Bayesian Network-Based Risk Prediction in Virtual Organizations

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Abstract. To support and increase the success rate of collaboration in Virtual Organizations (VOs), usually formed within Virtual organizations Breeding Environments (VBEs), their operation stage and performance of their tasks must be continuously monitored and supervised. A task in the VO is either planned to be performed by an individual partner or jointly by a group of partners, and typically consists of several sub-tasks defining the day-to-day activities of its involved partners. However, VOs are dynamic and therefore detailed activities related to sub-tasks are defined gradually during their operation phase. In this paper, as the base for discovery of potential task failures, past performance and record of previous sub-tasks' fulfillment of each partner (so-called agent) is considered for appraisal of its trustworthiness. Furthermore, the communication characteristic of the agent and its current workload in all its involved VOs within the VBE are also considered as input for measuring its potential probability of failure on currently assigned sub-tasks. For tasks that involve several partners, a Bayesian network is created during the VO's operation phase, and used for measuring their failure probabilities. These two potential risk measurements in VOs enable their coordinators to appropriately identify the weak points in their planning of upcoming VO activities, as well as assisting them with advice on how to intervene and change the situation.

Keywords: Virtual Organizations · VO supervision/coordination · Failure risk prediction · Task performance promises · Trustworthiness · Responsibility template

1 Introduction

To respond to the emerging opportunities in the market, some autonomous and heterogeneous agents registered in a Virtual organization Breeding Environment join forces and form a VO. Research on the success rate of Virtual Enterprises in business show that at least 30 % of the established VOs end up either in failure or operate under the pressure of high risks for failure [1]. Primarily, three categories of risks for organizations involved in a virtual organization are highlighted in the literature [2], including: internal, external, and network-related, in relation to the success rate of virtual organizations.

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Network-related risks are those addressing collaborative relationships among organizations, and are typically caused by lack of trust, insufficient information sharing, clash of cultures, etc. To support the success of collaboration among the involved organizations in the VOs, it is necessary to define a framework and provide support functionality through which the risks can be mitigated.

VO is a goal-oriented network, which means during its formation/creation stage, a set of targets are gradually defined, and the main sub-goals and their tasks to be performed for achieving those targets are pre-planned. However, during the operation/evolution stage of the VO's life-cycle, these high level sub-goals and their tasks need to be detailed out into a set of specific sub-tasks, to be each performed either by a specific partner, or jointly by a group of partners. In our research, we focus on risks that mostly rise during the operation phase of the VOs, when large number of tasks and sub-tasks are planned and scheduled (or are being gradually planned), each to be performed either individually by one partner, or jointly by a group of partners. To support the success of collaboration in VOs, it is necessary that its planned activities are monitored, supervised, and coordinated, in order to discover and/or predict potential risks of failure in their fulfillment. Our novel approach to forecasting and managing potential risks of failure in VOs is founded on analyzing partners' past and present behavior in performing the tasks to which they have committed. Our approach contributes to developing novel methods and mechanisms for monitoring both individual behavior and collective behavior of partners in VOs [3]. The factors that are considered for potential risk in VOs in our research are focused on three specific risks, including: low trustworthiness, insufficient communication, and heavy workload. These three factors play a major role as causes for risk during the operation phase of the VO's life cycle. Therefore, our approach concentrates on measuring the trust level, communication level, and workload level of each VO partner, acting as an agent, within a VBE [4]. These are used as the criteria for discovering potential probability of activity failures in currently assigned sub-tasks to agents.

Trust is commonly considered as a main countering factor to the risks that may rise in networks, due to agents' opportunistic behavior, creating uncertainty and ambiguity, and thus an agent's low trustworthiness influences its risk of failure in fulfilling its responsibilities, while agent's high trust level positively influences its successful completion of assigned sub-tasks and being cooperative in the VO. In our approach [5], a set of trust-related norms are already defined that can be monitored for VO partners, depending on the importance and timeliness of responsibilities assigned to them. There is also a direct relationship between trust and communication in VOs. More trust is established in the network when there is effective communication, and insufficient or failing communication among partners in a VO, is typically followed by its failure. A third risk factor considered in our approach is the current workload on the staff and resources that are owned by the VO partners, and this considers the workload of each agent within the entire VBE and in relation to all its commitments. For instance, if a VO partner is simultaneously involved in several VOs, its workload may become too heavy and its resources and staff overloaded, which must be considered when measuring its potential risk to fail the already committed responsibilities or when volunteering to undertake new responsibilities.

It should be noted that the main goals and sub-goals of the VOs are usually reflected through high level tasks to be undertaken by its partners. These are typically included in the VO contracts, which are agreed and signed during the VO's creation phase among its partners. Nevertheless, considering that VOs are dynamic organizations, typically the sub-tasks related to daily activities to be performed by the partners are gradually defined during the VO's operation phase [5]. Furthermore, some sub-tasks need to be executed sequentially, while some others concurrently, which implies the existence of certain causal relationships among different tasks and sub-tasks. The responsibilities accepted by different VO partners in performing each sub-task constitute promises from partners to perform those sub-tasks. A responsibility template can represent task/sub-tasks, with the related promises/commitments from VO partners to perform them, as well as inter-relationships among the sub-tasks. Promises made to perform sub-tasks, are formulized as the norms for the promising partner. These causal inter-relationships can be modeled through a Bayesian network. When and if a VO partner violates one of its related norms, the risk prediction process discovers if there are other sub-tasks assigned to that partner, which will now become risky. For calculating the failure probability of every individual sub-task, the above mentioned factors are considered. For joint tasks and sub-tasks, promised by a group of partners, the Bayesian network provides their failure probabilities at any point in time, which in turn enables the VO coordinator to identify their associated potential risks, and possibly to decide reassigning the risky tasks and sub-tasks, for which our approach also facilitates finding the best-fit candidates for the reassignment.

The remaining structure of this paper is as follows: Sect. 2 provides the related works. Section 3 addresses risk factors considered in this. How to find the weakest/most risky planned task/sub-task in the VO is investigated in Sect. 4. Finally, Sect. 5 provides the conclusion of this research.

2 Related Works

Coordinating a Virtual Organizations (VO), with the awareness about any potential risk of failure in fulfilling some of its tasks, clearly increases the chance of its success, and thus the effective achieving of its goals and sub-goals. Literature review illustrates different definitions for risks in various environments. Risk in an organization is defined in [6] as the probability of an event that can influence the organizations' objectives, either negatively or positively.

In our research, we seek to identify risks in the VOs, due to the VO partners who may violate some of their norms (promises they have made to fulfill some sub-tasks), and consequently threatening the success of the VO.

Factors Related to Risk. Three risk factors related to the supply chains, including the internal, external and network-related risks are identified in [2]. Changes in industry market, political situation, social atmosphere, etc. are categorized as the sources for external risks threatening the involved organizations, while events such as strikes, machine failure, etc. are placed in the internal risks categories. All other risks raised from the collaborative relationships among organizations in a VO, are clustered under the network-related risk category. Being two forms of collaborative networks, there is a large similarity on internal and external risk factors between the supply chains and virtual organizations. However, the factors related to their network-related risks are different between the virtual organizations and supply chains. In supply chains, every organization is one member in the chain, thus knowing about and dependent on two other organizations, which appear before and after it in the chain. Also, every organization is contracted to perform its own sub-task within the chain, so the success/failure of each organization depends primarily on receiving the needed output from its predecessor organization in the chain as well as performing its own contracted tasks well. The case of VOs however is very different. All its partners are jointly responsible for achieving the goals and sub-goals of the VO, and therefore, the success or failure of every one of its involved organizations is directly dependent on the success or failure of the VO as a whole. This joint responsibility is the main reason why even when one partner cannot perform its sub-task in the VO, other partners volunteer to perform it instead, so that the VO as a whole can succeed. The joint responsibility notion in turn creates complex inter-relationships among the involved partners. Modeling the individual and collective cooperative behavior of organizations that are involved in VOs is challenging. Once an organization's behavior is monitored and modeled within a VBE, and through its involvement in a number of VOs, its patterns can be established, and used for reasoning about predication of its behavior in its forthcoming sub-tasks.

In [2] a list of important sources/causes for network-related risks in VOs is provided, which includes: lack of trust, lack of clarity in the agreements/commitments, partners heterogeneity, loss of communication, lack of information sharing, heavy workload, ontology differences, heterogeneity in structure and design, cultural differences, and geographic distance, etc. In other words, any of these sources represents the existence of a risk in the VO, and depending on its severity can contribute to its failure. From this list of risk sources, trust, commitment, and information sharing are investigated further in [7], specifically focused on the creation phase of the VOs, and finding the potential risk of collaboration for the industrial partners and logistics operators that wish to get involved in the formation of a new VO.

In our research, we focus on three factors of trust, communication, and workload of the organizations (considered as agents), in order to predict the probability of failure for each of these agents in fulfilling their individual assigned sub-tasks during the VO operation phase. As such, violation of a trust-related norm by an agent triggers the risk prediction process to consider further involvement of that agent in the responsibility template of the VO. Our algorithm focuses on dynamic measurement of agent's trustworthiness and potential risks associated with it during the operation phase of the VOs, and therefore very different from approaches applied during the VO creation phase [7, 8].

Risk Prediction Approaches. A number of approaches, some of which parameterized, are employed for modeling and prediction of risks, such as the FTA (Fault Tree Analysis), the ETA (Event Tree Analysis) and the ANP (Analytic Network Process). FTA uses the combination of AND and OR gates to build the failure model [9]. It calculates the probability of failing for the top level event(s), based on the data extracted from their lower level events. This method is however limited to a binary prediction, and it only treats instantaneous failures, i.e. it does not include and/or consider any delays in time. Furthermore, a main drawback of FTA is related to building the accurate tree which requires a great effort.

In [7], estimation of the failure risk for individual partners is routed in ETA. ETA addresses all potential consequences resulted by an initiating event, to which the probability for their occurring can be assigned. In addition to individual risk, collective risk is also addressed in [7] which is evaluated through fault tree analysis. The limitation of the ETA approach is however related to the number of event trees that it generates, since one event tree is needed for assessment of risks for each partner, therefore the time complexity of the approach and its algorithm is high.

ANP is a multi-criteria decision making method that produces a structured influence network of clusters containing nodes. The network contains source node, intermediate nodes and sink nodes indicating different criteria. The origin of the influence path is shown by a source node, while the destination of influence path is illustrated by a sink node. In [10], the authors compare ANP with other multi-criteria decision making methods. However, the ANP model has also the limitation to require filling up many questionnaires as input.

In our approach, a Bayesian Network (BN) is developed, which consists of a set of nodes representing its variables and a set of directed arcs representing relationships between those variables. If variable A causes B then there is a directed arc from A to B and A is the parent of B. To each node, a conditional probability is assigned which indicates the probability of the variable associated to the node, given the probability of the variables associated to its parents. In our research, nodes represent the failure in fulfilling the sub-tasks, tasks, or goals. The probability of occurring failure in fulfilling of the individual sub-tasks is measured based on the trustworthiness, communication level and workload of the responsible agents. Then, the probability of failure occurring in joint-tasks is calculated according to the Bayesian network rules.

The benefits of BN to assess risks in natural hazards are illustrated in [11]. Roed et al. in [12] propose a framework considering human and organizational factors in hybrid causal logic (HCL) to perform a risk analysis. This framework is developed based on traditional risk analysis tools (FTA and ETA) accompanied by the Bayesian Network. In our approach, we use BN to recognize risky tasks to support the success of collaboration in VOs. The BN is built during VO operation phase, and if task planning is changed then the graph representing BN is easily updated, which is not easy in other mentioned approaches that need more effort to stay up-to-date with changes in task planning.

3 Risk Factors

The ability to predict the reasons of particular events is crucial in risk management. Based on the state-of-the-art in the area, different risk sources can be identified, among which three specific ones are considered in our research, including: lack of trust, lack of communication, and heavy workload. These three play a vital role as causes for risk during the operation phases of the VO’s life cycle, and are addressed in more details in the following paragraphs.

3.1 Trust Level

Trust plays an important role in virtual organizations and in relation to identification of risk factors. Establishing trust is primarily rooted in the behavior of involved partners. Therefore, monitoring the behavior of organizations involved in the VO and how they are performing their commitments can provide good indications for predicting some of the weak points in the near future plan of activities, which can cause risks in the VOs. Subsequently, notifying the VO coordinator about such weaknesses and the risks that are associated with them assists the coordinator with taking timely and appropriate strategic actions. For this objective, we have developed a framework, addressed in [3], which enables formalizing responsibilities and commitments of agents to perform their sub-tasks in the VOs. It further supports the VO coordinator with monitoring partners' behavior through identification of any potential violation in the set of defined norms for the VO.

In support of the VO coordinator with monitoring partners' behavior, we have earlier defined in [5] three kinds of behavioral norms, including the socio-legal norms, the functional norms, and the activity-related norms, which in one way or another constrain the partners' behavior in the VO. The socio-legal norms are related to aspects such as leadership rights that are agreed and signed by all partners usually through a so called consortium agreement.

During the VO formation/creation stage, partners commit themselves to collectively fulfill the objectives of the VO. Then through negotiating contracts, the general terms of each partner's main responsibilities in the VO are indicated as its coarse-grained tasks. The assignment of coarse-grained tasks to partners (frequently assigned as joint tasks for a number of partners to perform together) corresponds to the functional norms in the VO. However, and mostly due to the dynamic nature of VOs, these contracts cannot and do not determine the details of partners' day-to-day sub-task assignments and activities that they perform. Therefore, a template is only extracted in this phase which is called in our research Goals-Tasks-Interdependency-Template (GTIT) which is instantiated during the VO operation phase.

At different times during the VO operation phase, definition and assignment of day-to-day sub-tasks to each partner are achieved, complying with its general responsibilities, as specified in its VO contract. To assign the day-to-day sub-tasks, agreements are made within the VO between each partner who commits to perform the sub-task and its task leader. Every such agreement to commit to a sub-task, generates a promise in the VO. Fulfillment of these promises in the VO corresponds to the activity-related norms. Clearly, the activity-related norms are in conformance with the functional norms in the VO. We have implemented the behavior monitoring functionality of our approach in a tool called VOSAT (Virtual Organization Supervisory Assistant Tool) [5], within which the focus of behavior monitoring is on the activity-related norms. VOSAT is applied to assist the VO coordinator by giving useful information about the VO partners' behavior as monitored during the operation phase of the VO.

To enable monitoring and reasoning about the activity-related norms, promises must be concisely defined and formalized. In our proposed framework, a set of rules are defined according to which the state of each promise is changed, and adding new facts to the knowledge base. Every promise goes through different states during its life cycle [3], some of which are briefly described below. The state of a promise which requires a priori fulfillment of some conditions is called conditional. This means, only when any/all required conditions are fulfilled (before their deadlines), that the state of a promise is/becomes unconditional. Otherwise, if the a priori conditions for a promise are not fulfilled on time, then the state of the promise is/becomes dissolved. If a sub-task for which a promise is made is fulfilled before/on its deadline, then the state of the promise is/become kept and if the deadline is passed and the sub-task is not fulfilled, then the state of the promise is/become not kept. If the reason for the failure in fulfilling a sub-task is beyond its promiser's control, then the state of the promise is/become invalidated, and finally a promise is/becomes released when the promisee cancels it, which requires pre-agreement with the task leader.

To evaluate the overall trust value of each agent, the VOSAT framework applies a comprehensive fuzzy evaluation method. This method is a multi-criteria decision making approach that evaluates the influences of various factors on a certain element, applying fuzzy mathematical methods [13]. For example, construction project management can be evaluated using fuzzy comprehensive evaluation in which three evaluation factors are the degree of controlling project objectives, the need of supporting of the owners and support ability of the owners and contractors. In our approach, we apply two specific fuzzy factors, namely the personal norm abidance, and collective norm abidance. To evaluate the personal norm abidance for an agent A, the past interaction/collaboration experiences of agent A with all other agents in the VBE are considered, e.g. the number of all kept promises made by A to other agents, and the number of all violated promises. To evaluate the collective norm abidance for an agent A, all ranking suggestions received for an agent A from other agents are aggregated. Through applying this method, it is possible to measure the violation of trust-related norm for each agent, which is then used to predict the potential risk of failure for this agent.

3.2 Communication Level

The second important risk factor in virtual organizations after trust is related to failing needed communication with other partners, which is typically followed by failure in virtual organizations [14]. In other words, agents' timely and periodic reporting on the status of progress in activities under their responsibilities, e.g. by email in relation to performing a sub-task to both the task-leader and other involved partners in joint tasks, by email in relation to a Work Package to the VO coordinator, etc. is vital to the success of the VO.

Communication processes in VOs complements the VO's structures. In other words, goals of the VO as well as the partners responsibilities are reflected and clarified through their effective communication. There is in fact a direct relationship between trust and communication, meaning that more trust can be established in a collaborative networks, as a consequence of better communication.

Nevertheless, sometimes communications among agents fail. The Ratio of Failure for an agent in its required communication, is calculated through the following equation:

$$RFC\left(A_1\right) = \frac{n_f}{N}$$

A_1 shows the agent for whom we calculate the potential Risk of Failure in Communication (RFC), related to fulfilling the sub-tasks under its responsibility in the VO. The n_f shows the number of his failed communications in this VO, and the N shows the total number of required communications by this agent in the VO.

In our approach we consider that a threshold percentage for tolerating failures in communications can be defined in each VO, by its coordinator. This threshold is then compared against the RFC of an agent. If the RCF is larger than the pre-defined threshold, then their difference indicates the percentage of not-tolerated lack of communication by the agent in that VO. This difference represents the probability of Lack of Communication (LC) for the agent A_1.

3.3 Heavy Work Load

When a partner is involved in two or more VOs simultaneously, there is a risk of resources and/or staff insufficiency to undertake all its responsibilities. There is not much related work referring to this aspect, however in [8] an agent's bidding for tasks in several VOs is considered as a source of risk. In our approach, we define a Ratio of Over-workload Commitment for each agent $ROC(A_1)$, as a risk factor. If positive, this shows the percentage of over commitment of an agent A_1, when considering all its commitments to different VOs in the VBE, in comparison to the real person-months in a year that the agent has planned to invest in this VBE. Equation below:

$$ROC(A_1) = \frac{\sum_{i=1}^{n} \frac{PM_i}{y_i} - N}{N}$$

Where PM_i shows the Person-Month that organization A_1 commits in VO_i, y_i is the duration of VO_i in years, n shows the number of VOs in which A_1 is involved, and N is the maximum person-month that A_1 has planned for being involved in the VBE, as specified in its profile/competency information at the VBE. In our approach we consider that a threshold percentage for tolerating over-commitment can be defined in each VO. If the $ROC(A_1)$ is larger than this pre-defined threshold for an agent, then their difference indicates the probability of Heavy Workload (HW).

3.4 Relative Weights Comparing Risk Factors

To determine the three criteria weights used to calculate the probability of the risk, related to individual sub-tasks, an Analytic Hierarchy Process (AHP) [15] is adopted. The approach ponders a set of evaluation criteria, and a set of alternative options through which the best decision is to be made. The AHP produces a weight for each evaluation criterion according to the decision maker's criteria paired comparisons. The higher the weight, the more important is the related criterion. In order to compute the weights of the different criteria, the approach initiates the creation of a paired comparison matrix A.

The matrix A is an $m \times m$ matrix, where m is the count of evaluation criteria considered to be compared. Let us assume that each a_{jk} indicates the relative importance of the j^{th} factor to k^{th} factor, so there are three possibilities:

$a_{jk} > 1$, if the j^{th} factor is more important than the k^{th} factor
$a_{jk} < 1$, if the j^{th} factor is less important than the k^{th} factor
$a_{jk} = 1$, if the two criteria have the same importance

There are two constraints: $a_{jk} \times a_{kj} = 1$ and $a_{jj} = 1$ for all j.

Table 1 indicates suggestive numerical scales for relative importance between any two factors [15].

Table 1. Relative importance where comparing every two factors [15]

Status	Value
Equally important	1
Slightly more important	3
More important	5
Greatly more important	7
Fully more important	9
For comparison between margins mentioned above	2, 4, 6, 8

After building the matrix A, it is possible to derive from this matrix a normalized paired comparison matrix, by making the sum of the entries on each column equal to 1. Therefore, each entry in column i is divided by the sum of the entries of that column. Ultimately, the criteria weight vector w (that is an m-dimensional column vector) is constructed by averaging the entries on each row of the normalized matrix. Of course, the consistency among assigned weights should be checked as explained in [15].

Generally, the AHP computations are directed by the decision maker's experience, hence AHP can be considered as a means to translate the decision maker's evaluations into a multi criteria ranking. Figure 1(a) shows an example of VO coordinator's opinion about comparing the influences of Lack of Trust (LT), Lack of Communication (LC), and Heavy Workload (HW) on the failure probability of individual tasks. Weights in Fig. 1(a) are selected by the area experts, based on the weights they suggested in Table 1, e.g. in this example the VO coordinator has decided that the weight of lack of trust is 7 times more important than the lack of communication (which also indicates the former is greatly more important than the latter), consequently the weight for the lack of communication in contrast to the lack of trust is 1/7 which equals to 0.14.

Considering the weight matrix shown in Fig. 1(a), the sum of entries in columns from left to right are respectively 8.33, 1.25, and 13. Then in order to normalize these values, each entry in column i is divided by the sum of the entries of that column. Consequently, the matrix is changed as shown in Fig. 1(b).

	LC	LT	HW
LC	1	.14	3
LT	7	1	9
HW	.33	.11	1

(a)

	LC	LT	HW
LC	1/8.33=0.12	.14/1.25=0.112	3/13=.23
LT	7/8.33=0.84	1/1.25=0.8	9/13=.69
HW	.33/8.33=.039	.11/1.25=0.088	1/13=.076

(b)

Fig. 1. (a) An example of weights suggested for comparing the LT, LC, and HW based on the values defined in Table 1. (b) The normalized version of the matrix in (a)

The resulted weight vector is then {(.12 + .112 + .23)/3 = 0.15, (.84 + .8 + .69)/3 = 0.78, (.039 + .088 + .076)/3 = 0.07}. This in turn means that for example, the probability of failure in fulfillment of an individual task, given the violation of trustworthiness of the responsible agent, and when there is no lack of communication and heavy workload, is 78 %. These weights are then used in the Conditional Probability Tables (CPT), explained in the next section.

4 Proposed Approach for Risk Prediction

In the VO contracts, some general tasks are defined for the partners, in order to fulfill the VO goals and sub-goals. As illustrated in Fig. 2, we define one template called the Goals-Tasks-Interdependency-Template (GTIT) for a VO during its creation phase. The GTIT reflects the pre-defined goals and main tasks hierarchy and their inter-relationships to the VO partners, as they are typically specified in the VO contract. During the VO operation stage however, each of the main task is divided into several sub-tasks, and the sub-tasks are committed by specific partners, thus representing their different day-to-day activities. Therefore, the GTIT of a VO will dynamically get instantiated and expanded with more details during the operation phase of the VO, generating the Partner-Responsibility-Interdependency-Tree (PRIT) that represent current activities of the VO. At any time, there is only one current PRIT at the VO, which can be dynamically updated to either reflect new assignment of subtasks to partners, reassignment of main VO tasks or sub-tasks from one partner to another, or even due to higher level changes in the VO's goals and sub-goals.

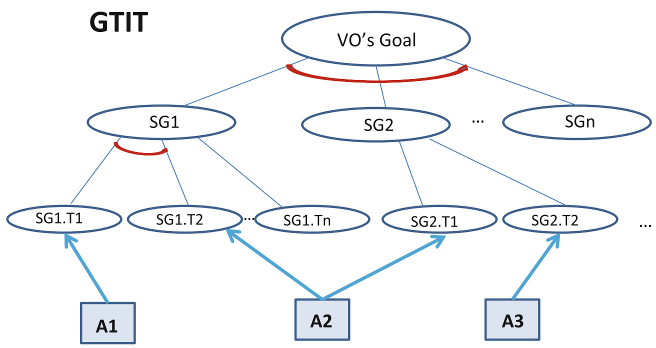


Fig. 2. The Goals-Tasks-Interdependency-Template, created during the VO creation phase. **T** is for a task, **SG** is for a Sub-Goal, and **A** is for an agent who is responsible for a particular sub-task.

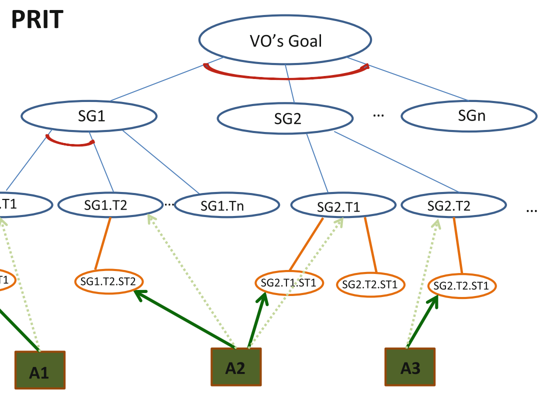


Fig. 3. An example of current Partner-Responsibility-Interdependency-Tree, created during the VO operation phase

A simple case of the extended GTIT template, called Partner-Responsibility-Interdependency-Tree (PRIT) is illustrated in Fig. 3.

In our research, the causal inter-relationships among sub-tasks, tasks, and goals are modeled through a Bayesian network. As mentioned before, three main sources of risks regarding VOs are taken into account, focused on: *trust*, *communication*, and *work-load*, and then the Bayesian network is applied to find the failure probabilities of joint-tasks or joint-sub tasks at each point in time, and subsequently the VO coordinator can properly recognize and reassign risky tasks.

Clearly, the risk analysis can be addressed during all phases of the VO life cycle, i.e. creation, operation, evolution, and dissolution. However, the focus of our work is on the operation and evolution phases.

4.1 Bayesian Network

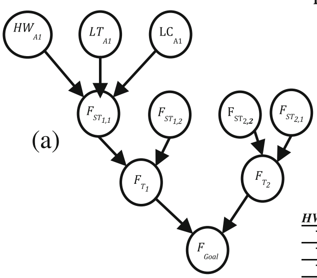
Bayesian networks are frequently used for modeling of complex systems. A Bayesian network is a DAG (Directed Acyclic Graph). This graph consists of some nodes that representing variables and some edges representing relationships between the variables. A directed edge from variable A to variable B is considered if A is the parent of B meaning A causes B. To each node, a conditional probability is assigned which indicates the probability of the variable associated to node given the probability of the variables associated to its parents.

In this research, each node in Bayesian network represents the failure in fulfillment of a task/sub-task. The conditional probability table related to each node shows a basis for identifying how much responsibility an involved agent or group of agents have committed toward a task fulfillment.

During the VO operation phase, when the sub-tasks are defined in details or dynamically changed, the Bayesian network is established and changed accordingly. For instance, when the PRIT for the VO is changed to represent that a new partner has entered to the VO with certain new responsibilities, or when a partner leaves the VO while its responsibilities are delegated to others, the Bayesian network is updated accordingly. Moreover, when and if the trust, communication and workload level of an agent is dramatically changed, it may in turn increase the probability of its failure or success in tasks in which the agent is involved, as well as the failure or success of other dependent tasks, and consequently the failure or success of the entire VO.

4.2 Example

In this section, an example is presented to address the proposed method. Suppose that a VO is created and three organizations (A_1, A_2, A_3) are involved in it. The VO's goal is to fulfill two high level tasks T_1, and T_2. During the operation phase of the VO, a number of sub-tasks, e.g. $ST_{1,1}, ST_{1,2}$ for task T_1, and $ST_{2,1}, ST_{2,2}$ for task T_2, are defined. Furthermore, A_1 is responsible for $ST_{1,1}$, A_2 for $ST_{1,2}$, $ST_{2,1}$, and finally $ST_{2.2}$ is the responsibility of A_3. The purpose here is to find out if there are any tasks at risk caused for instance by any decrease in the level of trust or communication, or any increase in the workload of related agents. The Bayesian network representing this example is shown in Fig. 4(a), which represents these three performance criteria concentrated only on agent A_1. Here, $F_{ST_{1,1}}$ for Agent A_1, refers to the potential failure of sub-task $ST_{1,1}$, where LT_{A1}, LC_{A1}, and HW_{A1} respectively represent the lack of trust, lack of communication, and heavy workload, related to this agent, and calculated based on the approaches respectively explained in Sects. 3.1–3.3.



(a)

$$
\begin{aligned}
P(F_{ST_{1,1}}) = {} & P(F_{ST_{1,1}} | HW_{A1} = 0, LT_{A1} = 0, LC_{A1} = 0) * P(HW_{A1} = 0, LT_{A1} = 0, LC_{A1} = 0) \\
& + P(F_{ST_{1,1}} | HW_{A1} = 0, LT_{A1} = 0, LC_{A1} = 1) * P(HW_{A1} = 0, LT_{A1} = 0, LC_{A1} = 1) \\
& + P(F_{ST_{1,1}} | HW_{A1} = 0, LT_{A1} = 1, LC_{A1} = 0) * P(HW_{A1} = 0, LT_{A1} = 1, LC_{A1} = 0) \\
& + \ldots \\
& + P(F_{ST_{1,1}} | HW_{A1} = 1, LT_{A1} = 1, LC_{A1} = 1) * P(HW_{A1} = 1, LT_{A1} = 1, LC_{A1} = 1)
\end{aligned}
$$

(b)

HW	*LT*	*LC*	**P(F$_i$|HW, LT, LC)**
T	T	T	1
T	T	F	0.93
T	F	T	0.22
T	F	F	0.15
F	T	T	0.85
F	T	F	0.78
F	F	T	0.07
F	F	F	0

(c)

$F_{ST_{1,1}}$	$F_{ST_{1,2}}$	**P(F_{T_1} | $F_{ST_{1,1}}$, $F_{ST_{1,2}}$)**
T	T	1
T	F	0.3
F	T	0.7
F	F	0

(d)

Fig. 4. **(a)** Bayesian network for finding the failure risk of the VO's goal, represented by F_{Goal}. **(b)** An example of BN rules to find the probability of $F_{ST_{1,1}}$. **(c)** The Conditional Probability Table (CPT) for nodes showing failure in individual sub-tasks shown by F_i. **(d)** The CPT for node F_{T_1}.

The CPT related to the conditional probabilities of failure in individual tasks is then calculated based on the weights explained in Sect. 3.4 as shown in Fig. 4(c). Therefore, for example, if the ratio of agent's failed communication is more than the tolerated threshold, the percentage of its committed person-month in a year is more than pre-defined threshold, and also the agent violates its trust-related norm then the conditional probability of failure in its individual task is 100 % (15 % + 78 % + 7 %). This situation is shown in the first row of the CPT shown in Fig. 4(c).

Assume that the responsibility of A_1, and A_2 in fulfillment of task T_1 are 30 %, and 70 % respectively, while the responsibility of A_2 and A_3 in fulfillment of task T_2 might be 80 % and 20 % respectively. Now we can establish the CPTs for F_{T_1}, and F_{T_2} based on how much responsibility each involved agent or group of agents have in their fulfillment. For example, the CPT for F_{T_1} based on this assumption is shown in Fig. 4(d).

An example of the communication, trust, and workload values for A_1, A_2, and A_3 both at time t_0 and time t_1 are shown in Table 2. The failure probabilities of tasks T_1 and T_2 are then calculated based on the Bayesian network rules as shown in Fig. 4(b). Furthermore, a threshold for risky tasks is considered, to identify which VO task is risky. For example, if this threshold is 0.7 then at time t_0 none of the tasks are at risk, but at time t_1 both tasks T_1 and T_2 are considered risky. However, task T_1 is more risky than T_2 because both of its involved agents, i.e. A_1 and A_2, have high level of trust violation at this time, while the values of these three criteria for A_3 that is involved in T_2 are improved in contrast to the other two, to time t_0.

Table 2. Task probabilities for the Bayesian network of Fig. 4(a).

Time step	Agent	$P(C), P(T), P(W)$	$P(F_{ST_{1,1}})$ $[A_1]$	$P(F_{ST_{1,2}})$ $[A_2]$	$P(F_{ST_{2,1}})$ $[A_2]$	$P(F_{ST_{2,2}})$ $[A_3]$	$P(F_{T_1})$ $[A_1, A_2]$	$P(F_{T_2})$ $[A_2, A_3]$
t_0	A_1	0.5, 0.7, 0.5	0.657	0.5785	0.5785	0.5	0.602	0.5628
	A_2	0.5, 0.6, 0.5						
	A_3	0.5, 0.5, 0.5						
t_1	A_1	0.5, 0.7, 0.5	0.657	0.814	0.814	0.3636	**0.7669**	0.7239
	A_2	0.5, **0.9**, 0.5						
	A_3	**0.2, 0.4, 0.3**						

5 Conclusions

This paper addresses an extension to our earlier work on the VOSAT framework, emphasizing and supporting prediction of risk in VOs related to joint-tasks. Considering the VO's goals, identifying sources of risk in relation to the performance of planned daily activities of VO partners is critical in the risk analysis process for the success of the VO. The VOSAT framework provides mechanisms to reason about partner's trust-related norms, and their influence on VO risk analysis. Besides the trustworthiness, two other factors, the communication level and the workload level of each agent are also considered for calculating the failure probability of individual sub-tasks and in turn as potential sources for risks in VOs. Our proposed model for measuring the risk of failure related to joint-tasks, not only presents the inter-relationship among the main relevant factors, but also captures the causality among them. Therefore, based on the Partner-Responsibility-Interdependency-Tree (PRIT) which is developed during the VO's operation phase, a Bayesian network is created and kept up to date, in order to assist and enable the VO coordinator with identifying the weakest points and the high risk tasks in the VO's plan of activities.

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