Uncertainty analysis of the durability of Guyanese wood fiber insulation panels using a Credal Network

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Key words: Wood fiber insulation, Credal networks, Incompleteness, Biological durability, Reasoning modeling, Imprecise Dirichlet model (IDM).

Context and objective

Wood-fiber insulation panels made from residual biomass represent a sustainable solution for construction in French Guiana (Bossu et al 2023). However, their hygroscopic nature makes them vulnerable to biodeterioration, especially under tropical conditions marked by high humidity and biological threats such as fungi and termites (Kartal et al 2013). In this context, **durability** refers to the material's ability to resist **biological degradation over time**, particularly in response to two major agents: **wood-decaying fungi** and **wood-feeding termites**. Fungal decay enzymatically breaks down cellulose, hemicelluloses, and lignin, while termites directly consume wood, both leading to mass loss and compromised mechanical integrity of the material. The durability of wood-fiber panels depends on several factors, including wood species, chemical composition, density, moisture behavior, and environment exposure. Understanding and improving the uncertainty of such degradation is essential for their long-term use in sustainable building systems, particularly in equatorial regions like French Guiana where environmental pressures are especially aggressive.

While probabilistic methods such as Bayesian Networks (BNs) have proven useful in risk analysis (Wang 2025), they require precise probabilities, which are often unavailable in new material systems with limited experimental data. To address this limitation, we propose using a Credal Network (CN) (Cozman 2000)—a generalization of Bayesian Networks that accommodates imprecise probabilities, allowing to provide probability intervals rather than exact values. This makes CNs well-suited for modeling uncertainty in small-sample or expert-driven contexts. This approach enables more robust durability predictions and explanations, while guiding material improvements and preventive strategies, thereby strengthening the reliability and applicability of local bio-based insulation solutions in challenging environments.

The aim of this study is to explain and predict the durability of materials against attacks by temperate subterranean termite species *Reticulitermes flavipes*, the tropical dry-wood termite

Cryptotermes spp, and decay caused by the white rot fungus *Pycnoporus sanguineus*. To achieve this, credal networks are employed, which explicitly account for both epistemic and stochastic uncertainty due to from limited, incomplete, or missing data.

Materials and methods

Data description

The panels are manufactured from wood fibers extracted from three classes of residual resources: industrial by-products from sawmills, fast-growing species abundant in agricultural clearing areas, and species with a high potential for forest plantations. Associated with the chemical composition of insulation board materials (hemicelluloses, cellulose, lignin, extractive and ash), Tab. 1 **lists the features considered in this study.**

Tab. 1 : Manipulated features, TE (resp. TG, F) corresponds to *Reticulitermes flavipes* (resp. *Cryptotermes sp* and *Pycnoporus sanguineus)*

Feature	Description	Unit
Ratio	$\frac{\text{Cellulose+Hemicelluloses}}{\text{Lignin}}$	(-)
Cotation{TG,TE}	Visual examination based on EN 118 (2014) expressed in a rating scale (e.g. 1 corresponds to superficial erosion of insufficient depth to be measured)	[1:Attempted attack; 2:Slight attack; 3:Average attack; 4:Strong attack]
MC	Moisture Content after fungal exposure	(%)
MassLoss{TG,TE}	Anhydrous mass loss after termite exposure	(%)
MassLossF	Anhydrous mass loss after fungal exposure	(%)
Durability{TG,TE}	Durability class against *Reticulitermes flavipes*, *Cryptotermes sp* according to EN 350 (2016)	[Moderately durable, Sensible]
DurabilityF	Durability class against *Pycnoporus sanguineus*, according to EN 350 (2016)	[High durability, Durable, Moderately durable; low durability]
Durability	Min(Durability{TG,TE}, DurabilityF)	[High durability, Durable, Moderately durable; low durability, Sensible]

Credal networks and strong extension

When available data or prior knowledge about a variable *X* is limited or insufficient, assigning a single precise probability distribution can be unreliable. A credal network (CN) is an extension of Bayesian networks which combines graph theory with imprecise probability theory where imprecision is introduced in probabilities by means of credal sets (Troffaes 2007) (i.e. a convex collection of probability mass functions). Their network structure provides an intuitively appealing interface for human experts to model highly interacting sets of variables, resulting in a qualitative representation of knowledge, while convex sets of conditional probability distributions allow for the consideration and quantification of stochastic and epistemic uncertainties related to the system. CNs specify a closed convex set $K(\boldsymbol{X})$ of multivariate probability mass functions over the whole set of variables $\boldsymbol{X}$. Under the strong extension (Couso et al 2000) hypothesis (i.e. CN may be interpreted as a robust model of a precise yet ill-known BN), the joint credal set $K(\boldsymbol{X})$ over $\boldsymbol{X}$ may be formulated as:

$$K(\boldsymbol{X}) = CH\{p(\boldsymbol{X}): p(\boldsymbol{X}) = \prod_{i=1}^{n} p(X_i|\mathrm{Pa}(X_i)), p(X_i|\mathrm{Pa}(X_i)) \in K(X_i|\mathrm{Pa}(X_i))\} \quad (1)$$

where $\boldsymbol{X}$ denotes a random vector, *CH* denotes the convex hull, $\mathrm{Pa}(X_i)$ denotes the set of parent nodes of the node X_i and $K(X_i|\mathrm{Pa}(X_i))$ is the closed convex set of the probability mass function for the random variable X_i given $\mathrm{Pa}(X_i)$. Using a robustified version of the Dirichlet model, commonly referred to as the Imprecise Dirichlet Model (IDM) (Bernard 2009), $K\big(X_i|\mathrm{Pa}(X_i)\big)$ may be defined by:

$$K\big(X_i|\mathrm{Pa}(X_i)=x_j\big) = \left\{p_{ij}: p_{ijk} \in \left[\frac{N_{ijk}}{s+N_{ij[k]}}, \frac{s+N_{ijk}}{s+N_{ij[k]}}\right], \sum_k p_{ijk} = 1\right\} \quad (2)$$

where [.] denotes a sum, N_{ijk} denotes the number at which the state $(X_i = x_k|\mathrm{Pa}(X_i) = x_j)$ occurs in database and s is the strength of priori belief compared to the observed data. Prior weight s=1 is chosen in this paper because it reflects prior ignorance without observation and its influence diminishes naturally when data increases (Walley 1991).

The use of credal network enables various modes of reasoning, known as inference, which consists in getting information about the state of a set of variables $\boldsymbol{X_Q}$ given evidence about other variables $\boldsymbol{X_E}$. Inference on a credal network comes down to assess lower and upper bound on the probability $p\big(\boldsymbol{X_Q}|\boldsymbol{X_E}\big)$:

$$\underline{p}\big(\boldsymbol{X_Q}|\boldsymbol{X_E}\big) = \min_{p\in K(\boldsymbol{X})} \frac{\sum_{X_i\in X\setminus \boldsymbol{X_Q}\cup \boldsymbol{X_E}} \prod_{i=1}^{n} p(X_i|\mathrm{Pa}(X_i))}{\sum_{X_i\in X\setminus \boldsymbol{X_E}} \prod_{i=1}^{n} p(X_i|\mathrm{Pa}(X_i))} \quad (3)$$

An upper bound can be obtained by maximizing and $\bar{p}\big(\boldsymbol{X_Q^c}|\boldsymbol{X_E}\big) = 1 - \underline{p}\big(\boldsymbol{X_Q}|\boldsymbol{X_E}\big)$. Precise inference is an NP-Hard problem due to the existence of probabilistic convex sets in CN. Many algorithms, exact and approximate, have been proposed to deal with CN. In this study a simple Monte-Carlo sampling algorithm (Gentle 2009) is used consisting to sample randomly classical Bayesian network by using extreme conditional probabilities in $K(\boldsymbol{X})$.

To make decisions under uncertainty with imprecise probabilities, probability intervals may be compared associated with different hypotheses. There is **no universally best method** among expected utility, maximality, E-admissibility, interval dominance, **Γ-maximin, Γ-maximax, *etc.*** — it depends on the **decision context** and users **tolerance for uncertainty (**Troffaes 2007). In this study, Γ-maximin will be used, which involves adopting a cautious approach by selecting the option with the highest minimum probability.

Results and discussion

The structure of the Credal Network and the discretization of features are based on expert opinion (Fig. 1, 2). For example, experts estimate that an extractive content below 6.5% is considered moderate to low, whereas values above 6.5% are considered high. The structure informs how information flows through the network. For instance, the variable CotationTG, given DurabilityTG, Extractive, Ash, and Ratio, is independent of the rest of the variables. That means that if the hemicelluloses-to-lignin ratio, ash content, extractive content, and the durability class of the panel against *Cryptotermes spp*. are known, then additional information about other components would not provide any further insight into the degradation rating (CotationTG). Global durability is an aggregation of the three durability assessments (against *Reticulitermes flavipes*, *Cryptotermes spp*., and *Pycnoporus sanguineus*), where the overall evaluation corresponds to the worst-case durability among the three. All credal sets $K\big(X_i|\mathrm{Pa}(X_i)\big)$ are estimated according to Eq. 2.

Deductive reasoning

Deductive inference corresponds to inferring likely values of X_Q (e.g., durability) given X_E (e.g., known chemical composition) using Eq. 3. For instance, from evidence:

X_E ={Cellulose ≤ 54.5%, Hemicellulose ∈ [9.75%, 12%[, Lignin ≥ 28%, Extractive < 6.5%, Ash < 0.8%},

Fig. 1 displays that this configuration corresponds to *Dicorynia guianensis* (i.e Ang_cop in Species box in Fig.1) and there is a 58.46% certainty that the moisture content in the panel will remain below 32%. However, it is also possible for the moisture content to reach up to 84.65%, meaning there is only a 15.35% certainty that it could exceed 32% in the panel. This panel configuration resists attacks from *Reticulitermes flavipes* better (with $p(\text{CotationTE}\in\{1,2\}|X_E)>70\%$) than from *Cryptotermes spp* (with $p(\text{CotationTG}\in\{3,4\}|X_E) > 66\%$). It also appears to have durable behavior with respect to fungal decay, with $p(\text{DurabilityF}\in\{\text{Durable,High durability,Moderately}\}|X_E) > 59\%$ but is not considered durable overall due to its low resistance to *Cryptotermes spp* attacks.

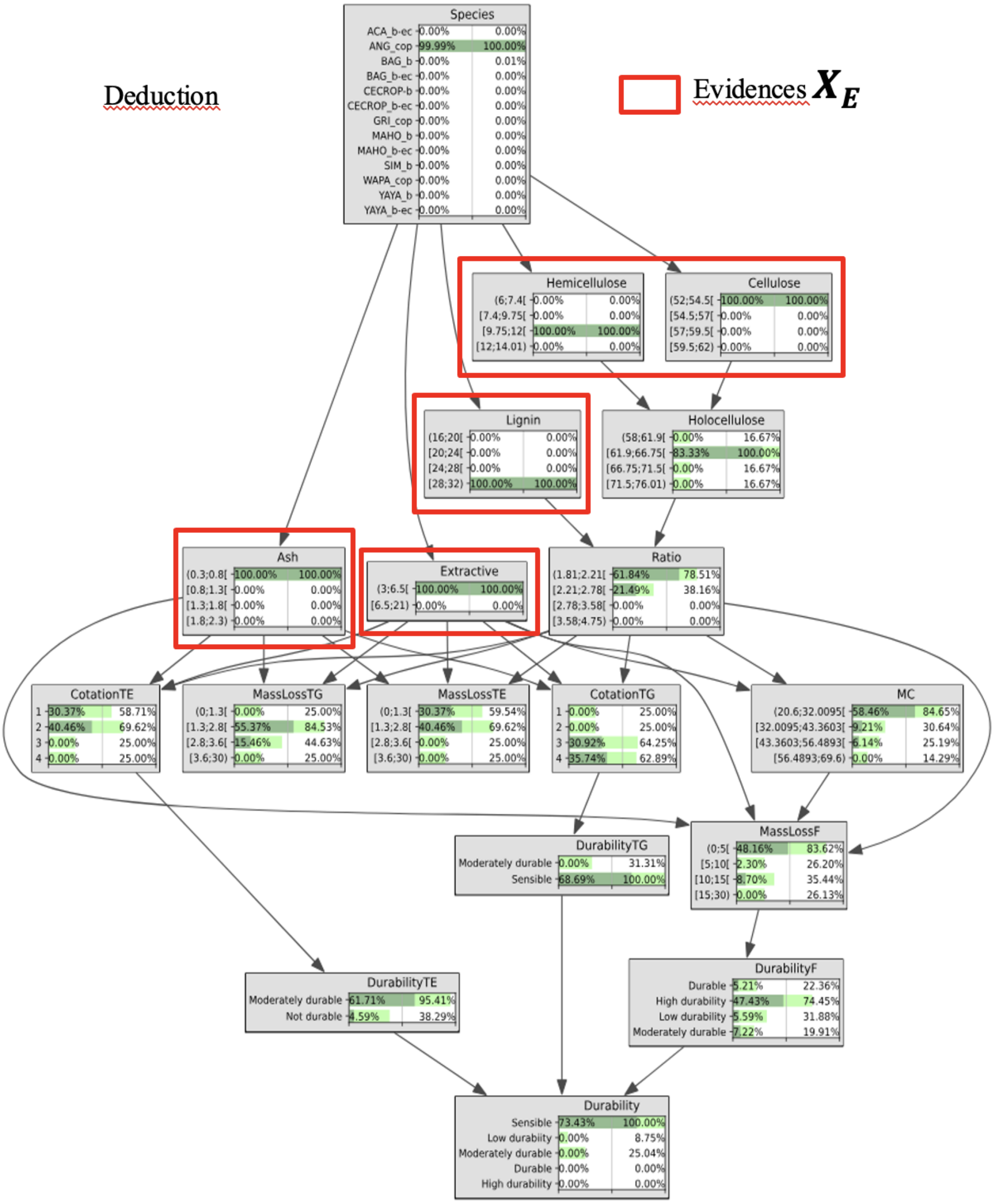

Fig. 1: Credal network model illustrating predictive inferences given the evidences marked in red boxes.

Abductive reasoning

Abductive inference corresponds to finding the most probable explanation(s) $\boldsymbol{X_Q}$ (e.g. chemical composition) given $\boldsymbol{X_E}$ (e.g., an expected durable wood fiber board). For instance, we seek to determine which chemical composition—and therefore which wood species—would most likely result in a durable insulating panel. From evidence:

$\boldsymbol{X_E}$ = {DurabilityTE=Moderately durable, DurabilityTG=Moderately durable, DurabilityF=High durability}

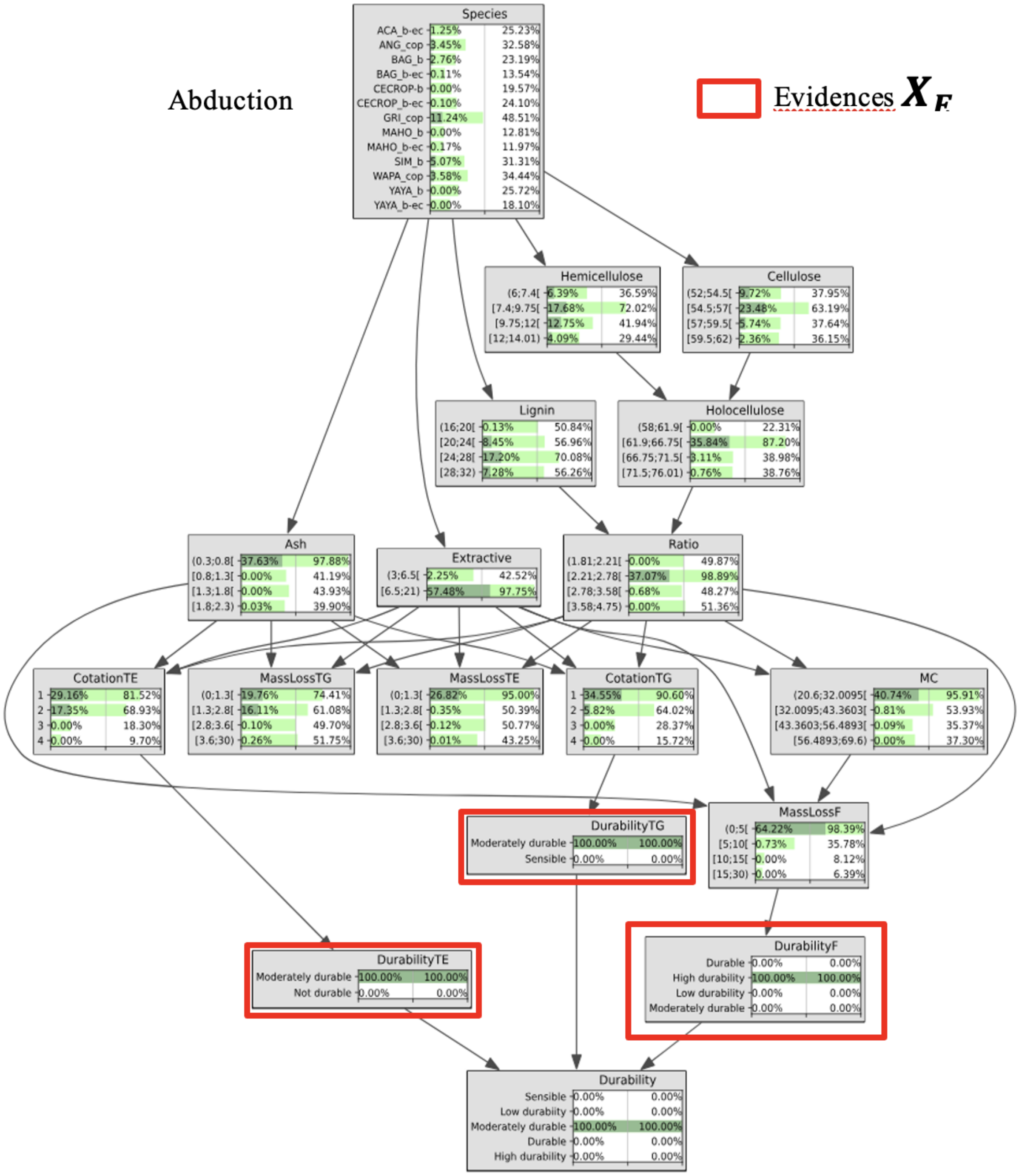

Fig. 2: Credal network model illustrating abductive inferences given the evidences marked in red boxes.

The model (see Fig.2) estimates that it is (1) 37,63% certain that the ash content is below 0.8%; (2) 57,48% certain that the extractive content is above 6.5%. Given the variability of wood species and the lack of data, and by adopting a cautious strategy (i.e Γ-maximin), the model indicates that it is preferable to select species with an ash content below 0.8%, an extractive content above 6.5%, and a lignin (respectively hemicellulose and cellulose) content between 24% and 28% (respectively between 7.4% and 9.75%, and between 54.5% and 57%), which corresponds to *Sextonia rubra* (i.e Grip_cop in species box in Fig. 2)

Conclusion

This study demonstrates that Credal Networks offer a robust framework for modeling the durability of wood-fiber insulation panels under uncertainty. By accommodating imprecise probabilities and expert knowledge, this approach supports cautious, data-informed decisions for sustainable material selection in tropical environments like French Guiana.

Acknowledgements

The authors would like to thank the project ANR-22-CE43-0019 PANTHER²-Guyane from where the database originated. In addition, this work has benefited from an "Investissement d'Avenir" grant managed by Agence Nationale de la Recherche (Centre d'Etude de la Biodiversité Amazonienne, CEBA, ref. ANR-10-LABX-25-01). This study uses the PyAgrum[1] library, a scientific C++/Python toolkit for Probabilistic Graphical Models, developed at the Laboratoire d'Informatique de Paris VI.

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