Probabilistic relational models with class hierarchies to represent and simulate the multi-layer system of construction projects.

Tran Thi Thuy Phuong

Univ. Bordeaux, I2M, UMR 5295, F-33400 Talence, France

Prix Jeunes Chercheurs "René Houpert"

RÉSUMÉ. *De nombreux facteurs et évènements tels que des erreurs humaines ou des aléas naturels peuvent conduire à l'échec des projets de construction (non-respect des délais, des coûts…). En dépit d'une documentation importante sur la gestion des risques, aucune approche holistique n'est proposée pour représenter un projet de construction intégrant aussi bien des dimensions techniques et humaines qu'envrionnementales. Dans cet article, un modèle générique et holistique innovant, basé sur le formalisme de modèles relationnels probabilistes avec hiérarchies de classes (PRM-CHs), a été développé pour analyser et propager les risques dans les projets de construction. Ce modèle est capable de (1) décrire et instancier tout type de projet de construction, (2) tenir compte de l'incertitude et (3) simuler et prédire le comportement de chaque variable à différents niveaux de détail au cours du projet de construction. Afin d'illustrer cette approche, un cas réel simplifié (rénovation de projet routier à Hue, Vietnam) est proposé.*

ABSTRACT. *Many factors as human errors or natural hazards may cause immediate or long-term construction project failures, delays, etc. Despite a substantial literature about risk management, none holistic approach is proposed to represent construction project integrating technical, human or sustainability dimensions. In this paper, an innovative generic and holistic model, based on the formalism of probabilistic relational models with class hierarchies (PRM-CHs), has been developed to analyse and to propagate risks in construction project. This model is able (1) to describe and to instantiate any kind of construction project, (2) to take into account uncertainty and (3) to simulate, predict the behaviour of each variable at different level during the construction project. In order to illustrate this approach, a simplified real case which is extracted from a road project renovation in Hue (Vietnam) is proposed.*

MOTS-CLÉS: *Projet de construction, Gestion des risques, Modèles relationnels probabilistes avec hiérarchies de classes.*

KEYWORDS: *Construction project, Risk management, Probabilistic relational models with class hierarchies.*

Nomenclature	
A, B	Attributes
$\mathcal{A}$	Sets of attributes
A(C)	Sets of attributes associated with the concept C
BN	Bayesian Network
C	A concept
$\mathcal{C}$	Sets of concepts (entities)
c	An element (an object or an instance)
C.A	An attribute of the concept C
c.A	An attribute of the element c
CPT	Conditional Probability Table
$\mathcal{I}$	Set of instances
$\mathcal{I}$(C)	Set of instances (elements, objects) associated with the concept C
PRM	Probabilistic Relational Model
R	A relation
$\mathcal{R}$	Sets of relations
$\mathcal{R}$(C)	Sets of relations associated with the concept C
$\mathcal{V}$(C.A)	Sets of values of the attribute A of the concept C
σ_R(C)	Skeleton of each concept
P(.)	Probability measure

1. Introduction

Each project is a unique and temporary process that consists of many activities which are performed and controlled by actors to achieve requirements under the conditions of time, cost, quality [ISO 03]. Most construction projects do not reach their expected results regarding time, cost and quality, due to the internal and external environment variations [LOV 02], as the impacts of human factors [AND 99], natural hazards [MID 07], technological hazards etc. It exists a lot of examples of project failing to reach their objectives (time, cost, quality). Recent examples in France are the 'Philharmonie de Paris' project that was delayed about 24 months and whose final cost exceeded the prior estimate by 276 M€, the budget of 'Musée des Confluences' in Lyons which changed from 61 M€ (initial cost) to 253 M€ (final cost).

There existed some researches mentioning about building a holistic relational model of construction project. Tepeli *et al*. [TEP 02] tackled to construction project integrating technical, human dimensions in different level like relational database. In order to analyse risks impact on time, cost and quality of construction project, Taillandier *et al*. [FRA 15] developed an agent-based model in which agent represents construction project component integrating well technical and human dimensions. Boateng *et al*.[BOA 15] analysed holistic approach which mentioned on social, political, environmental, economic, and technical risks in one detailed level. Although there exists a substantial literature about risk management in civil engineering, and if a wide variety of tools and methods have been proposed to improve the risk management, such works suffer from the weak fragmented representation of knowledge and from the lack of common vocabulary.

In this sense, the hierarchical ontology paradigm enables to formalize, structure and share the knowledge by providing a hierarchic organization of concepts and of their relations ([KHA 14], [JIA 13], [GIL 05]). El-Diraby *et al.* [ELD 05] developed an ontology into many levels for the construction domain allowing to share a common vocabulary and retrieval of information. Sun *et al.* [SUN 09] presented how taxonomies (about change causes and change effects) may be used by professionals to manage changes during the construction projects. Jiang *et al.* [JIA 13] provided an ontology-based semantic retrieval method to use projects' experience for risk management of construction project but their analysis was restricted to risks of cost overrun. Niu *et al.* [NIU 15] developed a first version of a taxonomy (a part of ontology) to address actual construction contractual claim issues. Zhong *et al.* [ZHO 15] developed an ontological and semantic model for construction risk knowledge formalization. None holistic approach is proposed to represent construction project integrating as well technical, human dimensions and sustainability dimension at different levels. Hierarchical ontology describes the system but that formalism is not capable of simulating the behaviour of the system while taking into account uncertainty at different detailed levels. In this context, the framework of probabilistic relational models with class hierarchies (PRM-CHs) [GET 07], like probabilistic relational model (PRM) [MED 10], provides a practical mathematical formalism that allows to describe complex stochastic dynamical systems but in different detailed levels. The hierarchical network structure provides an intuitively appealing interface for human experts to model highly-interacting sets of variables, resulting in a qualitative representation of knowledge.

The aim of this paper is to propose an innovative generic and holistic model in order to improve the risk management in construction project. It combines the development of a specific hierarchical ontology with PRM-CHs to analyse and propagate risks deriving from all uncertainties existing in this complex, dynamic and multi-scale system. The paper is organized as follows: The next section gives an overview about the manipulated PRM and PRM-CHs. Section 3 proposes a generic holistic modelling of construction projects based on PRM-CHs. Section 4 shows an implementation of a real simplified case-study of a road and bridge construction in Hue, Vietnam. Finally, section 5 shows how this approach can deliver quantified results and how they can be analysed.

2. Methodology

2.1. Probabilistic relational models (PRMs)

Probabilistic relational models (PRMs) [GET 07][PIE 12] extend the formalism of Bayesian networks by relying on ontology scheme; the attributes (as named properties and characteristics) A of concept C, denoted C.A, represent random variables. It enables to structure knowledge using ontology paradigm (concepts, attributes, and their relations) and to take into account uncertainty over relations by adding conditional probability between attributes. Formally, PRMs may be formalized by:

– A set of nodes c.A for all $C \in \mathcal{C}$, $c \in \mathcal{I}(C)$ and $A \in \mathcal{A}(C)$ where $\mathcal{I}(C)$ denotes the set of instances of type C and $\mathcal{A}(C)$ denotes the set of attributes relation associated with the concept C. For example, fig.1.a, fig.2.a displays a graphic structure with two concepts (C) *Environment* and *Actor* (i.e. $\mathcal{C} = \{C_1, C_2\} = \{Environment, Actor\}$). Attributes *Aggressiveness* (resp. *Cost*) allows to give some properties about the concept *Environment* (resp. *Actor*). That is $\mathcal{A}(Environment)=\{A_1\}=\{Aggressiveness\}$ and $\mathcal{A}(Actor)=\{A_2\}=\{Cost\}$. Fig. 1.b. and 2.b displays an instantiation of ontology model where $\mathcal{I}(C_1)=\mathcal{I}(Environment)=\{c_1^1\}=\{Environment\ of\ a\ project\}$, $\mathcal{I}(C_2)=\mathcal{I}(Actor)=\{c_2^1, c_2^2\}=\{Owner\ of\ a\ project,\ Contractor\ of\ a\ project\}$. Set of nodes (c.A) consists of $c_1^1.A_1$, $c_2^1.A_2$, $c_2^2.A_2$, i.e. *Environment.Aggressiveness, Owner.Cost*, *Contractor.Cost* (fig. 1c and 2.c).

– A set of parents $Pa(c.A) = (U_1, ..., U_l)$ where U_i may have the form c.B or γ(c.R.B) for all $i \in (1, ..., l)$ where R is a slot chain (i.e. combination of relations) and γ is an aggregation operator. For example, dashed arrow in fig. 2.a. encodes the reference slot *Environment.Impacts=Actor* and dashed node encodes the reference node *Actor.Impact*$^{-1}$*.Aggressiveness.* Hence*, Owner.Cost* and *Contractor.Cost* depends on:

- $\gamma(Owner.Impacts^{-1}.Aggressiveness) = \gamma(Owner.Cost)$
- $\gamma(Contractor.Impacts^{-1}.Aggressiveness) = \gamma(Contractor.Cost)$

– The conditional probability distributions P(c.A|Pa(c.A)), by assuming that P(c.A|Pa(c.A)) = P(c'.A|Pa(c'.A)) for all $(c,c') \in \mathcal{I}(C)^2$. For $u \in \mathcal{V}(U)$, $P(c.A|u) : \mathcal{V}(C.A) \rightarrow [0,1]$ defines a probability mass distribution over V(C.A) where V(C.A) denotes the domain of attribute values. For example, Fig. 2.a. shows the conditional probability table associated with the node *Actor.Cost* where Pa(*Actor.Cost*)= γ(*Actor.Impact*$^{-1}$*.Aggressiveness)* and $\mathcal{V}$*(Actor.Cost)*={Negative, Neutral, Positive}.

An instantiated model (denoted σ_R) (fig. 1.b) in the PRMs formalism (also named skeleton), specifies the set of objects $\sigma_R(C)$ for each concept C and the relations R between the objects, i.e. $\sigma_R(C) = < \mathcal{I}(C), \mathcal{R}(C) >$. The difference between σ_R and the ontological model instantiation comes from we do not affect any values to attributes. For a given skeleton σ_R, the PRM structure induces a ground Bayesian network (see fig. 2.c) and we have:

$$P(\mathcal{I}) = \prod_{C \in \mathcal{C}} \prod_{A \in \mathcal{A}(C)} \prod_{c \in \sigma_R(C)} P(c.A|Pa(c.A)) \qquad [1]$$

Figure 2.c depicts the ground Bayesian networks stemming from the PRM model in Fig. 2.a associated with the skeleton in Fig 2.b. Unlike Bayesian networks, PRMs model specify independence networks in a generic way that can be applied to any relational structure. The most common task that we wish to solve is to estimate and check the coherence of the marginal probabilities $P(X_Q|X_E=x_E)$ where X_Q is a set of query variables and X_E is a set of evidences.

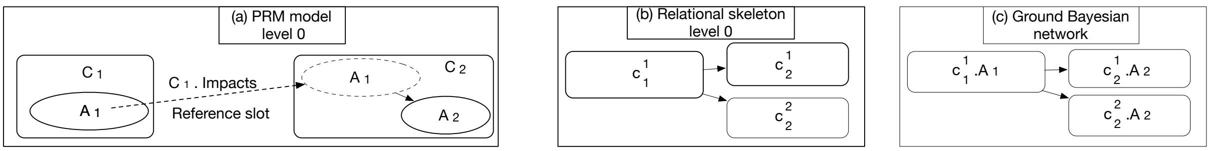
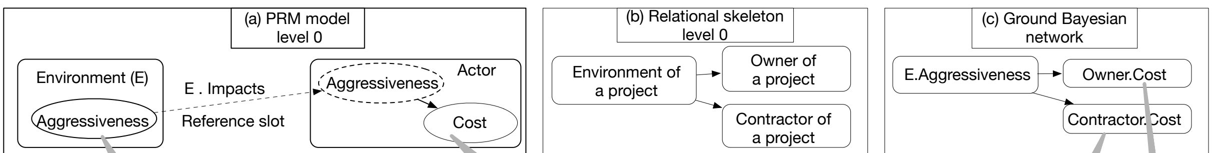


Figure 1: *(a) PRM structure; (b) a skeleton associated with the PRM Structure; (c) equivalent ground Bayesian network stemming from the skeleton and the PRM structure.*



P(Aggressiveness)		
Negative	Neutral	Positive
0.2	0.5	0.3

	P(Cost|Aggressiveness)		
	Negative	Neutral	Positive
Negative	0.6	0.3	0.1
Neutral	0.2	0.6	0.2
Positive	0.1	0.3	0.6

	P(Cost|Aggressiveness)		
	Negative	Neutral	Positive
Negative	0.6	0.3	0.1
Neutral	0.2	0.6	0.2
Positive	0.1	0.3	0.6

Figure 2: *(a) Example of a PRM structure; (b) an example of a skeleton associated with the PRM structure; (c) an example of equivalent ground Bayesian network stemming from the skeleton and the PRM structure.*

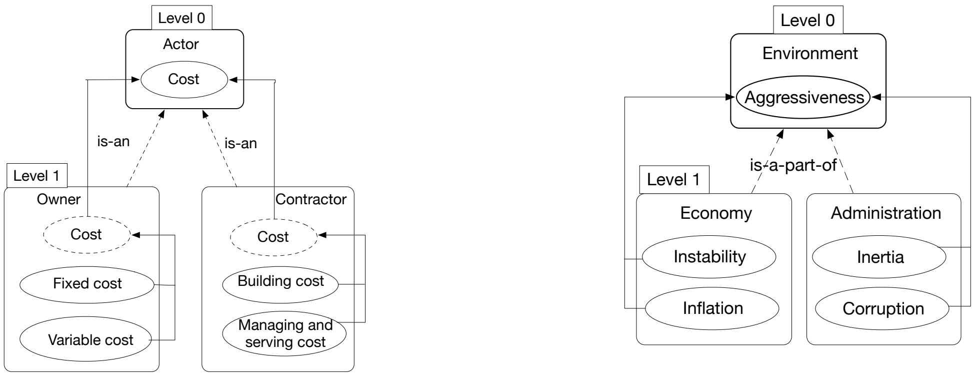
2.2. Concept specification and concept inheritance

The building of the ontology on which will be based the PRM requires the formalization of domain knowledge. Ontology formalism allows to define a hierarchical structure representation of domain knowledge. It enables to define concepts with different levels of details; for instance, the concept *Actor* at a macro level, is refined in *Contractor*, *Owner*, etc. at finer level of detail. Thus, each concept belongs to a defined level of details. Two relations allowing to refine concept are proposed in the model:

-Taxonomies: denoted « is-a » (or « is-a-kind-of ») define a partial order over the set of concepts characterized by tree structures and known as specification relation; all elements of A will be in B.

-Partonomies: denoted « is-a-part-of » describe concepts that are parts of other concepts. It expresses composition relations, *i.e.* B composes of A (*resp.* A is a part of concept B); an element of B composes an element of A.

In taxonomy relation, sub-concept inherits and refines all the characteristics of its concept. For example, *Owner* is an *Actor*, hence *Cost* of *Actor* will be inherited *Owner*. Furthermore, *Owner* have new attributes (*Fixed cost*, *Variable cost* specific to *Owner), Contractor* have two new attributes (*Building cost*, *Managing and Serving cost*) in relation with *Cost*; these new attributes enable to refine the *Cost* attribute regarding the specificity of the *Owner* and *Contractor* (fig. 3.a). In partonomy, composition characteristics of all finer concepts (*Economy.Instability*, *Economy.Inflation*, *Administration.Inertia*, *Administration.Corruption*) makes the total characteristic of its concept (*Environment.Aggressiveness*) (fig. 3.b*).*



(a) (b)

Figure 3 : *Attribute inheritance of taxonomy (a) and partonomy (b)*

Our hierarchical ontology of construction project mixes generalization (IS-A) and partitive (IS-A-PART-OF) relations.

3. Generic model of construction project

Based on the PRM-CH framework, we develop a holistic model for construction project risk management in different levels of detail. There are totally three levels of detail in our model named macro (level 0), meso (level 1), and micro (level 2). This paper focuses on two levels of domain description: macro and meso levels (resp. level 0 and 1). In the macro level (level 0), all information about concepts and attributes is the most general. For example, concept *Actor* and its attribute is *Productivity*. In the meso level (level 1), information of concept and attribute in the level 0 will be more specialized. For example, sub-concept of *Actor* is *Contractor*, its attribute is *Productivity in constructing*. Table 1 presents the 6 level-0 concepts and their 27 related level-1 concepts.

Table 1: *Finer concepts of level 1.*

Level 0 Concepts	Type of relation	Level 1 Concepts
Environment	*Partonomy*	*administration, climate, economy, ecosystem, extreme event, law documents, third party*
Resource	*Partonomy*	*human resource, machine, material*
Actor	*Taxonomy*	*consultant, contractor, designer, owner, project manager, supplier*
Contract	*Taxonomy*	*building contract, consultant contract, design contract, project manager contract, supply contract*
Activity	*Taxonomy*	*activity in feasibility phase, activity in implementation phase, activity in operation phase*
Product	*Taxonomy*	*completed procedure, building, list of repaired maintenance works.*

Figure 4 displays the relationships between the sub-concepts at level 1 refining the six concepts of level 0. 16 attributes have been identified at level 0 (see fig. 5.a) whereas 69 attributes have been identified at level 1 (fig. 5.b). A share scale is used to assess every attribute. It is a discrete qualitative scale $\mathcal{V}$(C.A) = {SSN,SN,N,E,P,SP,SSP} corresponding to a level impact ranging from strong strong negative (SSN) impact to strong strong positive (SSP) impact about construction project. The value « E » corresponds to the expected (central) behaviour of system.

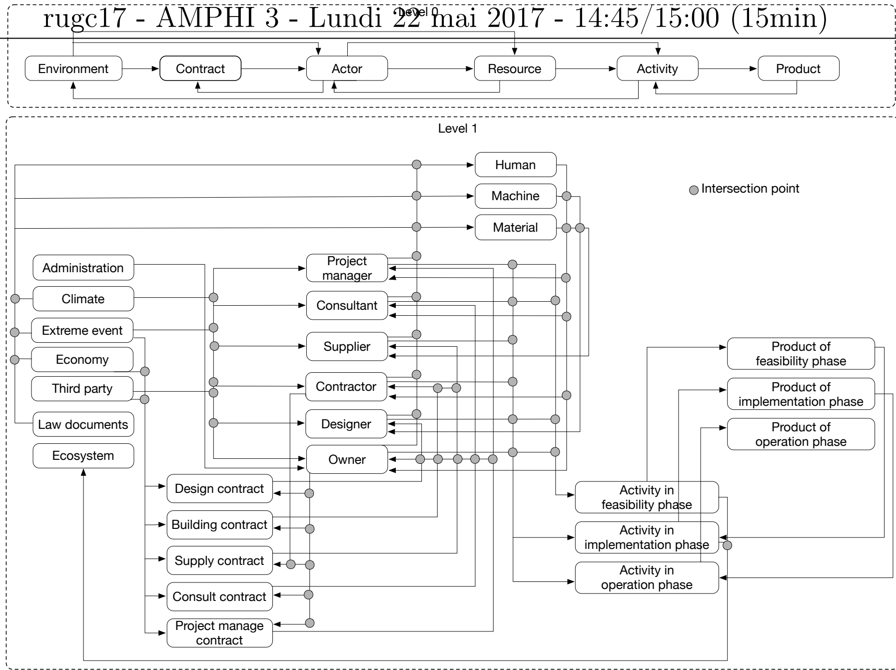
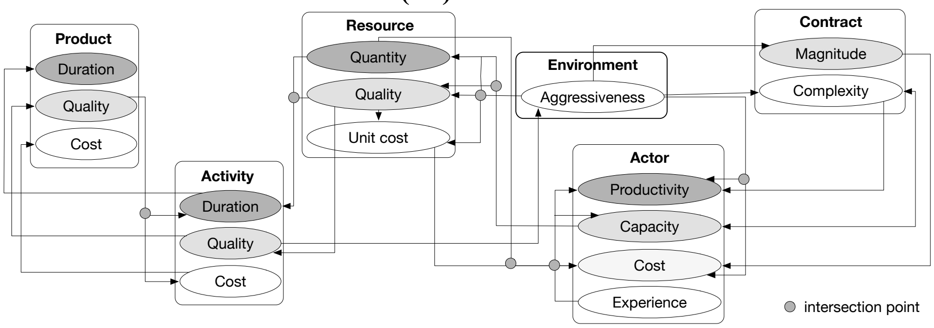


Figure 4: *Interaction between level 0 and 1 concepts.*

The uncertainty regarding the relations between attributes is modelled by a conditional probability distribution. The model includes 32 dependencies at the level 0 and 317 dependencies at the level 1 (fig. 5).

(5.a) *Level 0*



(5.b) *Level 1*

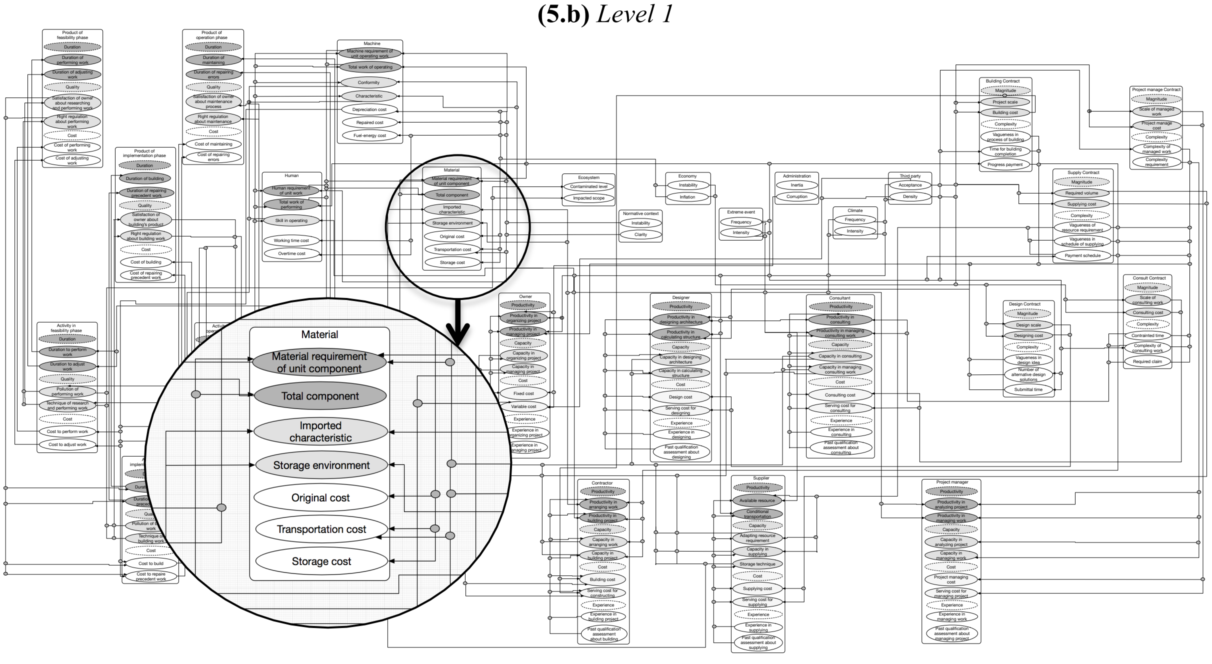


Figure 5: *Dependence relation between variables of level 0 (5.a) and 1 (5.b).*

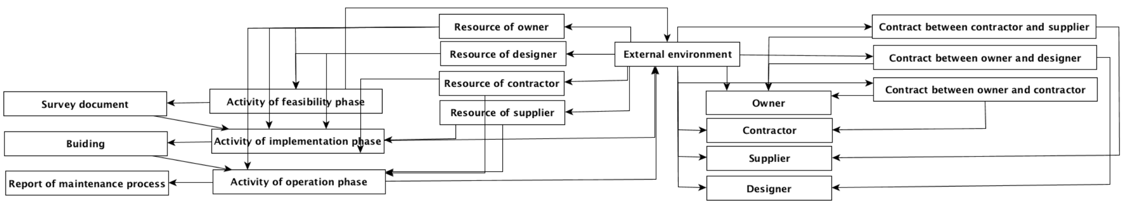
This huge number of dependences induces a high complexity for the model and an important calculation time to perform inferences. Inference in PRMs consists in propagating influence between the interrelated objects in order to calculate attribute probability distribution. When the skeleton is small, exact inference may be used [LAU 88] whereas when it is very large, approximate inferences are preferable [CAN 07][MUR 99]. Due to the complexity of the model, a double strategy was used: approximate inferences (computationally efficient on massive variables) and partial aggregation (divides multiple dependences into smaller groups of integration).

4. Instantiated case and results

In order to illustrate the model, we instantiated it according to a real case study. The 2BS project is located near Huong river. Based on preliminary studies, the cost of project was estimated to more than 6 billions Vietnam dongs (VND) (≈ € 242 000). Before the starting of the project, it existed an old road and bridge (named Lich Doi) which was built 17 years ago. Because of its degradation and increasing demands in transportation, the construction and renovation project 2BS was performed during 2013. Project 2BS was planned to be performed in 10 months, but because of many negative events which happened in the perimeter of the project or in its environment (minimum salary of worker increased, inflation caused cost increase of some resources, temperature was higher than normal condition, a big storm caused a flood, local residents were reluctant, some workers were fired or ill, some machines were broken), it last two months (i.e. 20%) more than planned and the cost was increased by more than 0,5 billion VND (≈ € 19 700, i.e. 8%).

The model was instantiated at level 0 and at level 1 in order to check the consistency of model result at these two levels. There are totally 18 and 43 elements in level 0 and 1 respectively (fig. 6) which were jointed to project 2BS.

(6.a) *Level 0*



(6.b) *Level 1*

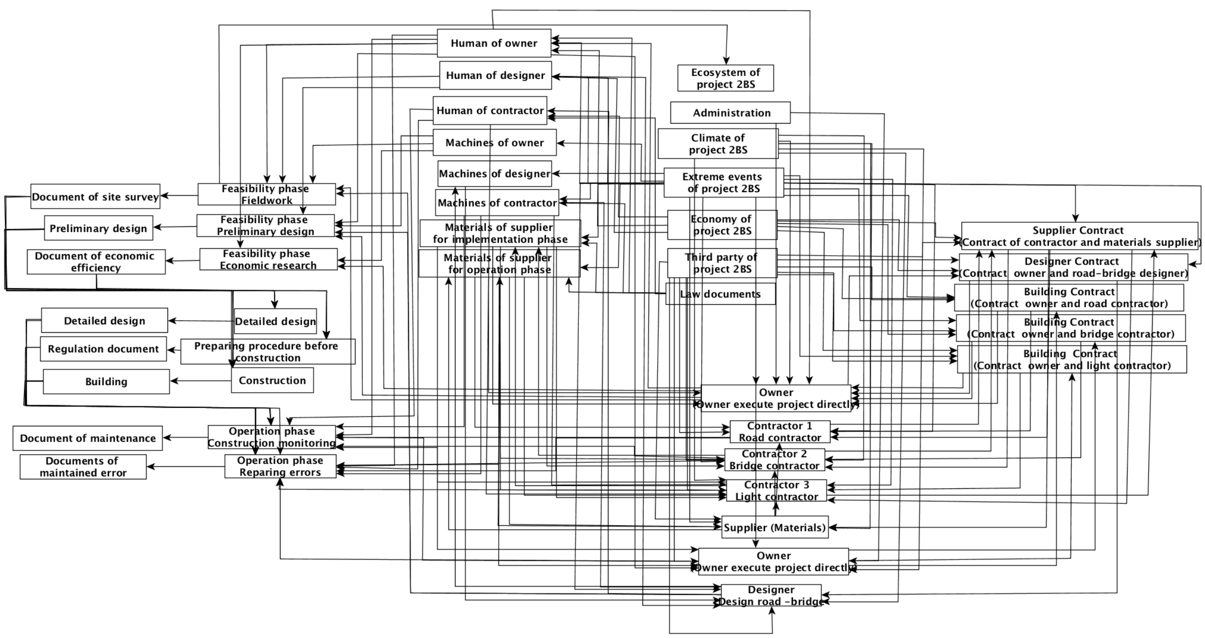


Figure 6: *The relational skeleton of all elements in level 0 (6.a) and level 1 (6.b) of project 2BS.*

Model is now tested according to two scenarios:

- the real scenario of project, as it happened (see $\text{Scenario}_{\text{project}}$ in Tab. 2),
- an alternative scenario in which it is assumed that supplier and designer, faced with the risk of missing the project objectives have adapted their capacity and their productivity during the project to face with (attributes in bold in $\text{Scenario}_{\text{project+}}$ Tab. 2). In the second scenario, all others variables are unchanged.

Table 2: Scenario$_{project}$ and Scenario$_{project+}$ of project 2BS

Scenario$_{project}$	**Corresponding situation**
economy.Value=SN	Inflation
climate.Value=SSN	Temperature
extreme_event.Value=SSN	Storm followed flood
resident.Value=SN	Opposition of the resident to project
human_for_implementation.Cost=SN	Pay increased
human_for_implementation.Quantity=SN	Personal accident
human_for_implementation.Quality=SN	Breakdown machines

Scenario$_{project+}$	**Corresponding situation**
economy.Value=SN	Inflation
climate.Value=SSN	Temperature
extreme_event.Value=SSN	Storm followed flood
resident.Value=SN	Opposition of the resident to project
human_for_implementation.Cost=SN	Pay increased
human_for_implementation.Quantity=SN	Personal accident
human_for_implementation.Quality=SN	Breakdown machines
designer.Capacity=SSP	*Experienced designer*
designer.Productivity=SSP	*Plentiful team*
supplier.Capacity=SSP	*Reliable supplier*
supplier.Productivity=SSP	*Large supplier*

Figures 7.a to 7.c synthesize the marginal probability distributions of the three attributes of the *building* (*resp. Quality* on fig. 7a, *Cost* on fig. 7b, and *Duration* on fig. 7c), given scenario$_{project}$ in gray colour and scenario$_{project+}$ in white colour. According to Figures 7.a to 7.c, scenario$_{project}$ has a strong negative impact for the project with highly left-skewed distributions, whose values are N or SN, in good agreement with what was reached by the real (and unique) project. The real project (2BS) last two months (*building.Duration*) more than planned and the cost (*completion of construction.Cost*) was increased by more than 0,5 billion VND (≈€19 700). On the other hand, scenario$_{project+}$ highlights that a very strong positive capacity and productivity of designer and supplier would have a positive effect over the response of the system. For instance, we can observe that the duration of product operation dissymmetry would disappear, and that the distribution of quality would also approach a symmetrical shape. However, the cost distribution is quite identical for the two alternatives, which implies that the model tells that changing the productivity and capacity of the supplier and designer has only a small impact on the product cost.

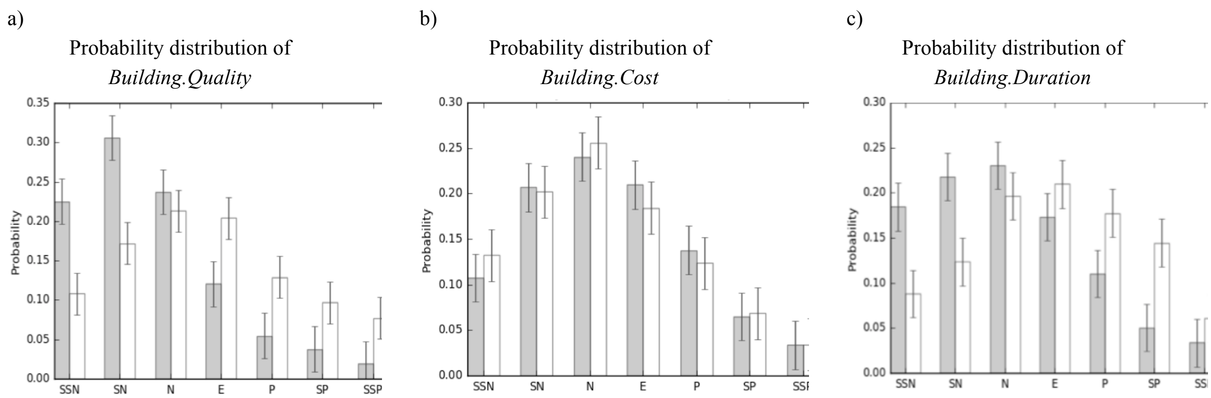


Figure 7: Marginal probability distribution of (a) the *quality*, (b) the *cost* and (c) the *duration* of *building* given scenario$_{project.}$ and scenario$_{project+.}$

With level 1, which is always attached with level 0, we will calculate the marginal probability P(interest variable|scenarios) of the same interest variables (*Building.Quality*, *Building.Cost*, and *Building.Quality*) given the same scenarios as level 0.

The calculation process of level 1 have not finished yet, hence we still do not have results of level 1. If the marginal probability of level 1 is approximately equal (the same tendency) to that one of level 0, the system of construction project is coherence.

These results highlight: (a) some variables of model are more or less sensitive according to observation and the model allow to assess this sensibility, (b) the behaviour of system regarding marginal probabilities is relevant and consistent (i.e. the results are consistent with predicable values according to the three scenarios), (c) the coherence of the system in different levels.

5. Conclusion :

We have proposed in this paper a generic model which is supported by the development of a domain ontology, defining and describing all relevant entities in the context of risk management in construction over two levels of description (three levels are currently available in the complete model). This model has been built by means of the formalism of probabilistic relational model with class hierarchies (PRM-CHs) in order to define a dependency network between all attributes of all entities and to quantify uncertainty over this network in different level. The generic holistic model allows to (1) implement any kind of construction project, (2) to take uncertainty into account and (3) to do simulations. We have illustrated and highlighted our approach by instantiating a road and bridge project renovation in Hue (Vietnam) on the basis of our generic model. This work is still on-going and the next step will be to check the consistency of the simulations in further detailed level. The model will also be applied to other more important civil engineering projects, and we will finally study how the model can be used in practical project risk management, in order to identify its more risky areas and find efficient risk responses.

Acknowledge

We would like to thank L. Torti and P.H. Wuillemin (research engineers of LIP6 – Information laboratory of university Paris 6) introduced to us the O3PRM language implementation in aGrUM (agrum.lip6.fr) which use a strong object-oriented syntax [TOR 13].

REFERENCES

[ISO 03] *"ISO 10006, Quality Management Systems - Guidelines for Quality Management in Projects",* 2003.

[LOV 02] P. E. D. Love, G. D. Holt, L. Y. Shen, H. Li, and Z. Irani, "*Using systems dynamics to better understand change and rework in construction project management systems*," vol. 20, no. August 2015, pp. 425–436, 2002.

[AND 99] Andrew R. Atkinson, "The role of human error in construction defects," *Struct. Surv.*, vol. 17, no. 4, pp. 231–236, 1999.

[MID 07] M. H. Middelmann, *Natural Hazards in Australia: Identifying Risk Analysis Requirements*. 2007.

[TEP 02] E. Tepeli, "Processus formalise et systemique de management des riques pour des projects de construction complexes et strategiques," 2002.

[FRA 15] Franck Taillandier, Patrick Taillandier, Esra Tepeli, Denys Breysse, Rasool Mehdizadeh, Fadi Khartabil., "A multi-agent model to manage risks in construction project," *Autom. Constr.*, vol. 58, pp. 1–18, 2015.

[BOA 15] P. Boateng, Z. Chen, S. O. Ogunlana, "An Analytical Network Process model for risks prioritisation in megaprojects," *Int. J. Proj. Manag.*, vol. 33, no. 8, pp. 1795–1811, 2015.

[KHA 14] S. Khan, M. Safyan, "Semantic matching in hierarchical ontologies," *J. King Saud Univ. - Comput. Inf. Sci.*, vol. 26, no. 3, pp. 247–257, 2014.

[JIA 13] S. Jiang, J. Zhang, H. Zhang, "Ontology-based semantic retrieval for risk management of construction project," *J. Networks*, vol. 8, no. 5, pp. 1212–1220, 2013.

[GIL 05] L. Gillam, M. Tariq, K. Ahmad, "Terminology and the construction of ontology.," *Terminology*, vol. 11, no. 1, pp. 55–81, 2005.

[ELD 05] T. A. El-diraby, C. Lima, B. Feis, "Domain Taxonomy for Construction Concepts: Toward a Formal Ontology for Construction Knowledge," *J. Comput. Civ. Eng.*, vol. 19, no. 4, pp. 394–406, 2005.

[SUN 09] M. Sun, X. Meng, "Taxonomy for change causes and effects in construction projects," *Int. J. Proj. Manag.*, vol. 27, no. 6, pp. 560–572, 2009.

[JIA 13] S. Jiang, J. Zhang, H. Zhang, "Ontology-based Semantic Retrieval for Risk Management of Construction Project," *J. Networks*, vol. 8, no. 5, pp. 1212–1220, May 2013.

[NIU 15] Kia Niu, R. R. A. Issa, "Developing taxonomy for the domain ontology of construction contractual semantics : A case study on the AIA A201 document," *Adv. Eng. INFORMATICS*, 2015.

[ZHO 15] B. Zhong, Y. Li, "An ontological and semantic approach for the construction risk inferring and application," *J. Intell. Robot. Syst.*, vol. 79, no. 3–4, pp. 449–463, 2015.

[MED 10] G. Medina Oliva, P. Weber, E. Levrat, B. Iung, "Use of probabilistic relational model (PRM) for dependability analysis of complex systems," *IFAC Proc. Vol.*, vol. 9, no. PART 1, pp. 501–506, 2010.

[GET 07] L. Getoor, N. Friedman, D. Koller, A. Pfeffer, B. Taskar, "Probabilistic Relational Models," *Introd. to Stat. Relational Learn.*, pp. 129–174, 2007.

[PIE 12] Pierre-henri Wuillemin, L. Torti, "Structured probabilistic inference," *Int. J. Approx. Reason.*, vol. 53, no. July, pp. 1–15, 2012.

[TOR 10] L. Torti, C. Gonzales, P.-H. Wuillemin, "Reinforcing the Object-Oriented Aspect of Probabilistic Relational Models," *Proc. 5th Eur. Work. Probabilistic Graph. Model.*, pp. 273–280, 2010.

[SCH 09] M. Schmidt, K. Murphy, "Modeling discrete interventional data using directed cyclic graphical models," *Proc. Twenty-Fifth Conf. Uncertain. Artif. Intell. (UAI '09)*, pp. 487–495, 2009.

[PFE 00] A. Pfeffer, D. Koller, "Semantics and inference for recursive probability models," *Proc. Natl. Conf. Artif. Intell.*, no. August, pp. 538–544, 2000.

[AUS 04] N. Aussenac-gills, J. Mothe, "Ontologies as background knowledge to explore document collections," *Actes la Conférence sur la Rech. d'Information Assist. par Ordinat.*, pp. 129–142, 2004.

[TOR 13] L. Torti, P. Wuillemin, I. De Paris, V. I. Upmc, "O3PRM language Specification," pp. 1–11, 2013.

[LAU 88] Lauritzen, Spiegehalter, "Local Computations with probabilities on graphical structures and their application to expert systems," *Expert Syst.*, vol. 50, no. 2, pp. 1–4, 1988.

[CAN 07] A. Cano, M. Gomez, S. Moral, J. Abellan , "Hill-climbing and branch-and-bound algorithms for exact and approximate inference in credal networks," *Int. J. Approx. Reason.*, vol. 44, no. 3, pp. 261–280, 2007.

[MUR 99] K. Murphy, Y. Weiss, M. Jordan, "Loopy Belief Propagation for Approximate Inference: An Empirical Study," vol. 1, 1999.