uncertain-  
 208 ties, explicitly in the model and the results, contrary to most other complete methodologies, *column 5,*  
 209 *Table 1*).
- 210 • Decision-making by using sensitivity analysis to rank PSFs.
- 211 • Applied to a recent high-speed railway accident scenario (most methods are either proposed for the nuclear  
 212 domain, very few are generic, *column 6, Table 1*).

213 Furthermore, all the necessary details are provided in this paper to aid an analyst or an engineer to apply the  
 214 proposed methodology. It can be applied to other transportation systems such as road vehicles. The rest of this paper  
 215 is organized as follows: Section 2 starts off with an overview of the PRELUDE methodology. Subsections thereof  
 216 give the theoretical background of the mathematical framework employed, followed by the main contribution of  
 217 this work. It is explained and concluded with a discussion on the quantification results. The case study is presented  
 218 in Section 3, where the proposed methodology is employed for a retrospective analysis of a railway accident  
 219 scenario. The paper ends with conclusions and perspectives in section 4.

TABLE 1: Comparison of some main HRA methodologies

HRA methodology	Qualitative analysis <sup>1</sup>	Quantification framework <sup>2</sup>	Quantitative support data: source <sup>3</sup>	Uncertainty quantification: in model / in data (theory elements) <sup>4</sup> ◆	Domain application <sup>5</sup>	Validation / type / in domain <sup>6</sup>	Recent extensions or adaptations <sup>7</sup>
THERP [55]	Identification guidelines, task and PSF list	Multiplier	Empirical and expert	No / Yes (probability percentile bounds)	Nuclear ♣	Yes / empirical and expert / nuclear	
SLIM [56]	No lists (optional PSF list)	Multiplier (expert estimate focused)	No (guidelines for experts)	No / Yes (probability bounds)	Nuclear ♣	Yes / expert comparative approach / nuclear	HuPeROI [57]
HEART [49]	Generic task and PSF list	Multiplier	Empirical and expert data	No / Yes (probability percentile bounds)	Generic	Yes / empirical and expert comparative approach / nuclear	RARA [48]
CREAM [58]	Generic task and PSF list	Multiplier	Other (HEART, THERP, etc.)	No / Yes (probability percentile bounds)	Generic ♣	No / No / No / No♣(industrial nuclear, off-shore, space, etc.)	Fuzzy [17], Bayesian [59], CREAM [25]
MERMOS [60]	Identification guidelines, no lists	Conditional probability (expert estimate focused)	No (guidelines for experts, and empirical)	No / Yes (conditional and expert probability)	Nuclear	Yes / empirical and expert / nuclear	
ATHEANA [61]	Identification guidelines, no lists	Conditional probability (expert estimate focused)	No (guidelines for experts)	No / Yes (probability bounds)	Nuclear	No / No / No♣(limited industrial usage in nuclear)	
NARA [18]	Task and PSF list	Multiplier (similar to HEART)	Empirical and expert data	No / Yes (probability percentile bounds)	Nuclear	No / No / No♣(nuclear)	
SPAR-H [62]	Task and PSF list	Multiplier (similar to THERP)	Other method (THERP)	No / Yes (probability distributions)	Nuclear ♣	No / No / No / No♣(nuclear)	Bayesian [63]

<sup>1</sup> *Qualitative analysis* states if the method provides *identification guidelines* for guidance on how to perform task analysis or identify more PSF. If it provides *PSF list* and either a domain specific task list or generic task list based on task characteristics (e.g. diagnosis and action).

<sup>2</sup> *Quantification framework* identifies how the HEP or a similar entity, is computed.

<sup>3</sup> *Quantitative support data* refers to the numerical values available with the model guidelines. They are used by the analysts to quantify based on the context to analyze, their *source* is then specified.

<sup>4</sup> *Uncertainty quantification* is the explicit representation of uncertainty (all types). In *the model*, it is generally epistemic, and *in the data* it is mainly the aleatory uncertainty.

◆ marks, as also remarked in [64], that none of these methods make a distinction between aleatory or epistemic nature of the uncertainties.

<sup>5</sup> *Domain of application* is the domain in which the methodology was first proposed.

♣ indicates if the model has been applied in other domains, other than its domain of initial application.

<sup>6</sup> *Validation* specifies the *type* of validation - if it was done, and the *domain* specific data used to validated the model.

♣ marks the models which have either not completely validated or public reports are not available, however are used in the industrial domain as stated in parentheses.

<sup>7</sup> *Recent extensions or adaptations* of the quantitative part model.

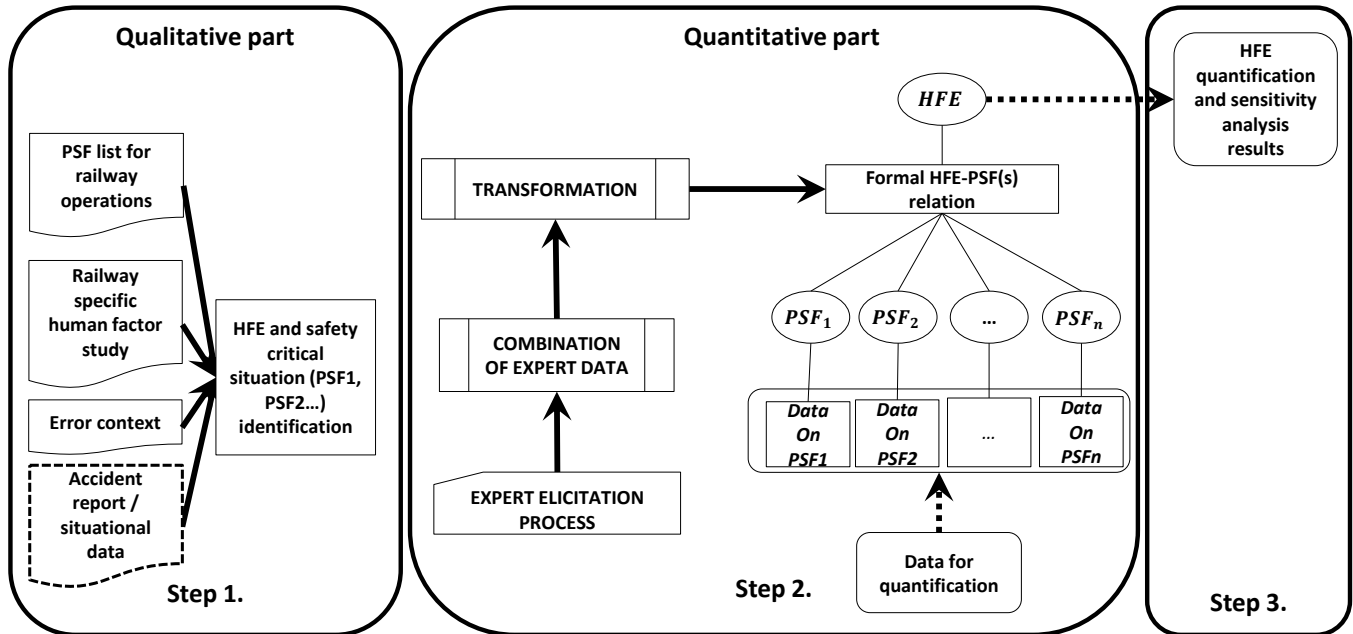


Fig. 1: Overview of the PRELUDE methodology. Step 1. is the qualitative part which aims to identify and characterize a safety critical situation, as HFE and a set of PSFs; Step 2. is the quantitative part, which builds the VBS model from expert data; and Step 3. presents the final HFE quantification and sensitivity analysis results.

## 2 THE PRELUDE METHODOLOGY

220

PRELUDE an acronym for *Performance shaping factor based human Reliability assEssment using vaLUation-baseD systEms*, is a human reliability analysis methodology. The complete methodology entails a qualitative part which accounts for human factors and domain specific considerations, a quantitative part which builds an expert system formalizing expert knowledge and providing formal decision-making. To illustrate the proposition, an overview of the PRELUDE methodology is presented in Figure 1. The qualitative and quantitative propositions are detailed in sections 2.2, 2.3 respectively. Finally quantification using a simple example of the obtained VBS model is discussed in section 2.3.4. PRELUDE methodology, as presented in this paper is applied to the railway domain, but it is also adaptable to other applications.

The qualitative proposition of PRELUDE is centered on PSFs and aims for a characterization of a safety critical situation as a set of PSFs. Appropriate rail-specific sources are employed towards concertizing the human factors background of the methodology. The final variable of interest for PRELUDE as with most HRA models is an HFE. HFEs are predefined in terms of disruptions to component, or system functioning, in which humans are involved, either by causing the failure or not preventing or mitigating the failure, and represents the basic unit of analysis in the HRA. It should be remarked that a noticeable difference must be maintained when performing prospective vs. retrospective analysis, since the objective of the analysis changes the variables and their interpretations. This work presents an retrospective analysis approach. However, for a prospective analysis, a discussion to identify HFEs from a human factors study is also presented.

The quantitative part of PRELUDE aims to adequately address all types of uncertainties, especially epistemic, in modeling human reliability and representing expert opinions. Therefore, present work employs VBS and BFT. Thus, before detailing the proposition, the next section presents a background on BFT, combination methods and basic notions of VBS.

241



## 2.1 Theoretical background

### 2.1.1 Belief Functions Theory and Valuation-based Systems

Dempster-Shafer theory also known as evidence theory or belief functions theory (BFT) was first proposed in [65] and later extended in [66]. It works with upper and lower probability instead of precise values, with generalization of the Bayesian theory of subjective probabilities. The main contents of this theory are the combination and representation of evidence or knowledge. Evidence can be represented by a basic probability (belief) assignment and distinct pieces of evidence are combined by using a combination rule. It can represent and propagate both (epistemic and aleatory) types of uncertainty. It has been applied to different domains of applications, e.g. data fusion [67], reliability and risk analysis [68] [69], and some aspects of HRA [24].

A model based on BFT can be represented with an Evidential Network (EN). This graphical view offers an easy visualization and usage by non-experts in BFT, and an intuitive display of results. Valuation-Based Systems (VBS) were first defined in [70], and later in [71]. Such ENs present some notable qualities when dealing with uncertainty and decision making [24]. Thus, this framework offers adequate tools to work with uncertainty in data and experts. VBS can also be used to represent several domains for combination of the information viz. Bayesian probability theory, possibility theory, BFT, propositional logic, etc. Present work employs BFT, some of its basic elements are detailed as follows:

**Variables and configurations:** A finite set of variables are used to model the problem at hand. Let's represent this set of all the variables in the problem by  $E = \{X_1, X_2, \dots, X_n\}$ . For each decision making problem, inference is then drawn only on a reduced domain of interest  $\Phi$ . For, a variable  $X$ , its frame  $\Omega_X$  holds all possible values of this variable, also called as the frame of  $X$ . Further, for a finite non-empty sub-set of variables  $\Phi \subseteq E$ ,  $\Omega_\Phi$  denotes the Cartesian product of  $\Omega_{X_i}$  for  $X_i$  in  $\Phi$ :  $\Omega_\Phi = \times \{\Omega_X | X \in \Phi\}$ . Here  $\Omega_\Phi$  is called the frame (of discernment) for  $\Phi$ . The elements of  $\Omega_\Phi$  are considered as configuration of  $\Phi$ . For example, a set of variables  $\Phi = \{X_1, X_2\}$ , and their respective frames are:  $\Omega_{X_1} = \{a_1, b_1\}$  and  $\Omega_{X_2} = \{a_2, b_2\}$ , then the frame of discernment for the configuration becomes  $\Omega_\Phi = \{(a_1, a_2), (a_1, b_2), (a_2, b_1), (b_1, b_2)\}$ .

**Valuations and Basic Probability assignments (BPA):** A valuation  $m^{\Omega_\Phi}$  holds the knowledge about the possible values of variables in  $\Phi$ . The set of valuations is denoted by  $\Psi_\Phi = m^{\Omega_\Phi} : \Phi \subseteq E$ . A valuation represented by  $m^{\Omega_\Phi}$  is used to represent knowledge about the possible values (or sets thereof) of  $\Phi$ . The set of all the valuations in the problem set  $\Psi_E$  is further divided into two types of valuations: the direct valuations (posterior or input)  $\Psi_D$  holding the evidence about the input variables; and the prior domain  $\Psi_P$  holding the valuations that relate the variables amongst themselves. In this work direct valuations are valuations on singletons of  $E$  and prior assignments contain at least two elements of  $E$ . Since, VBS can represent knowledge in different domains; it is possible to express valuations using basic probability assignments (BPAs), possibilities, and so on. Present work uses BPAs, which are an example of a non-zero valuation [72], as described below.

Basic Probability Assignments also known as *mass functions* are a way of representing confidence in a certain proposition. That is, the confidence that  $X$  is equal to a certain numerical or a linguistic value of its frame of discernment. For a variable of interest  $X$  and its frame,  $\Omega_X$ , the mapping  $m^{\Omega_X} : 2^{\Omega_X} \rightarrow [0, 1]$  that assigns values to the non-empty sets of the power set  $2^{\Omega_X}$  in the interval  $[0, 1]$ , is called a basic probability assignment. Further, these mappings are such that for a set  $A \in X$  of the power set  $2^{\Omega_X}$ :  $\sum_{A \subseteq \Omega_X} m^{\Omega_X}(A) = 1$ ,  $m^{\Omega_X}(A) > 0$  and  $m^{\Omega_X}(\emptyset) = 0$ . Here,  $A \subseteq \Omega_X$  is called a focal set. A BPA:  $m^{\Omega}(A)$  hence, reflects the degree of belief (subjective probability) committed to that part of the evidence which exactly points to  $A$  and  $A$  only. It may be noted that  $A$  can either be a singleton (a single value  $A = \{a\}$ ) or set of elements ( $A = \{a, b\}, \{a, b, c, \dots\}$ ). A given BPA is similar to a probability function if the focal sets are singletons ( $m(A) : A = \{a\}$ ). Further, BPA  $m^\Omega$  is assigned to each subset of  $2^\Omega$  instead of  $\Omega$ , similar as in classical probability theory. Therefore, each focal set has a BPA (strictly positive) based on the evidence about that focal set. Uncertainty about  $X$ , that is, absolutely no knowledge about the true value of  $X$ , is represented as the BPA assigned to the whole frame i.e.  $\Omega_X$ . It is represented as  $m^{\Omega_X}(\Omega_X)$  or simply belief assigned to  $\Omega_X$ . This also extends towards defining relation between two variables (a configuration). For example, let  $X$  and  $Y$  be two variables with frames  $\Omega_X = \{a, b\}$  and  $\Omega_Y = \{c, d\}$  respectively. The relation between  $X$  and  $Y$  is represented as a joint belief or joint valuation, defined on frame  $\Omega_{XY} = \Omega_Y \times \Omega_X$  that is  $\Omega_{XY} = \{(a, c), (a, d), (b, c), (b, d)\}$  [73]. Here, the joint BPA assignment  $m^{\Omega_{XY}}$  is used to represent the belief about

291 the possible relation(s) given by a subset of  $2^{\Omega_{XY}}$ , between variables  $X$  and  $Y$ . For example,  $m^{\Omega_{XY}}(\{(a, c)\}) = 0.8$ ;  
 292  $m^{\Omega_{XY}}(\{(b, c), (b, d)\}) = 0.2$ , are some BPAs representing joint valuations, given that they respect the conditions  
 293 of its definition. In this work, the term *direct belief structure* will be used when talking about evidence on single  
 294 variable  $X$ , for its frame  $\Omega_X$ . And *configuration belief structure* for referring to joint valuations which represent  
 295 relational evidence between two or more variables. That is, for  $X$  and  $Y$ , the BPA  $m^{\Omega_{XY}}$  and corresponding focal  
 296 sets will be the constituents of a *configuration belief structure*. This structure formally defines the relation between  
 297  $X$  and  $Y$ . Hereafter, these terms *focal set* and *assigned belief or BPA value* are used to refer to the contents of a  
 298 *belief structure*.

299 **Combination and marginalization:** Once the knowledge is represented it has to be combined to make  
 300 inferences. VBS works on valuations as the objects to be combined or marginalized. A mapping  $\oplus : \Psi_1 \times \Psi_2 \rightarrow \Psi$   
 301 is called combination which aims to combine the knowledge. The combination of multiple valuations:  $\oplus \Psi$ , is called  
 302 the joint valuation. As discussed previously, within the framework of BFT there are several combination rules that  
 303 allow combination of knowledge held by several pieces of evidences. Marginalization is a projection on the frame  
 304 of the variable of interest (i.e. it aims to crystallize the available combined knowledge on elements of  $\Omega_X$  for  
 305 the variable of interest  $X$ ). Intuitively, combination corresponds to aggregation of knowledge and marginalization  
 306 corresponds to crystallization thereof [70]. Under BFT-based usage of VBS, any one of various combination  
 307 methods can be employed (more in Section 2.1.2). Although Dempster's rule of combination in BFT corresponds  
 308 to the combination operation in VBS [72] and is what current work employs.

309 **Upper and lower probability bounds:** After performing a combination, the results obtained can be  
 310 interpreted in the form of a lower ( $Pr_{inf}$ ) and upper bound ( $Pr_{sup}$ ) or measure on the variable's values. For two  
 311 subsets  $A$  and  $B$  of the variable of interest  $X$ , these are defined as below:

$$\begin{aligned} Pr_{inf}(A) &= \sum_{B \subset A} m(B) \\ Pr_{sup}(A) &= \sum_{B \cap A \neq \emptyset} m(B) \end{aligned} \quad (1)$$

312 Here, the length of the interval (i.e.  $Pr_{sup}(A) - Pr_{inf}(A)$ ) or belief on the frame:  $m(\Omega_X)$  represents this  
 313 imprecision (epistemic uncertainty) about  $A$ . Finally, suffice to say that the actual probability of  $X$  being  $A$  is  
 314 included in the closed interval composed of the lower and upper bounds. Furthermore,  $Pr_{sup} > Pr_{inf}$ , and if  
 315 there is an absence of epistemic uncertainty  $Pr_{sup}(A) = Pr_{inf}(A) = Pr(A)$ . Unlike fuzzy set-based approaches  
 316 probability bounds ease comparison and interpretation of results. Furthermore, it may be noted that all these  
 317 formulas are compatible with the Bayes rule.

### 318 2.1.2 Combination rules

319 Since, this work is also interested in BFT from the perspective of combination of expert data, this section presents  
 320 a brief description thereof. It may be observed that these combination rules can be used irrespective of the source  
 321 of data, however, since present work concerns only with experts, the term expert data or opinion is used hereafter.  
 322 The combination rules and methods employed in present work are briefly given here. Some, well-known methods  
 323 are: A simple arithmetic average, and a weighted average with specific weighting factors for each expert. These  
 324 weights can be based on an expert's expertise or domain knowledge and are assigned by an analyst. Through, an  
 325 independent consensus or vote between the judgments provided by the experts. Methods rooted in BFT can also be  
 326 used, a more general and exhaustive discussion can be found in [74]. In general, Dempster's rule of combination  
 327 [65] or product-intersection rule has widespread usage partially because of its ease of application. It considers  
 328 that the experts are equally reliable and independent. Furthermore, it manages small conflicts by redistributing the  
 329 conflicting BPA in a uniform way to other focal elements using a normalization factor  $1 - k$  (where  $k$  is a measure  
 330 of the degree of conflict). Yager's rule [75] was introduced as a modification of Dempster's rule, to address among  
 331 others, the normalization factor leading to counterintuitive results in cases of highly conflicting evidence. It detects  
 332 conflict similar to the Dempster's rule, however, it is managed by redistributing the conflicting BPA to the frame  
 333 of discernment (i.e., it considers conflict as an additional source of uncertainty). To quote [75]: "In this case we

334 are saying that since we don't really know anything about the conflicted portion, we let it be distributed among  
 335 all the elements rather than just those in the focal sets". Suffice to say, there exists plenty of other combination  
 336 rules such as minimal commitment principle, conjunctive, disjunctive, etc. Each of these rules offer a different  
 337 set of hypothesis to model and combine knowledge. It may be noted that, when dealing with experts, reliable  
 338 and independent assumptions are common [76] and easily fulfilled. Furthermore, empirical data, under acceptable  
 339 assumptions can be also considered independent and reliable.

### 340 2.1.3 Comparison between BPAs using interval and distance metrics

341 In the context of belief functions theory comparing given BPAs using a metric such as distance can be useful. This  
 342 comparison can be used to measure similarity or dissimilarity between the information represented by two BPAs  
 343 for applications such as clustering, classification, etc. [77]. Such a pairwise comparison can be interesting when  
 344 BPAs are obtained from different information sources (sensors, experts, etc.) or after using different treatments  
 345 (such as after combination rules). This distance metric complements the usage of BFT by giving the user a tool  
 346 to interpret the degree of (non-)aliveness between belief functions in a meaningful way [78]. There are different  
 347 approaches to compare two BPAs, interested readers can refer to works such as [78] [79].

348 In the present work's usage of BFT another rather straightforward approach is to use *the middle of the interval*  
 349 for a given upper and lower probability bound (also known as the pignistic probability). Such a metric is often used  
 350 at the decision-making-level in the context of belief functions. In simpler usage it can also be used to compare  
 351 BPAs, such as the ones obtained after using different combination rules [80]. If different BPAs for a same frame  
 352 are to be compared, the middle of the interval for a value of interest (e.g. a HFE being true) can be used. It can be  
 353 limiting in the sense that only a variable's value of interest can be compared across different BPAs.

354 Secondly, in a more general sense, two BPAs on the same frame can be compared using distance metrics. One  
 355 of the rather well-known distance measures is *Jousselme distance* [77]. It proposes the use of a classical similarity  
 356 measure to achieve the comparison of two BPAs. Let  $m1$  and  $m2$  be two BPAs on the same frame  $\Omega$ . Then the  
 357 Jousselme distance  $d_J$  between  $m1$  and  $m2$  is defined as follows:

$$d_J(m1, m2) = \sqrt{\frac{1}{2}(\|m1\|^2 + \|m2\|^2 - 2\langle m1, m2 \rangle)} \quad (2)$$

358 where  $\langle m1, m2 \rangle$  is the scalar product defined by:

$$\langle m1, m2 \rangle = \sum_{i=1}^n \sum_{j=1}^n m1(A_i) m2(A_j) \frac{|A_i \cap A_j|}{|A_i \cup A_j|} \quad (3)$$

359 where  $n = |\Omega|$  and  $A_i$  and  $A_j$  focal sets of all the pieces of information represented by  $m1$  and  $m2$  respectively,  
 360 and  $\|m1\|^2$  the square norm of  $m1$ .

361 As a simpler form of comparing different BPAs for a given variable's value of interest, this paper uses the  
 362 middle of the intervals. Secondly, the distance metrics presented here  $d_J$  will also be computed to compare two  
 363 complete sets of information represented by two given BPAs.

### 364 2.1.4 A simple example

365 Current work's usage of aforementioned framework is explained by using a simple example. It is used to describe  
 366 proposed interpretations of the variables (HFE and PSFs) and valuations (direct and configuration belief structures)  
 367 in VBS. In a VBS's graphical representation, i.e. a VN, variables are represented by elliptical nodes, and valuations  
 368 are represented by diamond-shaped nodes, as shown in Figure 2. Here the set of variables of interest are  $E =$   
 369  $\{HFE, PSF_1, PSF_2\}$ , where  $HFE$  is the variable of interest and  $PSF_i$ , represents the PSFs.

370 Their respective frames are defined as  $\Omega_{HFE} = \{true, false\}$ , and for each of the PSFs as  $\Omega_{PSF_i} = \{nominal, poor\}$ .  
 371 The frames are comprised of finite discreet values the variable can take. The relation between the PSFs and HFE is  
 372 defined by using a *configuration belief structure*, the *BPA* represented graphically as  $m1$  in Figure 2. It is defined  
 373 on the frame  $\Omega_{\Phi} = \Omega_{HFE} \times \Omega_{PSF_1} \times \Omega_{PSF_2}$ . The other BPAs ( $m2$  and  $m3$ ) contain evidence on the variables  $PSF_1$

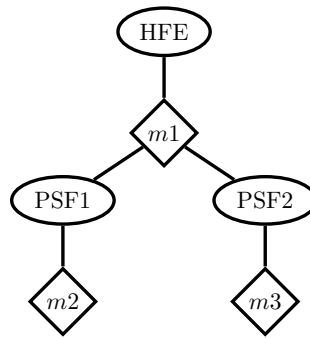


Fig. 2: A simple example and the associated variables modeled as a VBS (a VN).

374 and  $PSF_2$  respectively. As discussed before, they are *direct belief structures* and are used to represent data on  
 375 the PSF. These direct and configuration belief structures are then used to obtain the quantification results. These  
 376 quantification results i.e. upper and lower bounds are obtained by a combination of all the *BPA* and a projection  
 377 on  $\Omega_{HFE}$ . The next sub-sections present the qualitative and quantitative parts of the PRELUDE methodology.

## 378 2.2 Qualitative part

379 In some application domains (like railway) a PRA or PRA-like analysis with explicit considerations of HFEs are  
 380 unavailable. Thus, adequate propositions must be made to extract HFEs and identify safety critical contexts of  
 381 situations in operational conditions towards HRA considerations. This part describes the identification of the HFEs  
 382 and characterizes a safety critical situation using PSFs, i.e. variables of the proposed HRA model. In order to  
 383 represent the domain specific human factor concerns, present work uses a study by the EUAR's human factors  
 384 network – ‘Support Study for Human Factors Integration in European railways’ [81] (hereafter referred to as *EUAR*  
 385 *HF study* or simply *the study*). It presents a detailed analysis of human functions and goals in railway operations  
 386 in terms of operational safety and other system-level objectives. Also, as of the most recent information from the  
 387 authors its validation is in progress. The first sub-section presents a generic PSF list for rail operations. In the  
 388 second sub-section main focus shall be to identify PSFs to characterize safety critical situations in operational  
 389 conditions.

### 390 2.2.1 Performance Shaping Factors for railway operations

391 Generally speaking, PSFs in an HRA should be easy to use and adapted for the application domain. Current work  
 392 uses a rail-specific PSF list as originally proposed in [82]. It is used in present work as given in Table 2. Each  
 393 PSF is accompanied by a definition and a finite number of quantification levels, also known as factor ratings  
 394 [38] or rating scales or qualitative quality descriptors [4]. The term quantification levels or simply PSF levels are  
 395 used hereafter. These levels are similar to what is normally seen in other HRA models [62] and activities. This  
 396 qualitative work considers four levels (*good*, *nominal*, *poor* and *insufficient information*) for each of the PSFs  
 397 (Table 2). These are defined as follows (adapted from [26]):

- 398 • *Good*: A PSF assigned this level is conducive to good performance, such that it reduces the chances for  
 399 error, and thus, does not pose any safety issues.
- 400 • *Nominal*: It is assigned whenever a PSF is judged to support correct performance, but does not enhance  
 401 performance (contrary to *good*) or make tasks easier to carry out than typically expected.
- 402 • *Poor*: A poor level of a PSF is detrimental towards the accomplishment of an objective (leading to the  
 403 occurrence of a human error).
- 404 • *Insufficient information*: If an expert/analyst does not possess sufficient knowledge to determine whether a  
 405 PSF can affect a human's performance or if unable to choose among the other alternatives.

TABLE 2: PSF list with considered definitions and quantification levels, adapted from [82]

Performance Shaping Factor	Definition	Quantification Levels
Training	Have the correct knowledge to perform a job successfully and safely. Training might be needed to ensure skills are up to date and relevant, i.e., new procedures, different signaling systems, etc.	Good, Nominal, Poor, Insufficient Information
Experience	The accumulation of information and knowledge gained through interactions with the system and time spent in the work environment, this can be under conditions (or same route). Aspects like, bad habits learned, etc. should also be considered in addition to the, positive aspects.	Good, Nominal, Poor, Insufficient Information
Communication	The ability of team members to pass information to each other and a shared understanding of the situation using, system status, read-outs, etc. e.g. misunderstanding, omission of, information, mistaken location, incorrect communication actions. Human-machine communication aspects are not included in this PSF.	Good, Nominal, Poor, Insufficient Information
Situational Awareness	The perception of the elements in the environment within a volume of time and space. The comprehension of their meaning and projection of their status in the near future. As a more general definition “Skilled behavior, that encompasses the processes by which task-relevant information is extracted, integrated, assessed, and acted upon.” (Endsley 1995).	Good, Nominal, Poor, Insufficient Information
Task Load (Workload)	The actual task demand assigned to a person in terms of the number and type of tasks (varying complexity, importance, etc.). Task load can also be impacted by unplanned or emergency events.	Good, Nominal, Poor, Insufficient Information
Time load (Workload)	Time required or allocated for one or multiple tasks; this time perception can affect worker stress beyond the stress of having too many tasks. Available time to complete a task particularly in the context of driving activities related to high speed trains (both detection and completion of the task).	Good, Nominal, Poor, Insufficient Information
HSI quality	An umbrella term to consider the quality of human system interface. The broad context here includes the procedures, appropriate information displayed to the human at appropriate time or in an adequate way. It includes most ‘Machine-based factors’ directly influencing human behavior.	Good, Nominal, Poor, Insufficient Information

406 PSFs from this list will act as a basis for subsequent identification and characterization of safety critical situations.  
 407 Other factors will be interpreted as or mapped to PSFs from this list.

### 408 2.2.2 Identification of HFEs and safety critical context

409 EUAR HF and similar studies, which provide an operational safety-oriented analysis of human functions, can be  
 410 used to find detailed analysis on possible safety critical situations. For a prospective analysis, such studies can be  
 411 used to identify both HFEs and PSFs, whereas for a retrospective analysis the latter is more interesting.

412 Here, the identification of PSFs from EUAR HF study is explained for one particular human function. For the  
 413 definitions of terms (italicized) used from the study the reader can refer to the report available on EUAR website  
 414 (Pickup et al. 2013). Present work considers an HFE as a central starting point of analysis; a safety critical situation  
 415 is linked to the said HFE in operational conditions. This situation is identified and subsequently represented as set  
 416 of one or more than one PSFs. For this identification from a human factors study (viz. EUAR HF) a mapping, which  
 417 functionally matches the HFE to a relevant human function, is needed. Non-accomplishment of this function then  
 418 represents the HFE. The *human functions* and its higher level abstraction *human function goals* can be considered  
 419 a procedure and a task, respectively. Further, for the objectives of risk analysis and safety in general, only the  
 420 *System purpose/goal* of safety (i.e. *maintain safety*) is considered. Thus, a failure/error in the said *human function*  
 421 represents an HFE, at least for the kind of analysis of the current study is concerned. Safety relevant activities and  
 422 analysis thereof provided in the study consist of discussion on respective conditions (possible scenarios) or casual  
 423 factors (PSFs) that could possibly lead to errors. To identify an error-causing context (as a set of PSFs) *potential*  
 424 *for errors* and in some cases *potential for recovery* is used. Current approach only considers explicit statements  
 425 (or the PSFs stated to be the ones with largest influence) to identify this context. Further, it can be considered

TABLE 3: Defining Human Failure Type Context for the example HFE

Failure in Human function or HF	Performance Shaping Factor identification	Human Failure Type Context (HFTC)
ERA/HFG5/47: Not able to route / re-route passenger or freight service	<p><i>Source 1.</i> ERA/HFG5/47: Potential for error – “Trains could be routed towards other traffic, incompatible infrastructure (59), engineering possessions, or close to engineering work at high speeds. Errors could be influenced by <u>time pressure</u> or <u>complexity</u> in track layouts in some situations and locations and <u>problems with communications</u> (It could be important to consider additional risks at shift changeover).”</p> <p><i>Source 2.</i> PSF list – Training, Experience, <u>Communication</u>, Situational awareness, Task Load (Workload), <u>Time load</u> (Workload), HSI quality.</p> <p><i>Source 3.</i> Error Contexts – EC1 = {Training, HSI quality, <u>Task load</u>, <u>Communication</u>, <u>Time load</u>}</p>	$HFTC_{HFE} = \{Communication, Task Load, Time Load\}$

426 that the factors with a negative connotation (*potential for error*, etc.), have a significant effect on the human while  
 427 performing a said function. This, human function’s error-causing factors are then interpreted in terms of PSFs from  
 428 the PSF list (Table 2). Towards a more robust propositions, error context (ECs) as introduced in [19] are also used.

429 Since, ECs’ application domain is nuclear; the definitions were matched to the PSFs in the PSF list, to keep  
 430 interpretation of PSFs coherent. The third source is the entire PSFs list, discussed in previous section as a standard  
 431 base of factors. Common or recurring factors are then selected. The preference in selecting the PSFs in this work  
 432 such that - EUAR HF study, PSF list and accident/incident report, or safety critical situation/contextual factors  
 433 identified by experts or analysts - are assigned higher importance than ECs. As evident, a higher preference is  
 434 assigned to rail domain specific studies. Here, ECs are considered as a characterization of a generic human error  
 435 causing environment.

436 Thus, the proposition termed Human Failure Type Context – HFTC, is a qualitative construct which defines  
 437 a specific HFE (or a safety critical *human function*) in its safety critical situation. HFTC more generally aims to  
 438 characterize a safety critical situation as a collection (set) of factors (PSFs) which impede a safe accomplishment of  
 439 a function by a human, significantly more than individual PSF or other sets thereof. In other words, a simultaneous  
 440 presence of these factors in a situation will have considerable negative affect on human performance towards the  
 441 accomplishment of said function. This safety critical situation is represented as a set of PSFs specific to an HFE  
 442 written as  $HFTC_{HFE}$  where  $HFTC_{HFE} = \{PSF_i, PSF_{i+1}, \dots, PSF_n\}$ .

443 This approach is illustrated by constructing the HFTC for an example HFE. As discussed before this HFE  
 444 represents a failure of a human function, for illustration purposes it is taken after being mapped to a human  
 445 function from a EUAR HF study. Reference to EUAR HF study (more specifically the spreadsheet accompanying  
 446 it) is given as,  $ERA/HFGi/j$ , where  $i$  is the index of *human function goal* and  $j$  refers to the index of the  
 447 specific *human function*. Non-accomplishment of this *human function* defines the HFE. Human functional goal  
 448 ERA/HFG5 states ‘To control train movements in all operational circumstances’, under which there are multiple  
 449 (14) human functions. ERA/HFG5/47: *Route/re-route passenger or freight service* is chosen as the example  
 450 HFE. Table 3 gives the previously presented process of identifying the constituents of  $HFTC_{HFE}$ . Common  
 451 factors (underlined in Table 3) from the three sources are subsequently identified. This gives us  $HFTC_{HFE} =$   
 452  $\{Communication, TaskLoad, TimeLoad\}$ . Finally, each HFE is modeled as an VBS with its set of  $PSF \in HFTC_{HFE}$   
 453 in a VBS. This forms the quantitative aspect of the proposed model and is detailed in the next section.

### 454 2.3 Quantitative part

455 Quantitative aspect of this proposition concerns with formalizing the evidence(s) to build human reliability model  
 456 in VBS. Presently, this evidence is obtained from expert elicitations. Information from multiple experts is elicited  
 457 and combined, followed by a transformation to obtain the final configuration belief structure for the proposed VBS  
 458 model.

### 2.3.1 The expert elicitation process

After the variables of the VBS (HFE and its  $PSF_i : PSF_i \in HFTC_{HFE}$ ) are identified and defined, valuations are needed. In this case, these valuations formalize the relation between the HFE and PSFs using configuration belief structures. Towards this objective, a simple question-answer construct is used to capture focused domain knowledge from an expert. In current work it is the occurrence of a human failure (HFE in state *true*) under specific conditions (characterized by PSFs). Furthermore, the HFE and the PSFs need to be contextualized for the expert. This is accomplished by using information from the EUAR HF study. For a retrospective analysis it can also include comments of investigators, chronology of events, and other data often included in such reports. However, statements which are inferences of the investigators on the factors and HFEs can potentially influence expert beliefs, and thus should be avoided. This additional data hence aims to provide an expert a clear non-ambiguous description of the context.

The current work is only concerned with safety-critical aspects and negative effects of a PSF. Furthermore, explicit considerations of *insufficient information* are also not employed at present. Thus, only HFE being *true* and a PSF being *poor* or *nominal* are used in the questions. The question is then formulated as conditional on the HFE's occurrence (*true*) for a *poor* level of PSF. The text of the question thus forms a proposition and the questionnaire aims to obtain a degree of confidence (as an expert's opinion) on the truthfulness of that proposition. The question for the HFE and the concerned PSF is formulated as: Given the occurrence of a *poor* level of PSF, what do you think about HFE being *true*?

The response is expected on a probability scale – number of times out of 10, 100, 1000, etc., the HFE can be said to be *true*. An expert can use descriptors –  $d$  or give directly a subjective probability value. The natural language descriptors or simply descriptors are taken from ATHEANA's elicitation process [20], where similar quantities are elicited. They can however be modified to account for domain specific terminology and/or values. Nevertheless, current work uses them as they are given in [20], where these are defined as follows:

- 'Likely' – 0.5 (5 out of 10 would fail)
- 'Infrequently' – 0.1 (1 out of 10 would fail)
- 'Unlikely' – 0.01 (1 out of 100 would fail)
- 'Extremely unlikely' – 0.001 (1 out of 1000 would fail)
- 'Insufficient information'

Thus, the response from the expert takes the form "Given a *poor* level of a PSF the HFE is *true* with a probability of  $x$ ". Since they are probability values, a response should not exceed unity.

Furthermore, the reasons for eliciting experts for a PSF-HFE pair are as follows:

- A configuration belief structure can represent the conditional relations between multiple variables (PSFs and HFEs) and their values. Therefore, such explicit consideration can be made in the VBS.
- Inter-PSF relations for PSFs internal to a human can be considered generic and sourced from data on human cognition or behavior. For example, a human under extreme task load effecting situational awareness transcends application domain and acceptable generalizations can be made.
- If experts are elicited individually, multi-PSF questions might force them to make conclusions on factors out of their domain expertise. For example, a railway expert might be asked to comment on aspects of human cognition. This limitation is relevant because it is rather common in HRA assessment process to have multiple domain experts each with different expertise.
- Lastly, a HFE-PSF pair presents a generic and simpler context to visualize for the expert, making the elicitation process easier. On the other hand combined effect of multiple PSFs, such as PSF-PSF-HFE, might lead to misunderstanding of the situation and erroneous elicitation.

Hence, the aspects of combinations of PSFs are decoupled from the questions asked to the experts, and put in the core of the quantification model (VBS). Also, since present application is concerned with the *true* state of an HFE and negative effects of a PSF, a *good* level is not considered in the questions. However, the model and transformation can account for a *good* level. This inclusion can be interesting for multiple reasons, accounting

TABLE 4: The HFE’s description and relevant context description and question statements

HFE and questions	Context description and question statements
ERA/HFG5/47 – Not able to route / re-route passenger or freight service	<i>HFE</i> – A signaller was <i>Not able to (Route / re-route passenger or freight service)</i> ; <i>Personal and organizational goals</i> – “To respond to scenarios that require trains to be re-routed or travel to a different (unplanned) destination.”; <i>Generic context</i> – “Ensure train services can continue operations during engineering / maintenance work, enable engineering trains to get to the work area, provide adequate routing plans, this routing of trains could be planned prior to the work; require short term (re-)planning where there is limited notice of engineering work...”; <i>Potential for error</i> – “Trains could be routed towards other traffic, incompatible infrastructure, engineering possessions, or close to engineering work at high line speeds. Errors could be influenced by time pressure or complexity in track layouts in some situations and locations, and problems with communications (It could be important to consider additional risks at shift changeover).”
Question 1. <i>Task Load - HFE</i>	Given the occurrence of a <i>poor</i> level of <i>Task Load</i> , what do you think about <i>HFE</i> being <i>true</i> ?
Question 2. <i>Communication - HFE</i>	Given the occurrence of a <i>poor</i> level of <i>Communication</i> , what do you think about <i>HFE</i> being <i>true</i> ?
Question 3. <i>Time Load - HFE</i>	Given the occurrence of a <i>poor</i> level of <i>Time Load</i> , what do you think about <i>HFE</i> being <i>true</i> ?
Question 4. <i>all PSF nominal - HFE false</i>	Given the occurrence of a <i>nominal</i> level of <i>all the PSFs</i> what do you think about <i>HFE</i> being <i>false</i> ?

506 for the effect of a PSF on suppressing the negative effect of another PSF. Or more generally for a more inclusive  
507 human reliability approach. However, this requires some effort on expert elicitation, notably question structure,  
508 and combination. On the other hand, some rather intuitive data can be used from human factor studies or in case of  
509 empirical data – from simulator experimentation or near miss studies, towards a more inclusive human reliability  
510 approach. Nevertheless, it is not considered in the present quantitative proposition.

511 However, a case representative of normal conditions is added where no human error is considered. This  
512 consideration is represented by the question:

513 “Given the occurrence of a *nominal* level of all the *PSFs* what do you think about *HFE* being *false* ?”

514 For the HFE and its HFTC obtained after Table 3, questions are given in Table 4. The HFEs and PSFs  
515 are contextualized for the expert using data from EUAR HF study, more specifically in section *Personal and*  
516 *organizational goals*, *generic context* and *potential for error*. These choices are facultative and left to the discretion  
517 of the analyst. Present work aims at expert independence by eliminating direct expert interaction in the data  
518 collection process. For the case study we ensured that there was no interaction among the experts during the expert  
519 data collection process, and experts do not have access to each other’s responses. And their responses to a question  
520 are treated as independent pieces of evidence.

### 521 2.3.2 Combination of expert data

522 This section carries forward the discussion on combination rules presented in section 2.1.2. Furthermore, different  
523 field of expertise can be useful, especially with a domain such as HRA which touches on multiple domains  
524 (reliability, human factors, and application domain-knowledge). However, while mathematically aggregating the  
525 data, the hypothesis of the data aggregation method needs to be respected, and the choice remains with the analyst.

526 Thus, when constructing the quantitative human reliability model, PRELUDE offers to the analyst, a choice  
527 of the combination method to use. The choice depends mainly on the hypothesis attached to said rules which can  
528 be applied to evidence at-hand. This paper also provides an illustration of what different rules can be used, their  
529 hypothesis, and the results. Thus, all combination rules are used in the case study to illustrate some aspects of  
530 expert data combination, notably conflict. Some comments are also presented in the case study.

531 Present work’s objective is to understand and demonstrate, when and what method to use, based on the  
532 underlying hypothesis. All five of the combination methods are thus used in this paper (ref. section 2.1.2). A  
533 summary of their hypothesis and assumptions are given in Table 5.

534 For a proposition (what the question aims to measure) say ‘*X* is exactly *x* and only *x*’ an expert’s belief is  
535 represented by a *BPA*. The value of this *BPA*, say *b*, is a quantitative expert belief (a subjective probability) on the



TABLE 5: Combination rules and their hypothesis

Combination methods	Hypothesis and it's manifestation
1. Arithmetic average	All experts are equally reliable. The data received is thus, given equal weight.
2. Weighted average	A differentiation between experts' domain knowledge is made. This manifests as weights assigned to the evidence received from each expert.
3. Independent consensus or majority vote	There is a single correct answer to the question. Therefore, the answer which has the highest frequency (relative) is chosen. However, if no clear majority amongst the values/descriptors is found, an arithmetic average is used.
4. Dempster's combination rule	All the experts are equally reliable and evidences are independent. It is associative, commutative but non-idempotent. It essentially weakens the disagreement and strengthens the agreements in terms of conflict in the elicited values.
5. Yager's rule [75]	This rule assumes that all the experts are reliable and the evidences are independent. It is quasi-associative, commutative but not idempotent. Contrary to previous case the conflict manifests itself as uncertainty.

536 said proposition. Each expert's response is then modeled as a complementary belief structure. This goes to state  
537 that, for each expert, belief about the value of  $X$  being  $x$  is  $b$  and exactly  $b$ . Therefore, the belief of  $X = \{\bar{x}\}$  is  
538  $1 - b$ . This is then modeled as two focal sets with the associated  $BPA$  values. The belief structure in 4 gives the  
539 considered representation of expert data.

$$\begin{aligned}
m(\{x\}) &= b \\
m(\{\bar{x}\}) &= 1 - b \\
m(\Omega_X) &= m(\{x, \bar{x}\}) = 0
\end{aligned} \tag{4}$$

540 Finally, a single response (a quantitative value) for each question (PSF-HFE pair) is obtained; this is used in  
541 the next section to complete the VBS model construction.

### 542 2.3.3 Transformation

543 Combination of data gives a single piece of evidence per PSF-HFE pair. This evidence is a combined quantitative  
544 measure of the experts' opinion in each question's proposition. These measures and propositions are used for  
545 constructing the configuration belief structure for the VBS model. Towards this objective, a transformation is to  
546 define the final configuration belief structure of the VBS model.

547 First, each question's proposition represents a conditional piece of evidence, viz. a conditional belief of a state  
548 of an HFE given a state of a PSF. This conditional belief must be deconditioned to accommodate it in the dynamic  
549 part of VBS. The relations between variables should be transformed to valuations or joint belief. Thus, Smet's rule  
550 [73] is employed, it proposes a transformation of a conditional piece of evidence into a joint belief structure. It  
551 represents a relation between two variables  $A$  and  $B$ , defined as given in equation 5.

Given the conditional evidence if  $A = a$  then  $B = b$  with a  $BPA = x$ .

The rule is represented by a belief structure defined on  $E : \Omega_E = \Omega_A \times \Omega_B$ , such that: (5)

the focal set  $\{(a, b)(\bar{a}, b)(\bar{a}, \bar{b})\}$  is assigned a  $BPA = x$  and the focal set  $\Omega_E$  is assigned a  $BPA = 1 - x$

552 After deconditioning, using the rule given in equation 5, for every question, an initial belief structure is obtained  
553 which relates a particular PFS and a HFE with a  $BPA$  value. This initial belief structure is defined on the frame  
554  $\Omega_\Phi = \Omega_{PSFi} \times \Omega_{HFE}$ .

555 Second,  $HFE = \{\{true\}\}$  and  $PSF = \{\{poor\}\}$  is the minimal explicit information in a question's proposition.  
556 On the other hand, the VBS model quantifies using a set of valuations. For present work this valuation (the  
557 configuration belief structure) relates HFE and all the  $PSF \in HFTC_{HFE}$ . That is, it reasons with the HFE and  
558 with all the PSFs in an given safety critical situation (i.e.  $HFTC_{HFE}$ ). Effectively it is defined on the frame  
559  $\Phi : \Omega_\Phi = \{\Omega_{HFE} \times \Omega_{PSFi} \mid \forall PSFi \in HFTC_{HFE}\}$ , i.e. all the states of all the PSFs in an HFTC and the relevant

560 HFE. Hence, a transformation is needed to obtain the complete final configuration belief structure. Thus, a vacuous  
 561 extension is performed on the initial belief structure (if needed). This gives the intermediate belief structures for  
 562 each question. The second part of this transformation combines all the questions' propositions, represented as  
 563 their respective intermediate belief structures to obtain the final configuration belief structure. This transformation,  
 564 thus entails a vacuous extension of a question's initial belief structure giving the intermediate belief structure and  
 565 finally the combination thereof to obtain the final configuration belief structure.

566 This transformation is explained by using the HFE's questions given in Table 4. It is considered that after  
 567 combination (ref. section 2.3.2) the final probabilistic responses are obtained as follows:

- 568 • Combined probabilistic response for Question 1. : 0.05
- 569 • Combined probabilistic response for Question 2. : 0.2
- 570 • Combined probabilistic response for Question 3. : 0.001
- 571 • Combined probabilistic response for Question 4. : 0.95

572 *Question 1* from Table 4 can be written as: if  $Task\ Load = \{(poor)\}$  then  $HFE = \{(true)\}$ , with the combined  
 573 probabilistic response representing the quantitative measure of evidence on the truthfulness of said proposition,  
 574 here it is 0.05. This proposition is deconditioned using the rule in equation 5 giving two initial belief structures  
 575 (BPAs):

$$mQ1^{\Omega_{HFE} \times \Omega_{TaL}}(\{(poor, true)(\overline{poor}, true)(\overline{poor}, \overline{true})\})$$

$$= mQ1^{\Omega_{HFE} \times \Omega_{TaL}}(\{(poor, true)(nominal, true)(nominal, false)\}) = 0.05,$$

and (6)

$$mQ1^{\Omega_{HFE} \times \Omega_{TaL}}(\Omega_{HFE} \times \Omega_{TaL})$$

$$= mQ1^{\Omega_{HFE} \times \Omega_{TaL}}(\{(poor, true)(nominal, true)(poor, false)(nominal, false)\}) = 0.95$$

576 Similarly initial belief structures can be obtained for Questions 2 and Question 3. Each of these initial belief  
 577 structures contain two elements per set. Note that, Questions 4 however, represents a relation between all the PSFs  
 578 and the HFE. It is therefore interpreted as: if  $(TaskLoad, Communication, TimeLoad) = \{(nominal, nominal, nominal)\}$   
 579 then  $HFE = \{(false)\}$ . The initial belief structure thus in this case contains four elements per set. Thus, all of  
 580 the focal sets using equation 6 and combined probabilistic responses as the *BPA*'s are given below. These initial  
 581 belief structures (that is the respective focal sets and BPAs) for the questions obtained after deconditioning using  
 582 equation [73], are given below:

583 Question 1. represented as  $mQ1^{\Omega_{HFE} \times \Omega_{TaL}}$ , which gives first focal set as:  
 584  $\{(poor, true)(nominal, true)(nominal, false)\}$ , with a *BPA* = 0.05; and second focal set as:  
 585  $\{\Omega_{HFE} \times \Omega_{TaL}\} = \{(poor, true)(nominal, true)(poor, false)(nominal, false)\}$  with a *BPA* = 0.95.

586 Question 2. represented as  $mQ2^{\Omega_{HFE} \times \Omega_C}$  which gives first focal set as:  
 587  $\{(poor, true)(nominal, true)(nominal, false)\}$  with a *BPA* = 0.2 ; and second focal set as:  
 588  $\{\Omega_{HFE} \times \Omega_C\} = \{(poor, true)(nominal, true)(poor, false)(nominal, false)\}$  with a *BPA* = 0.8.

589 Question 3. represented as  $mQ3^{\Omega_{HFE} \times \Omega_{TiL}}$  which gives first focal set as:  
 590  $\{(poor, true)(nominal, true)(nominal, false)\}$  with a *BPA* = 0.001 ; and second focal set as:  
 591  $\{\Omega_{HFE} \times \Omega_{TiL}\} = \{(poor, true)(nominal, true)(poor, false)(nominal, false)\}$  with a *BPA* = 0.999.

592 Question 4. represented as  $mQ4^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}}$  which gives first focal set as:  
 593  $\{(nominal, nominal, nominal, false), (poor, poor, poor, false), (poor, poor, poor, true)\}$  with a *BPA* = 0.95 and sec-  
 594 ond focal set as:  
 595  $\{(nominal, nominal, nominal, false), (poor, poor, poor, false)$   
 596  $(nominal, nominal, nominal, false), (poor, poor, poor, true)\}$  with a *BPA* = 0.05.

597 As can be seen in the first column of above equations questions 1, 2 and 3 are defined on  $\Omega_{HFE} \times \Omega_{TaL}$ ,  
 598  $\Omega_{HFE} \times \Omega_C$  and  $\Omega_{HFE} \times \Omega_{TiL}$  respectively. Thus, these initial belief structures need vacuous extension. However,  
 599 Question 4 is already defined on the frame  $\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}$ . It thus, does not need a vacuous extension.  
 600 Thus, a vacuous extension is performed for questions 1, 2 and 3. This process is detailed below:

601 For Question 1's proposition the obtained *BPA*  $mQ1^{\Omega_{HFE} \times \Omega_{TaL}}$  is defined on the frame  $\{\Omega_{TaL} \times \Omega_{HFE}\}$ ,  
 602 whereas in the present VBS model, the configuration belief structure is defined on the frame  $\Omega_{HFE} \times \Omega_{TaL} \times$   
 603  $\Omega_C \times \Omega_{TiL}$ . Thus, a vacuous extension is performed by doing a cross product of the focal set of the initial belief  
 604 structures, and frame of *Task load* and *Communication*, this extension is given as follows:

$$\begin{aligned}
 mQ1^{\Omega_{HFE} \times \Omega_{TaL}}(\{(poor, true)(nominal, true)(nominal, false)\}) \\
 = mQ1^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}}(A) \\
 \text{where} \\
 A = \{(poor, true)(nominal, true)(nominal, false)\} \times \{\Omega_C \times \Omega_{TiL}\} \\
 = \{(poor, true)(nominal, true)(nominal, false)\} \times \{(poor, nominal)\} \times \{(poor, nominal)\} \\
 = \{(poor, true, poor, poor)(poor, true, poor, nominal)(poor, true, nominal, poor) \dots\}
 \end{aligned} \tag{7}$$

605 Here,  $A$  is the focal set for the *BPA*  $mQ1^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}}$ . The complete focal set thus obtained is defined  
 606 on the frame  $\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}$ . It thus, contains four elements per set, instead of previous two. Similarly,  
 607 equation 7 is repeated for all of the questions' focal sets, with appropriate frames to obtain intermediate belief  
 608 structures for each of them. After obtaining intermediate belief structure, for each question defined on the same  
 609 frame, a combination can be performed. This gives a single piece of relational evidence from all of the questions  
 610 for an HFE. The independence constraints are respected because the responses are independent of each other.  
 611 Hence, they can be combined using Dempster's rule as given in equation 8.

$$\begin{aligned}
 m1 = mQ1^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}} \oplus mQ2^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}} \oplus mQ3^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}} \oplus \\
 mQ4^{\Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}}
 \end{aligned} \tag{8}$$

612 This gives us the final configuration belief structure concluding the construction of the VBS model, from the  
 613 the simple questions (section 2.3.1). More generally, multiple PSFs and an HFE (PSF-PSF-...-HFE) questions are  
 614 not asked from the experts in present work, they can very well be implemented in the current proposed approach  
 615 (by adequately changing the vacuous extension). Nevertheless, in our configuration belief structure there is always  
 616 a component of an HFE. Pure PSF-PSF are currently not considered. However, mathematically speaking, as is the  
 617 case with the work discussed before [19], a PSFs influence on another PSF can be modeled using an intermediate  
 618 belief structure, which, for example can be a belief structure between Task Load and Communication; which then  
 619 links to the central configuration belief structure.

#### 620 2.3.4 Example HFE's quantification

621 For the HFE from Table 3, the domain of interest is  $\Phi = \{HFE, TaL, C, TiL\}$ . Here, HFE is the HFE under  
 622 analysis, and the PSFs are Task Load (TaL), Communication (C) and Time Load (TiL). Their respective frames are  
 623 defined as  $\Omega_{HFE} = \{true, false\}$ , and for each of the PSFs as  $\Omega_{PSFi} = \{nominal, poor\}$ . The relation between the  
 624 PSFs and HFEs, is defined by the configuration belief structure obtained after equation 8, represented graphically  
 625 as  $m1$  in Figure 3.

626 Here,  $m1$  is defined on the frame  $\Omega_{\Phi} = \Omega_{HFE} \times \Omega_{TaL} \times \Omega_C \times \Omega_{TiL}$ . The other BPAs  $m2$ ,  $m3$  and  $m4$  contain  
 627 evidence on the variables  $TaL$ ,  $C$  and  $TiL$  respectively. As discussed before, they are direct belief structures and  
 628 are used to represent data on the PSFs.

629 **Data for quantification:** PRELUDE's VBS model takes data on the PSF(s) to quantify the HFE (the  
 630 variable of interest). This data is represented in the direct belief structure(s). It can come from a given operational or  
 631 an accident context, and is assigned by an analyst. It simplifies the usage and eliminates the aspects of subjectivity  
 632 on the choice of PSFs and their affects (given the VBS model is constructed beforehand) by an analyst during the  
 633 analysis process.

634 Since, current application deals with a retrospective analysis, this evidence is obtained from relevant accident  
 635 analysis statistics. For present work [52] is chosen for its relevance to the domain and availability of data matching  
 636 the current need. That is the number of times a PSF was one of the causal factor(s) given there was a human

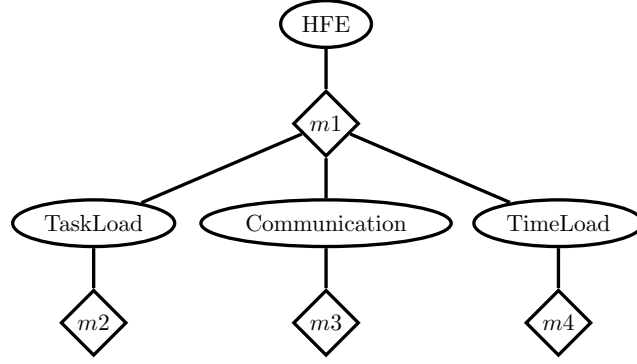


Fig. 3: The example HFE and related PSFs modeled as a VBS.

TABLE 6: Direct belief structures for HFE: from the R-PSF equivalent as identified focal sets and associated *BPA* values

Cause R-PSF from [83]	Identification frequency vs. Total number of accidents – $da_{PSF}$	PSF from Table 1 and representation in Figure 3	$m^{PSFi}(\{\{poor\}\})$ $da_{PSF}$	$= m^{PSFi}(\{\{nominal\}\}) = 1 - da_{PSF}$
Workload, Time pressure, Stress	$58/1676^1 = 0.0173$	Task Load ( $m2$ )	0.0346	0.965
Communication, Teamwork	$228/1676=0.136$	Communication ( $m3$ )	0.136	0.864
Workload, Time pressure, Stress	$58/1676=0.0173$	Time Load ( $m4$ )	0.0346	0.965

637 involvement in an event (accident, severe accident, etc.). Furthermore, if a PSF is identified as a cause of an  
 638 accident, it can be safely assumed to be in a *poor* state, or a state which degrades human performance in general.  
 639 Also, they arrive at R-PSF and their occurrence frequencies after merging the PSFs (and subsequently their  
 640 occurrence frequencies) in multiple steps (definitions, categorization, and threshold). That is, we can consider that  
 641 after these multiple levels of combinations, the resulting PSFs and their frequencies are sufficiently independent,  
 642 to be considered as such in our model.

643 Thus, in present case a direct belief structure represents proposition that a PSF level is ( $\{\{poor\}\}$ ). The  
 644 quantitative measure on this evidence is obtained as: number of times a PSF is reported to be a direct cause  
 645 vs. total number of events. Thus, the proposition is represented by the focal set ( $\{\{poor\}\}$ ) and the quantitative  
 646 measure on this evidence assigns the BPA:  $da_{PSF}$  (for direct assignment to a PSF). If PSF was not in a *poor* state,  
 647 it is everything except *poor*. That means, it is *nominal*, since for current work  $\Omega_{PSFi} = \{\{nominal, poor\}\}$  such  
 648 approximations are sufficiently conservative for present work. This gives us the proposition and evidence thereof  
 649 as  $m^{PSF}(\{\{nominal\}\}) = 1 - da_{PSF}$ . Similarly for all the PSFs, and thus, direct belief structures for the VBS model  
 650 are obtained (refer to  $m2, m3, m4$  in Figure 3). The direct evidences come from independent and reliable sources.  
 651 That is, all the evidence obtained from accidents are independent ( 1.5 PSFs identified per accident report) and  
 652 reliable (accident/incident investigation reports) [52]. Thus, in this case Dempster's rule can be employed.

653 **2.3.4.1 Quantification and sensitivity analysis results:** Figure 4 shows the graphical model of the  
 654 implementation for quantification of HFE (after representation in Figure 3) in VBS, with the direct and con-  
 655 figuration belief structures titled what they contain. The direct assignment for Task Load is represented by the  
 656 diamond shaped node – *DataOnTaL*. It contains two focal sets  $\{nominal\}$  and  $\{poor\}$ , and respective BPA values  
 657 as  $m^{TaL}(\{\{nominal\}\})$  and  $m^{TaL}(\{\{poor\}\})$ , the latter obtained from accident statistics, as discussed in the previous  
 658 section. Similarly for Time Load and Communication, the direct assignments are given in Table 6.

TABLE 7: Marginalization results for example HFE on  $\Omega_{HFE}$ 

Values of the example HFE	Measure on the HFE's values obtained after marginalization
{true}	0.00005
{false}	0.94981
$\Omega_{HFE} = \{true, false\}$	0.05014

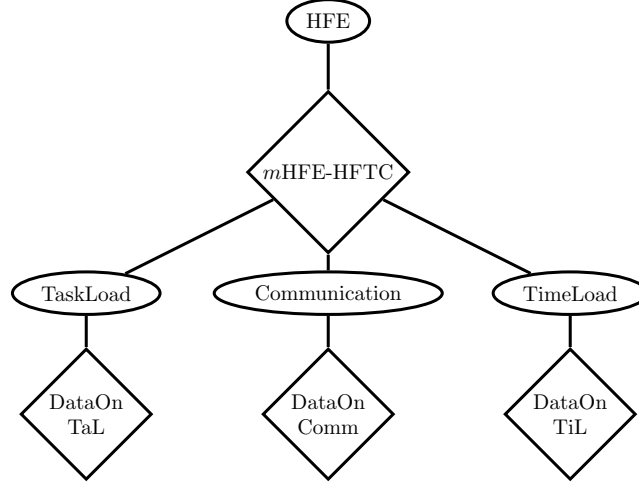


Fig. 4: Implementation in VBS for the quantification of HFE.

659 After defining all the direct belief structures, BFM (Belief Functions Machine) [84] is used to combine the  
 660 direct and configuration belief structures and marginalize for HFE. The results obtained by marginalization, i.e. pro-  
 661 jection on  $\Omega_{HFE}$  are given in Table 7. The obtained results are represented as upper and lower probability bounds  
 662 (equation 1). Since, human reliability analysis and also present work is concerned with an HFE being *true* these  
 663 quantification results are represented in the form of an interval, given as:  $[Pr_{inf}(HFE(true)), Pr_{sup}(HFE(true))] =$   
 664  $[0.00005, 0.05019]$

665 As a natural second step, a feedback for the analysis undertaken by the analysts can be performed. Such a  
 666 feedback aids decision making by allowing an analyst to perform a diagnosis on the individual PSFs, such an  
 667 activity can be interpreted as suggestions for improvements to be made to reduce HEP. In PRELUDE's context  
 668 sensitivity analysis aims to give a formal feedback towards safety objectives. It ranks PSFs in terms of their  
 669 contribution towards the variable of interest (HFE). This makes it possible to establish a priority ranking, towards  
 670 improvements in PSFs needed for effective gains in operational safety and to identify PSFs on the other end of  
 671 this list, which can be ignored.

672 In VBS terminology this step is known as a reverse propagation. The VBS model is modified as follows: given  
 673 the occurrence of the HFE (HFE is *true*, in present case), marginalize for every PSF (*poor* state) in the  $HFTC_{HFE}$ .  
 674 An HFE is assigned a direct belief structure as: the focal set of  $\{(true)\}$  with a BPA value equal to 1, and marginal  
 675 on all the other variable's (PSFs) states is calculated. The obtained marginal for each PSF is combined with the  
 676 direct evidence thereof (again using Dempster's rule). It is essentially an updating of evidences, a combination  
 677 of a prior (obtained from experts – the configuration belief structure and the HFE being *true*) and a posterior  
 678 (assigned for the application, represented by direct belief structure as obtained in section 2.3.4) evidence. Finally,  
 679 towards safety objectives only the state of PSF under analysis is kept (i.e. *poor*), other focal sets and their BPAs  
 680 are not discussed. The results of the sensitivity analysis are presented as a bar graph. From the marginal obtained  
 681 for the *poor* state of a PSF, relative values are calculated and presented in percentage form. In other words each  
 682 bar represents the relative percentage contribution of a PSF being *poor* leading to the HFE being *true*. This is

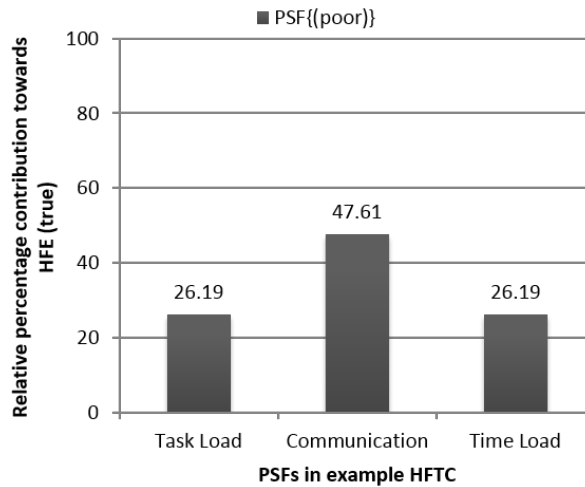


Fig. 5: Sensitivity analysis results for example HFE and associated PSFs.

683 interpreted as the contribution of a PSF towards causing an ‘error’. It is to be noted, that this choice of states  
 684 of the variables (*poor* and *true*) is driven by the objectives of the current analysis. A reverse propagation can be  
 685 performed on any variable and any of its state(s). The results obtained for the example HFE are shown in Figure  
 686 5. It can be seen that Communication has clearly a higher contribution than the other two PSFs. Thus it can be  
 687 concluded that improving the aspects of Communication should be the priority.

688 It can be remarked here that for questions of the example HFE, expert valuations (*bpa* values) are different  
 689 (i.e. combined probabilistic response for a question, as given in section 2.3.3). On the other hand, the direct belief  
 690 structures in Table 6 are the same for the case of Time Load and Task Load. Now, as seen in Figure 5’s, the  
 691 feedback seems to reflect direct evidence, as it states Task Load and Time Load (for their poor level) to be equally  
 692 likely contributors towards the HFE. However, it does not seem to reflect the differing expert valuations. This is  
 693 due to the fact that the configurations belief structure’s focal set is symmetric, as obtained by the transformation  
 694 approach from equation 8. This leads to the marginal obtained in the first step of sensitivity analysis being same  
 695 across all PSFs. This is a constraint stemming from the simpler questions asked to the experts, as a question  
 696 with more than one PSFs can have a non-symmetric focal set in the configuration belief structure. But then again  
 697 an expert might find it difficult to respond to such questions, however, other data sources (such as simulator  
 698 experimentation) can be used. This concludes the quantitative proposition employing the VBS model.

### 699 3 CASE STUDY

700 This section presents the application of PRELUDE on a recent catastrophic high-speed railway accident’s scenario.  
 701 In this accident human error was concluded to be as one of the primary causes. Data (factors, events, etc.) are taken  
 702 from the official investigation report [85]. This work neither aims to nor can achieve the detailed and exhaustive  
 703 analysis provided in the official investigation report. Here, the prime motive is to demonstrate the usage and  
 704 application of proposition as a retrospective analyses.

705 The usage of PRELUDE in this case study is demonstrated by employing the three steps as shown in Figure  
 706 1. This application process is generic; the way in which each step is conducted depends upon the purpose of  
 707 the analysis. Step 1 follows the traditional sense of defining the scope of the analysis, and analyzing an accident  
 708 scenario to identify the HFEs and related PSFs, to characterize a safety critical situation. For a prospective approach  
 709 this can be a procedure and operational context. Step 2 puts PRELUDE’s quantitative propositions from section  
 710 2.2 and section 2.3 into action – elicitation of data from experts, and combination and transformation thereof.  
 711 Finally, in Step 3, the quantification data for application (direct evidence) is entered in the model, and the results  
 712 of quantification and sensitivity analysis are presented and commented on.

TABLE 8: HFE and relevant procedures from the accident investigation report and national regulations

Identified Human Failure Event from the accident report	Source and procedure/task description
HFE1. Ineffective communication	<i>Accident investigation report</i> – “. . . a contributing cause was an absence of attention of the train driver . . . after answering a phone call. . .” No strict procedures/rules (except a guide to good practice in driving.)
HFE2. Not respecting the speed signals (in schedule book/table of speeds)	<i>Accident investigation report</i> – “. . . not respecting the prescribed maximum speed allowable by infrastructure, as established in the tables of maximum speeds mentioned in the train Schedule book. . .”
HFE3. Not reducing speed in time	<i>Accident investigation report</i> – “driver should identify the reference (point) to initiate the braking and to reduce the speed.” <i>Regulations</i> – “The driver shall endeavor to recognize the signs (signals) as far as possible and do not lose interest in their observation as (long as) it (train) has not crossed them.”

### 713 3.1 Step 1. Qualitative part: HFE and PSF(s) identification

714 Before the application of PRELUDE, this step defines scope of the analysis to limit the problem-set. Main  
 715 considerations include: type (retrospective), and detail (procedures, and human actions or functions). Since current  
 716 scope is limited to analyzing the accident scenario and demonstrating key aspects of the proposition, thus, only  
 717 the immediate HFEs and PSFs which are direct causes of the accident are analyzed.

718 The report provides a detailed and chronological account of noteworthy events which led to the accident  
 719 in question. It is thus, used to identify the HFEs. A reverse task-analysis approach is implemented, where the  
 720 starting point is the immediate safety critical events involving a human (HFEs) in the accident report. Further,  
 721 as needed detailed operating procedures and the signaling principles were consulted from the national regulation  
 722 documents, such as directive guidelines which contain procedures requiring ‘passive and immediate obedience’  
 723 from a human actor. These directives can be considered to have a higher priority than for example, non-regulatory  
 724 or non-normative guidelines such as ‘good practices in driving’. The sources and how they are used is given as  
 725 follows:

- 726 • Accident investigation report – identification of HFE (non-accomplishment of a task or function) and  
 727 description.
- 728 • National regulations – detailed description of the procedures, previously identified task is part of.
- 729 • Human factors studies (EUAR HF) – identification of safety critical situation mapping of human function  
 730 and previously identified HFE.

731 Finally, the identified HFE, excerpts from the report and the relevant procedures given in Table 8.

732 The plot in Figure 6 aims to show the HFEs (annotated in yellow-red ovals) in chronological occurrence of  
 733 the accident scenario. The horizontal axis represents distance from the accident point in meters and vertical axis  
 734 represents speed in km/h.

735 Further, the safety critical situation of the respective HFEs needs to be identified. This activity follows steps of  
 736 section 2.2 identify the PSFs and subsequently  $HFTC_{HFE}$  for every HFE. The EUAR HF study is also used here,  
 737 for additional identification of the PSFs, using a mapping of HFEs to *human function*. A *human function* which  
 738 matches closest to the HFE under analysis is identified from the EUAR HF study. *EUAR/HFG4/35* is defined as  
 739 “Maintain appropriate speed” which entails the *personal and organizational goal* – “To ensure movements at a  
 740 speed that is safe for the vehicle in the current conditions and in accordance with the timetable.” This definition  
 741 matches with both the *HFE2*: Not respecting the speed signals in schedule book) and *HFE3*: Not reducing speed  
 742 in time, as identified in Table 8. In addition to the sources used in section 2.2.2 (i.e. EUAR HF study, PSF list,  
 743 ECs) extracts from accident investigation report are also used to account for accident scenario specific PSFs. It  
 744 gives a retrospective account of casual factors that influenced the human towards those errors. For example, it  
 745 states – ‘the train driver (the human actor) did not brake (the activity required of him) because of distraction (the

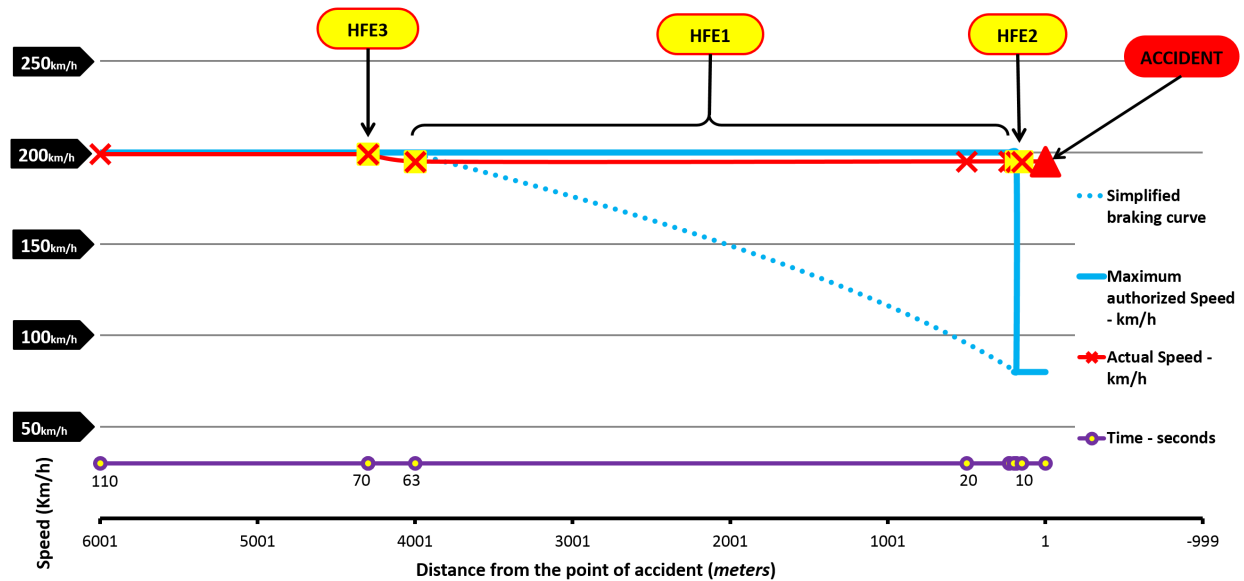


Fig. 6: Accident scenario: speed of the train vs. distance from the point of accident. The data points (cross marks) are other events as identified in the investigation report and the HFEs. Also a time scale is given to represent the time duration of the analyzed scenario.

746 factor)'. Hence, the context is dealing with the train driver performing the human function/task of braking; the  
 747 act of not braking (non-accomplishment) is the HFE. Here, 'distracted' becomes a factor of interest for a human  
 748 function's error (HFE) context  $HFTC_{HFE}$ . It is important to note that, the use of accident report augments the  
 749 HFTC's construction and is application specific (qualitative part, dashed document box Figure 1). All the identified  
 750 PSFs and their sources, and the recurring PSFs (underlined based on the preference presented in section 2.2.2),  
 751 and finally the HFTCs are given in Table 9.

TABLE 9: Identification of PSFs for defining HFTC for HFEs from the accident scenario

Human Failure Event	Performance Shaping Factor identification	Human Failure Type Context ( $HFTC_{HFE}$ )
HFE1	<b>EUAR/HFG5/53</b> – Communication; <b>PSF list</b> – Experience, <u>Communication</u> , Situational awareness, Task Load (Workload), Time load (Workload), HSI quality; <b>Accident investigation report</b> – <u>Communication</u> ; <b>Error Context</b> – <b>EC1</b> = {Training, HSI quality, Task load, <u>Communication</u> , Time load}	$HFTC_{HFE1} = \{Communication\}$
HFE2	<b>EUAR/HFG4/35</b> – Training (skill), Experience (local knowledge); <b>PSF list</b> – Training, Experience, Communication, <u>Situational awareness</u> , Task Load (Workload), Time load (Workload), HSI quality; <b>Accident investigation report</b> – <u>Situational Awareness</u> ('lack of attention'), <u>HSI quality</u> ('lack of regulation on track-side fixed preventive signaling'); <b>Error Context</b> – <b>EC2</b> = { <u>Situational awareness</u> , <u>Experience</u> }, <b>EC3</b> = {Task load, HSI quality, Time load, <u>Situational Awareness</u> }	$HFTC_{HFE2} = \{Experience, Situational Awareness, HSI quality\}$
HFE3	<b>EUAR/HFG4/35</b> – Training (skill), Experience (local knowledge); <b>PSF list</b> – Training, Experience, Communication, <u>Situational awareness</u> , Task Load (Workload), <u>Time load</u> (Workload), HSI quality; <b>Accident investigation report</b> – <u>Situational awareness</u> (as dissonant 'cognitive location'), <u>Time Load</u> (Figure 6); <b>Error Contexts</b> – <b>EC2</b> = { <u>Situational awareness</u> , <u>Experience</u> }, <b>EC3</b> = {Task load, HSI quality, Time load, <u>Situational Awareness</u> }	$HFTC_{HFE3} = \{Situational Awareness, Time Load, Experience\}$



TABLE 10: Context description and questions for HFE2 sent to the experts

HFE and questions	Context description and question statements	Other information
<i>HFE2. Not respecting the Speed Signals (in schedule book).</i>	Definition of HFE from Table 8, and more details, . . . speed change from 220km/h to 80km/h . . . track-side information is a marker indicating a change in maximum permitted speed.” <i>General remarks</i> – The signaling system/ATP in place does not protect against over speeding in the case of permanent maximum speed changes. The train driver is wholly responsible for this action.	PSFs and their definitions in HFTC <sub>HFE2</sub> (definitions of <i>Situational Awareness, HSI quality, Experience</i> also included here from Table 2)
Question 1. <i>Experience- HFE2</i>	Given the occurrence of a <i>poor</i> level of <i>Experience</i> , what do you think about <i>HFE2</i> being <i>true</i> ?	
Question 2. <i>Situational Awareness - HFE2</i>	Given the occurrence of a <i>poor</i> level of <i>Situational Awareness</i> , what do you think about <i>HFE2</i> being <i>true</i> ?	
Question 3. <i>HSI quality-HFE2</i>	Given the occurrence of a <i>poor</i> of <i>HSI quality</i> , what do you think about <i>HFE2</i> being <i>true</i> ?	
Question 4. all PSF <i>nominal-HFE2</i>	Given the occurrence of a <i>nominal level of all the PSFs</i> what do you think about <i>HFE</i> being <i>false</i> ?	
Answering aid/instructions: The response is expected on a probability scale, i.e. how many times out of 10, 100, 1000, etc. do you expect an HFE to be <i>true</i> . Or natural language descriptors can be used. They are defined as follows: <i>Likely, 0.5 (5 out of 10 would fail)</i> <i>Infrequently, 0.1 (1 out of 10 would fail)</i> <i>Unlikely, 0.01 (1 out of 100 would fail)</i> <i>Extremely unlikely, 0.001 (1 out of 1000 would fail)</i> <i>Insufficient information</i>		

752 From a functional perspective, the act of braking and respecting a speed signal forms one single function. In  
753 the EUAR HF study the scope of *human function* (HFG4/35) entails both HFE2 and HFE3. Since present work  
754 is concerned with a detailed and precise analysis of the accident scenario; hence, they were quantified as separate  
755 HFEs. An appropriate granularity level in accordance with analysis objectives and thus, appropriate source of data  
756 must be selected. Current approach, takes such data from multiple sources to precisely identify the PSFs involved.  
757 Such, details might not be otherwise observed, if a single point of view is taken.

### 758 3.2 Step 2. Quantitative part: Expert elicitation, data combination and transformation

759 Three experts with different domain expertise were consulted. Their combined expertise covers human factors  
760 engineering, railway signaling, BFT, and safety and reliability aspects of the railway domain in general. Such a  
761 variety of domain knowledge is in-line with what is advised by other such expert-data based methods. Further,  
762 independent elicitations were carried out. The experts were sent the questions and related context detail. Table 10  
763 shows the questions and descriptions for HFE2. Similar structure was followed for other HFEs identified in Step  
764 1.

765 The responses received were a mix of numerical values and descriptors (numerical equivalents therefore were  
766 used). The numerical values thus obtained, for each question from the three experts A, B, and C are given in  
767 Figure 7. Subsequently, data from each expert for each question was combined using different combination rules  
768 (section 2.3.2). For weighted average (WA) combination a choice was made to give a higher weight to expert with  
769 experience in the railway industry (expert C). Thus, the following normalized weighting factors were chosen: 0.2  
770 for expert A and B, and 0.6 for expert C. The combined values for each question thus obtained is also given in  
771 Figure 7.

772 Separate belief structures were generated (section 2.3.3) for each of the five combination methods. That is  
773 for each combination method used, different *bpa* was generated for each HFE’s VBS model. Expanding on  
774 the discussion of section 2.3.2, here we briefly comment on the different combination rules to demonstrate the  
775 difference. The Figure 7 shows in the form of the grouped bar plots for each question – the expert data (first three  
776 bars) and the data obtained after different combination rules (latter bars in the same group). The expert data for

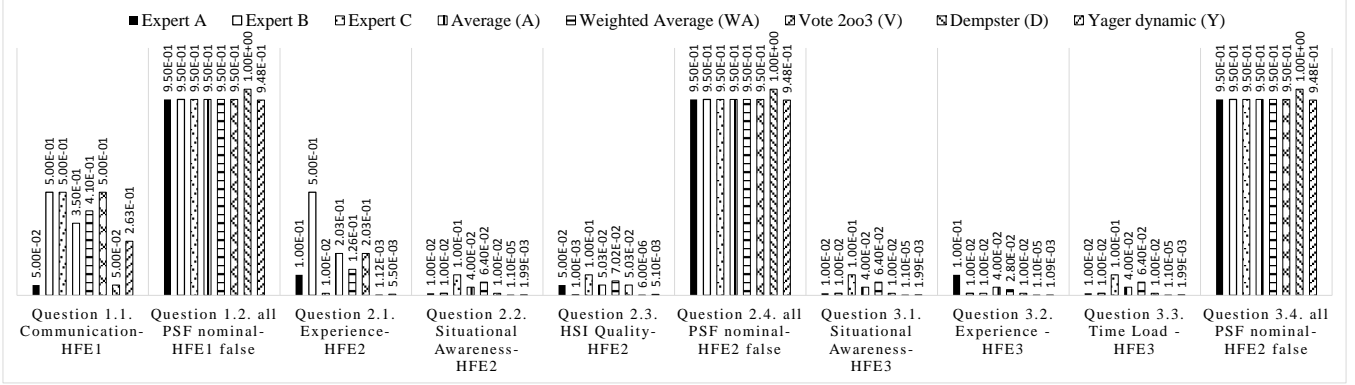


Fig. 7: Expert data (first three bars) and data obtained from the combination rules, for the case study.

TABLE 11: Direct belief structures (focal set and BPA) for the PSFs in the case study, identified similar to as in Table 6 from the R-PSF equivalent

PSFs used in the case study	BPA for focal set $m^{PSFi}(\{(poor)\})$	BPA for focal set $m^{PSFi}(\{(nominal)\})$
Communication	0.136	0.864
Experience	0.0787	0.9213
Situational Awareness	0.144	0.856
HSI Quality	0.1885	0.8115
Time Load	0.0173	0.9827

777 *question 1.1.* is commented here, similar comments can be made for other questions. It can be observed that expert  
 778 B and C give the same probability value, whereas expert A gives a significantly lower probability value. This  
 779 discussion is from the perspective of what the experts say (the probability values they give) and the combined data  
 780 that is obtained.

- 781 • A weighted average is different than simple average since it enriches an average by taking into account the  
 782 expertise of an expert (higher weight).
- 783 • A vote tends to account for essentially what majority of experts say, irrespective of their expertise (weight)  
 784 or the difference between the values themselves.
- 785 • In Dempster's rule the difference between the values is interpreted as as conflict ( $k$ ). Subsequently,  
 786 Dempster's rule manages this conflict by normalizing it. The higher the conflict, the more normalization  
 787 is performed. There is a conflict in this case, thus, a value smaller than previous combination rules is  
 788 obtained.
- 789 • Furthermore, non-idempotent nature of Dempster's and Yager's rule (Table 5 )gives some interesting results  
 790 for question 1.2., 2.4. and 3.4.
- 791 • Yager's rule computes the conflict similarly, but treats it as an uncertainty instead of normalizing it.  
 792 Therefore, a value higher than Dempster's rule is obtained. It may be noted that the version of Yager's rule  
 793 (dynamic) used here is quasi-associative (Table 5). That is the order in which the expert data is combined  
 794 has an influence on the combination result. Thus we see that, for question 3.1. vs. 3.2. Yager gives different  
 795 results (1.99E-03 vs. 1.09E-03).

796 When the conflict is low, (and all the experts are reliable) under situations of minimal or irrelevant conflict and  
 797 all of the sources can be considered reliable, a Dempster combination might be justified.

798 Here the frames for  $HFE2$  and  $HFE3$  were considered same as the example HFE in section 2.3.4, that is  
 799  $\Omega_{HFE} = \{true, false\}$ , and for PSFs as  $\Omega_{PSFi} = \{nominal, poor\}$ . With the exception of HFE1, here,  $\Omega_{Communication} =$   
 800  $\{good, nominal, poor\}$ , to demonstrate the ability to work with multi-state PSFs. The level good was treated

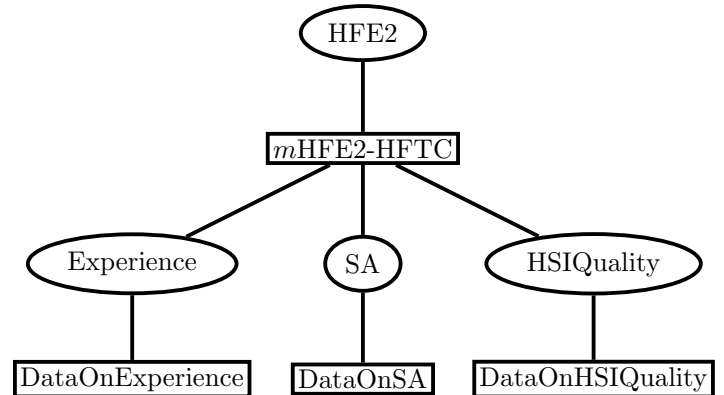
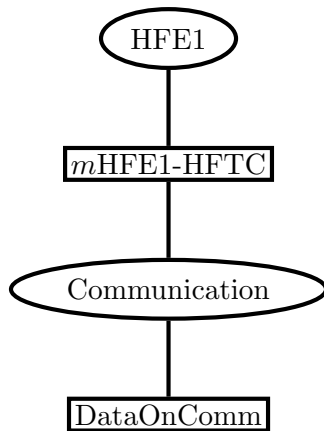


Fig. 8: VBS model of HFE1 and its HFTC. Fig. 9: VBS model of HFE2 and its HFTC.

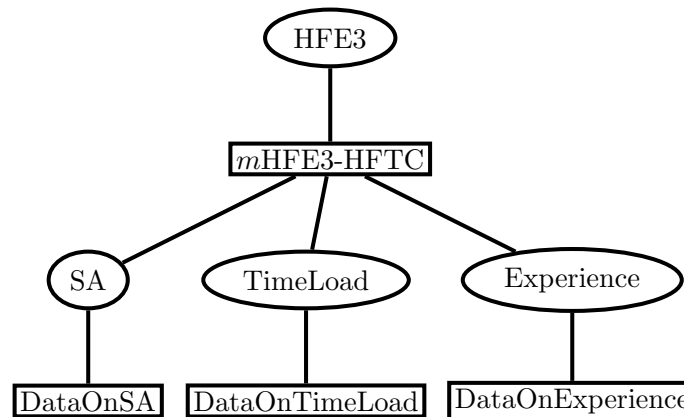


Fig. 10: VBS model of HFE3 and its HFTC.

801 similar to nominal as far as questions to the experts and quantification data (direct belief structure given in Table  
 802 11) are concerned. Configuration belief structures were defined and transformed the same way as other questions  
 803 (following steps of section 2.3.3). For all the HFEs the modeling in VBS is thus complete. The implementation  
 804 in VBS is given for HFE1 in Figure 8, HFE2 in Figure 9 and HFE3 in Figure 10. It can be noted that the human  
 805 reliability models thus constructed are not specific to the case study. It can be used wherever similar HFEs and  
 806 PSFs are identified. The quantification results and feedback/sensitivity analysis results are presented and discussed  
 807 in the next step.

### 808 3.3 Step 3. Quantification data and results

809 Finally, in the last column of Table 11 the data for quantification, i.e. direct evidence, for respective direct belief  
 810 structures are obtained from accident statistics data (explained in section 2.3.4). This data for quantification is  
 811 assigned to all the PSFs of the case study (data on PSFs as seen in Figure 8, 9 and 10).

812 Each of the combination rules used gives a different result. However, one combination rule can be chosen  
 813 to obtain the necessary results i.e. an interval for each state of the variable of interest (an HFE). Nevertheless,

TABLE 12: Top: *Middle of the probability interval* for the variable  $HFE1$  value of interest ( $true$ ) as obtained after combining data using different combination rules. Bottom: The pairwise *distance metric*  $d_j$  from equation 2, between the BPAs obtained for  $HFE1$ .

Middle of interval	mAverage	mWeightedAverage	mVote	mDempsters	mYagers
for $HFE1(true)$	0.113	0.117	0.124	0.071	0.108

BPA obtained from combination rule	mAverage	mWeightedAverage	mVote	mDempsters
mWeightedAverage	0.797	-	-	-
mVote	0.797	0.799	-	-
mDempsters	0.817	0.819	0.821	-
mYagers	0.797	0.799	0.801	0.82178

814 towards PRELUDE’s guide on the choice of combination methods (in addition to discussion in section 2.3.2) a  
 815 brief discussion is presented here. This comparison is different than what was discussed in the previous section,  
 816 where the combination of expert data and immediate results were discussed. Further, in this case the combination  
 817 rules are compared at the level of end-results, which are BPAs obtained for the HFE. Only  $HFE1$  are discussed  
 818 here, similar metrics can be computed for other HFEs.

819 Table 12 gives the middle of the interval for the variable of interest  $HFE1(true)$  as described in section  
 820 2.1.3. In this case the  $true$  value of HFE is chosen. It can be remarked that the middle of the interval for all the  
 821 combination rules are similar except for Dempster’s rule. This is because of the way in which it manages conflict  
 822 is different than Yager’s rule, and others which do not manage conflict explicitly (see section 2.3.2).

823 The distance metric  $d_j$  can take a maximum value of 1 [77]. Thus we can observe in Table 12 that all of the  
 824 BPAs have high distance values between them, that is they are dissimilar pairwise. However, relatively speaking  
 825 each BPA is at equal (maximum distances between two BPAs 0.821 and minimum 0.797) distances from each  
 826 other. In this case, the distances are not significantly informative, they do not provide sufficient information to  
 827 single out particular rules or a pair thereof which is dissimilar/similar to the others. Nevertheless, such a metric  
 828 can be useful when it is difficult to make a choice of combination rule only based on the underlying hypothesis.

829 The quantification results are represented in the form of upper and lower probability bound. The value of  
 830 variable of interest is an HFE’s true state. i.e.  $HFE(true)$ . The quantification results are given in Figure 11. The  
 831  $x$  axis marks the combination method used and the  $y$  axis is the probability value on a  $\log_{10}$  scale, with an axis  
 832 maximum of 0.2. The line-plot in  $y$  axis presents the log of lower and upper probability bound of  $HFE(true)$ . The  
 833 lower bounds for first three combination rules are of the order of  $10^{-3}$ , however for latter two (BFT-based) it was  
 834  $10^{-6}$ . Generally this is also the case with human error probabilities in other HRA methods. Nevertheless, for all  
 835 intents and purposes, the values obtained are indicative than representative.

836 The results of  $HFE1(true)$  have higher upper bounds due to the higher values obtained (an average of 0.35)  
 837 obtained from the experts. For both  $HFE2(true)$  and  $HFE3(true)$  in terms of interval size and lower bounds, a  
 838 clear distinction must be made between BFT-based (Dempster’s and Yager’s), and other combination rules. This  
 839 is due to the latter with implicit and the former with explicit handling of conflict. Weighted average implicitly  
 840 removes conflict by weighing values obtained from one expert (Expert C, for present case, Figure 7) more than  
 841 others. Nevertheless, the intervals are not completely disconnected since conflict is relatively less; if it was higher  
 842 significant changes could have been observed. Therefore, simpler combination methods are as effective when  
 843 conflict is low or ignorable. In the case where ( $HFE2$  and  $HFE1$ ) lower bound for Dempster’s rule is smaller  
 844 than Yager’s; this is due to the presence of high conflict in elicited data (ref. Figure 7). In Yager’s hypothesis,  
 845 the conflict amongst expert’s values is distributed as uncertainty, instead of normalizing the lower bound. Thus, in  
 846 both the cases of  $HFE2(true)$  and  $HFE3(true)$ , Yager’s rule gives a larger interval size as compared to Dempster’s  
 847 results. That is, even though it is an accurate/formal representation of uncertainty, in some cases it might make  
 848 decision-making difficult.

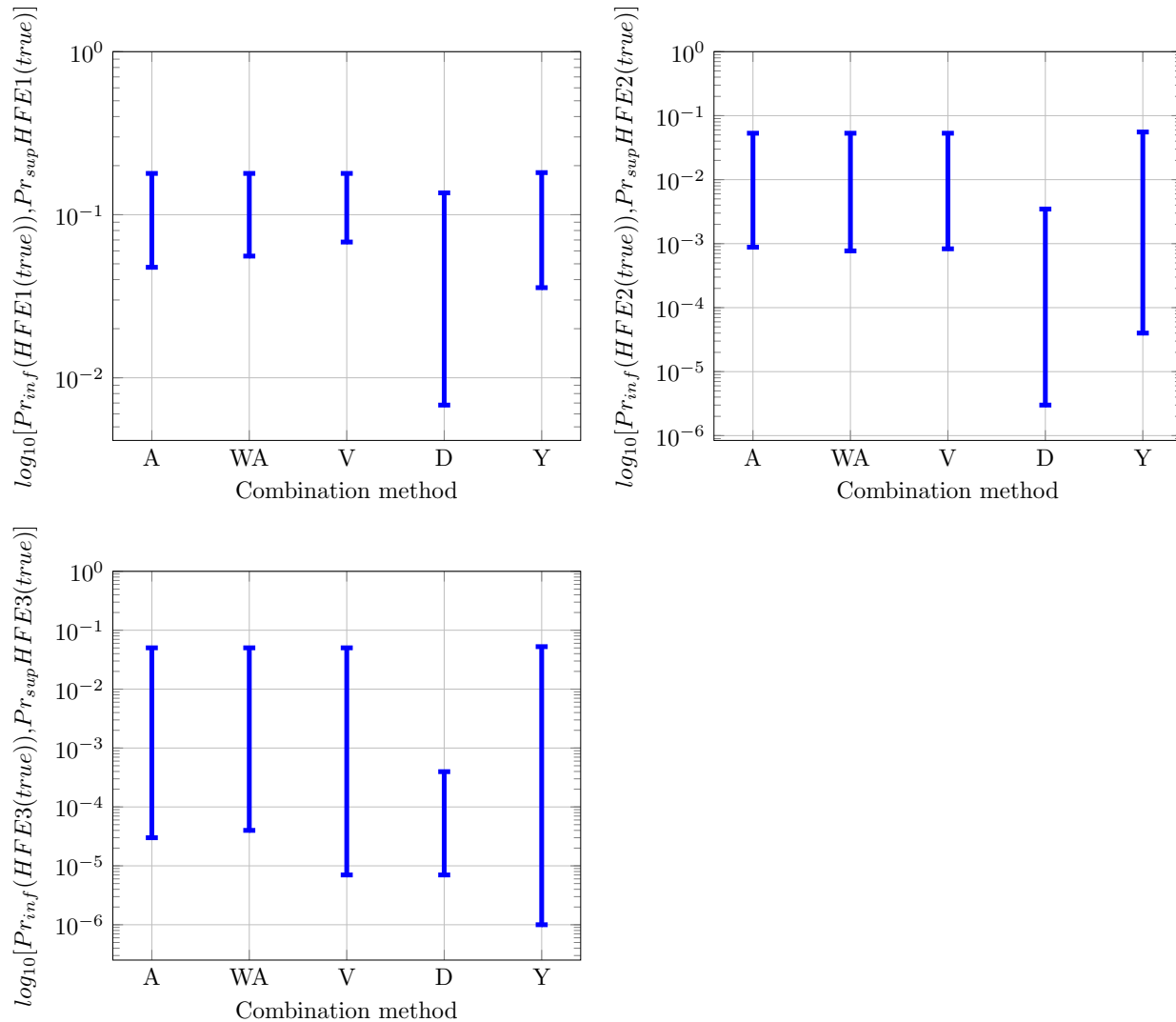


Fig. 11: Lower and upper bounds for an HFE's true state from VBS models obtained after combining expert elicitation using average (A), weighted average (WA), vote/independent consensus (V), Dempster's (D) and Yager's (Y) combination rules.

849 Towards keeping this choice open, PRELUDE methodology remains adaptable and only needs conditional  
 850 quantitative data on a PSF-HFE pair. The transformation (section 2.3.3) manages the rest to construct the VBS  
 851 model. This also ensures that explicit considerations of epistemic uncertainty (in the human error relational model)  
 852 are uniform irrespective of the combination rule used. Subsequently, for *HFE2* and *HFE3* a sensitivity analysis  
 853 (following the steps in section 2.3.4.1) is undertaken. *HFE1* is not analyzed further because it contains only one  
 854 PSF.

855 It can be noted that for each expert data combination method, different VBS models (configuration belief  
 856 structures) are generated, for space constrains it is not possible to discuss all of them here. Hence, only average  
 857 combination rule is selected for both HFE and only the *poor* level of a PSF is considered. Figure 12 shows the  
 858 obtained sensitivity analysis results. They are presented in the form of a relative percentage value, interpreted as a  
 859 relative contribution towards causing an *HFE* to be *true*. It can be seen that, *HSI quality* for *HFE2* and *Situational*  
 860 *Awareness* for *HFE3*, have the highest relative contribution. Hence, priority focus should be on improving aspects

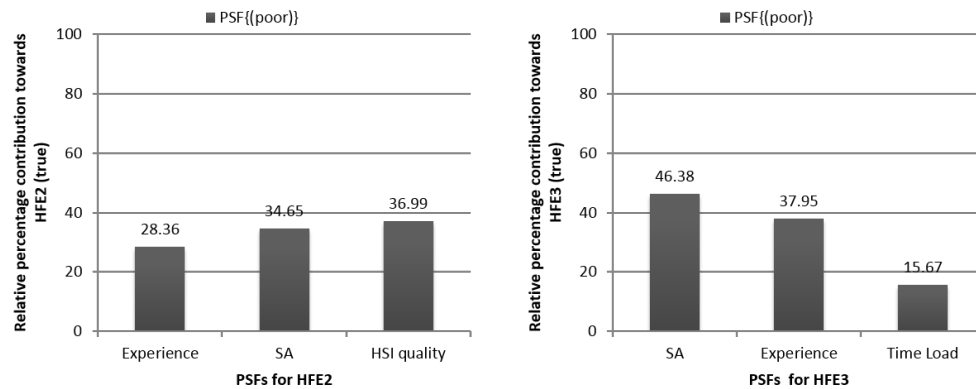


Fig. 12: Sensitivity analysis results of PSFs for the context of *HFE2* and *HFE3*.

861 of *HSI quality* and *Situational Awareness*.

862 The results effectively are also indicative of the reality (the accident investigation report) and expectations of  
 863 experts. *HFE2* can be classified as a “checking error” [86]; for a checking error the quality or source of information  
 864 (i.e. *HSI quality*) can be judged to be relatively critical than other factors. This corresponds to the results seen in  
 865 Figure 12. Thus, it can be remarked that the model gives results corresponding to conclusions from the human  
 866 error mechanisms. Furthermore, these results are also reaffirmed in the accident analysis report. The investigators  
 867 concluded that the availability of right information at the right time was indeed one of the issues. Subsequently, a  
 868 change of the placement of track-side speed markers was ordered. In particular, special considerations (more track-  
 869 side markers, gradual speed changes, etc.) are made for places where a high change in ceiling speed (200 km/h to  
 870 80 km/h, blue line in Figure 6) is required. For *HFE3*, PRELUDE’s analysis concludes that *Situational Awareness*  
 871 has the highest relative contribution. This also, corresponds to the concluding statement of the report that absence  
 872 of attention was one of the main causes of the accident. Thus, the proposed quantitative model presents results  
 873 coherent with expert and domain knowledge.

#### 874 4 CONCLUSIONS AND PERSPECTIVES

875 PRELUDE methodology in its current state is developed for and applied to a case study for the railway domain.  
 876 It may very well (with moderate efforts) be applied to other domains. A completely generic HRA model is rare  
 877 (table 1), and such models are often inspired by the notions of previous domain-specific HRA models.

878 It entails an expert system built using concepts from BFT in VBS which formally defines the casual elements of  
 879 a human reliability model. Decision-making capabilities are provided by using probability intervals and sensitivity  
 880 analysis to establish a priority ranking amongst the PSFs for a given safety critical situation. PRELUDE is centered  
 881 on Performance Shaping Factors specific for railway needs. PSFs and human factor studies are employed for an  
 882 adequate representation of human factors and operational safety concerns. It was also demonstrated as how to  
 883 employ human factor study towards HRA objectives. The expert system’s graphical representation as a VBS  
 884 allows for an easy representation of variables and their relationships, and, thus simplifies the usage by analysts  
 885 and non-experts in the mathematical framework.

886 A formal combination and transformation proposal is used to build the elements of quantitative human  
 887 reliability model from expert data. This approach to formally model human failure events as a function of the  
 888 PSFs in evidential networks (VBS) offers a novel perspective for human reliability quantification. The expert data  
 889 can be replaced by an empirical source, with the condition that it is in the form of a conditional probability, at the  
 890 very least HFE-PSF (the questions currently asked of the experts) or HFE-multiple PSFs. Conditional in terms of

891 the variable HFE and PSF, the states thereof poor or nominal, true or false, are not a limitation to BFT framework.  
 892 Thus, if the empirical data can be formulated as a (conditional) belief structure, it can be integrated into the VBS  
 893 model currently proposed.

894 Although, when combining evidences (direct and configuration belief structures) the resulting frame is the  
 895 product of the respective variables' frames, there the size of the product space may create a computational  
 896 bottleneck. That is to say, more granular variables with larger frames (i.e. multiple states of PSFs and HFEs)  
 897 are difficult to combine, compared to e.g. multiple variables (multiple PSFs and HFEs) with less number of states  
 898 (smaller frames). Some rules for combination of expert elicited data are also contrasted. A relatively straightforward  
 899 middle of the interval comparison, and a standardized distance metric are used. These metrics, as used in the context  
 900 of present work allow comparing the results obtained by using different combination rules in a quantitative manner.  
 901 It allows the experts to identify the appropriate choice of combination rule to use or justify the choice.

902 If particularly conflicting expert opinions are considered, it is observed that some methods result in larger  
 903 intervals than others. Thus, the choice thereof is left to the analyst; nevertheless, the usage of such methods needs  
 904 further investigation. Sensitivity analysis results were used to establish a priority rank towards improvements  
 905 in PSFs needed for effective gains in human reliability. Although it is more interesting if multiple PSFs and  
 906 multiple HFEs are modeled in the same EN, this might lead to non-evident sensitivity analysis results. The  
 907 proposition's implementation on a retrospective analysis of a real-world railway accident demonstrated the usage  
 908 of the methodology. Once the VBSs models are built the implementation is relatively straightforward, and interval  
 909 provides accurate representation of uncertainty in data (if any) and easy decision making. The results obtained  
 910 correspond to theoretical and expert expectations. Thus, VBS offers an adequate framework in its utility towards  
 911 newer generation of human reliability methods.

912 System level, risk-based inferences, and taking contribution of positive aspects of PSFs and human actions need  
 913 to be appended to PRELUDE towards a robust methodology. This is aimed at further simplifying the decision-  
 914 making capabilities, and performing a holistic analysis of a human error. Feedback or remarks of the experts on  
 915 the structure of questionnaire can also be obtained to improve the elicitation process, mainly to ensure that the  
 916 analyst and experts have the same understanding towards assuring the accuracy of obtained data. Validation using  
 917 simulator data and sensitivity analysis can be employed towards immediate verification objectives. Further, usage  
 918 of empirical data from operational simulators to reinforce expert knowledge and to validate the methodology needs  
 919 to be explored further.

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