A Novel Framework for Quantification of Supply Chain Risks

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Abstract

Supply chain risk management is an active area of research and there is a research gap of exploring established risk quantification techniques in other fields for application in the context of supply chain management. We have developed a novel framework for quantification of supply chain risks that integrates two techniques of Bayesian belief network and Game theory. Bayesian belief network can capture interdependency between risk factors and Game theory can assess risks associated with conflicting incentives of stakeholders within a supply network. We introduce a new node termed 'Game theoretic risks' in Bayesian network that gets its qualitative and quantitative structure from the Game theory based analysis of the existing policies and partnerships within a supply network. We have applied our proposed risk modeling framework on the development project of Boeing 787 aircraft. Two different Bayesian networks have been modeled; one representing the Boeing's perceived supply chain risks and the other depicting real time supply chain risks faced by the company. The qualitative structures of both the models were developed through cognitive maps that were constructed from the facts outlined in a case study. The quantitative parts were populated based on intuition and subsequently updated with the facts. The Bayesian network model incorporating quantification of game theoretic risks provides all the reasons for the delays and financial loss of the project. Furthermore, the proactive strategies identified in various case studies were verified through our model. Such an integrated application of two different quantification techniques in the realm of supply chain risk management bridges the mentioned research gap. Successful application of the framework justifies its potential for further testing in other supply chain risk quantification scenarios.

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1 Introduction

There are a number of key debates in the literature of risk focusing on the qualitative and quantitative aspects of risk assessment and therefore, choice of methodology must be given due consideration before its application in the field of supply chain risk management [1]. The application of risk theory to supply chain management is still in its early stages of research and there is requirement of conducting empirical studies of already established models. There is a major research gap of exploring established risk practices in other fields for application in the domain of supply chain risk management [1].

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This research study attempts to bridge the mentioned research gap by introducing a novel approach of combining Game theory and Bayesian belief network techniques. Game theory is used to model situations in which supply chain stakeholders have conflicting incentives while Bayesian belief network is a powerful technique to model the causal interdependency between various risk factors. Such a hybrid risk quantification framework has got its unique benefits as the two approaches complement each other and ignoring risks associated with conflicting incentives results in incorrect modeling of the real time situation.

The framework has been validated against an existing case study [2]. The case study was used to construct cognitive maps followed by modeling of the Bayesian networks. Working papers [3, 4] were consulted for establishing game theoretic modeling. This paper adapts the existing game models to incorporate features of continuous time domain and present value of money. Successful implementation of the framework on a case study advocates its potential for application in other supply chain risk management scenarios.

The concept of supply chain risk management is presented in Section 2. Basics of Bayesian network and Game theory are explained in Sections 3 and 4 respectively. Section 5 delineates the design of a novel framework that captures the dynamics of interacting risk factors. The details of the software are described in Section 6. Section 7 presents results and analysis while the conclusion is drawn in Section 8.

2 Supply Chain Risk Management

There are different perceptions of risk in the context of supply chain risk management. There is no clear distinction between risk and uncertainty in supply chain operations [5]. Risk is attributed to uncertain or unreliable sources that finally contribute to the supply chain disruptions while the uncertainty relates to the matching of fluctuating supply and demand in the processes. There are two important aspects of risk; the probability of risk event and its final impact. Most of the researchers have focused on the negative consequences of impact [6, 7, 8] but there is ambiguity regarding the choice of risk event itself. Similarly, there is no consensus regarding the selection of expected (supplier quality problems) or unexpected (wars, strikes, terrorist attacks) features of risk events. Risk in supply chain management relates to an event with small probability occurring abruptly that incurs major loss to the system. Supply chain risk management is defined as "the management of supply chain risk through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity" [6].

Based on a thorough study by carrying out direct observations of the researchers' output and gathering evidence through surveys of focus groups of researchers, following are the major research gaps in the field of supply chain risk management [9]:

- No clear consensus on the definition of supply chain risk management
- Lack of research on the reactive strategies once the risk event has occurred
- Shortage of empirical research in the field

Based on a thorough review of literature in the fields of risk and supply chain risk management, researchers have recommended following future research directions [1]:

- Lack of understanding of risk in supply chain risk management researchers
- Need for exploring already established risk practices in other fields for application in supply chain risk management
- Requirement of conducting case study based empirical studies in order to determine the current risk management methods used by various supply chains

- Need for developing robust and well-grounded supply chain risk management models that can only be materialized through clear understanding of risk and conducting sufficient number of empirical case studies

The risks can be viewed with respect to three broad perspectives [9]:

- A 'butterfly' depiction of risk that separates underlying causes, actual events and ultimate consequences
- Impact based perception in terms of disruptions and delays
- Network perspective in terms of local-and-global causes and local-and-global effects

3 Bayesian Belief Network

Bayesian belief network (BBN) is a graphical representation of causal relationships between variables and associated uncertainty in the dependency in terms of conditional probabilities [10]. The variables are represented by nodes while an arc (directed between two nodes) represents direct causal relationship. The network must be an acyclic directed graph which means that none of the nodes can be traced back while following the direction of arcs. Each node is provided with a set of conditional probabilities except the root nodes, in order to indicate the influence of parent nodes on the child node.

3.1 Application of BBN in Supply Chain Risk Management

Bayesian belief networks are helpful in benchmarking supplier risk profiles that can be used for the determination of key suppliers having major potential impact on revenues of an organization [11]. The model is designed for determining the supplier's external, operational and network risks. The results of the study can help managers focus on key suppliers based on the maximum Value at Risk (VAR) posed to the company. However, the proposed model seems to be industry specific and therefore, the generality of the Bayesian network is limited in scope. In another similar study, suppliers are benchmarked against their risks based on the sensitivity analysis [12]. However, a major limitation of the study is difficulty to get data from current and potential suppliers in populating the Bayesian network. Bayesian network has also been applied in managing risks associated with large engineering project [13]. A combination of Bayesian network and Total Cost of Ownership methods has also been used for selection of potential suppliers [14]. Bayesian network is suitable for modeling risks in case of buyer's incomplete and uncertain information about the suppliers.

4 Game Theory

Game theory was developed to explain the rationale for taking economic decisions that would not have occurred on the basis of simple cost-benefit analysis. Game theory can help the operations managers take appropriate decisions within a supply chain context [15]. A game in a business setting has following four basic elements [16]:

- The players (supply chain stakeholders)
- The rules of the game (policies, constraints)
- The complete set of actions or decisions for each player
- The outcomes or pay-offs resulting from each set of decisions

		Prisoner 2: Confess	Prisoner 2: Deny
Prisoner 1	Confess	-2, -2	0, -3
	Deny	-3, 0	-1, -1

Figure 1 Prisoner's dilemma.

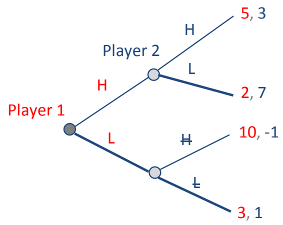


Figure 2 A sequential-move game.

4.1 Simultaneous-Move Games

In simultaneous-move games, each player must take action at the same time or without knowing the moves of other players. The players may have complete information of the pay-offs for each set of decisions. The most popular simultaneous-move game is the prisoner's dilemma where two criminals are apprehended by the Police and asked separately to testify against each other [17]. The game is modeled in Figure 1. Each player can either confess or deny. The first pay-off relates to the row player (Prisoner 1) while the second pay-off corresponds to the column player (Prisoner 2). If both players confess, each gets 2 years of imprisonment. If both deny, each gets 1 year of imprisonment. However, if one confesses and the other denies, the one confessing goes free while the other denying is awarded 3 years of imprisonment. Both the prisoners can be in a better situation by denying but the solution (Nash equilibrium) for this game is both prisoners confessing.

▶ **Definition 1.** *A Nash equilibrium is an action profile a^* with the property that no player i can do better by choosing an action different from a_i*, given that every other player j adheres to a_j*.* [18]

4.2 Sequential-Move Games

In sequential-move games, players take decisions in sequence. An example of such a game is provided in Figure 2. Solution of such games can be obtained through backward induction. Both the players represent competing industries and need to decide on the price of a product. The strategy of Player 1 is represented by (H, L) while that of Player 2 is given as (H~~H~~, H~~L~~, L~~H~~, L~~L~~). Player 1 has to take the decision first followed by Player 2. By looking at the terminal nodes, it is clear that L~~L~~ is the best strategy for Player 2 and knowing this, Player 1's best strategy is to choose L. Thus, (L, L~~L~~) is the solution (subgame perfect equilibrium) for this game.

▶ **Definition 2.** *A subgame perfect equilibrium is a strategy profile s^* with the property that in no subgame can any player i do better by choosing a strategy different from s_i*, given that every other player j adheres to s_j*.* [18]

5 A Novel Framework

The novel framework of combining the two techniques of Bayesian belief network and Game theory is shown in Figure 3. The hybrid framework reveals complementary effect of integrating these two modeling methods. Majority of the supply chain quantitative modeling schemes do not consider the risks of misaligned objectives (conflicting incentives) among supply chain partners. Modeling these risks through the Game theory approach and subsequent incorporation in the Bayesian belief network provide more realistic approach towards quantifying the supply chain risks. Bayesian networks have the advantage of capturing dynamic nature of the interacting risk factors.

Initially, the key risk factors are identified within the supply chain followed by qualitative modeling of the Bayesian network. Game theoretic modeling of the conflicting incentives is carried out through a detailed analysis of available information in the form of policies and/or partnerships. The players are identified and their strategies are established followed by the determination of their pay-offs. Finally, game theoretic analysis is performed and results are incorporated in the Bayesian network in the form of a small network of 'Game theoretic risks'. The 'Game theoretic risks' node is connected to an appropriate impact node and the conditional probability table of the child node is populated based on the game theoretic modeling results.

The entire Bayesian network is populated with conditional probability tables followed by the initial updating. Sensitivity analysis of the game theoretic risks is performed. In case of sensitivity being high, a fair strategy is devised followed by the game theoretic analysis of misaligned objectives. The loop is repeated until the acceptable sensitivity results are obtained. This process is followed by the sensitivity analysis of rest of the risk factors followed by determination of proactive risk mitigation strategies.

6 Software

The cognitive maps have been constructed in Decision Explorer. Bayesian belief networks can be modeled in a number of software including Hugin, AgenaRisk, Graphical Network Interface (GeNie), etc. We used GeNie for modeling and analyzing the networks. The software has been developed by the Decision Systems Laboratory, University of Pittsburg.

7 Analysis and Results

The developed framework is applied on an existing case study concerning the development project of Boeing 787 aircraft [2]. The analysis and results of Game theory and Bayesian network techniques are presented in following sections.

7.1 Game Theoretic Analysis

The discrete time based Game theoretic analysis concerning the development project of Boeing 787 aircraft revealed that there were conflicting incentives among the strategic partners [3]. We have developed our new game models on the basis of same study incorporating features of present value of money and continuous timeframe. Every project comprises two components of costs; direct and indirect costs. Direct costs relate to each task of the project including costs covering labor, material, shipping, etc. Indirect costs do not relate directly to the tasks but these are linked to the project duration. Overhead, delaying penalty, order cancellations and financial losses are some of the examples of indirect costs. A longer task is considered to lower direct costs while a longer project increases indirect costs [19].

The direct cost of a task reduces with the duration representing a convex function as shown in Figure 4. 'X_i' indicates the scheduled timeframe of the task. If either the Boeing or a Tier-1 supplier delays its task, it gets saving represented by 's_i'. In case of expediting the task, there is an associated cost represented by 'c_i'. The indirect cost of a project increases with the project duration representing a convex function as shown in Figure 4. 'X_s' indicates the scheduled timeframe of the suppliers' tasks while 'X_m' indicates the scheduled timeframe

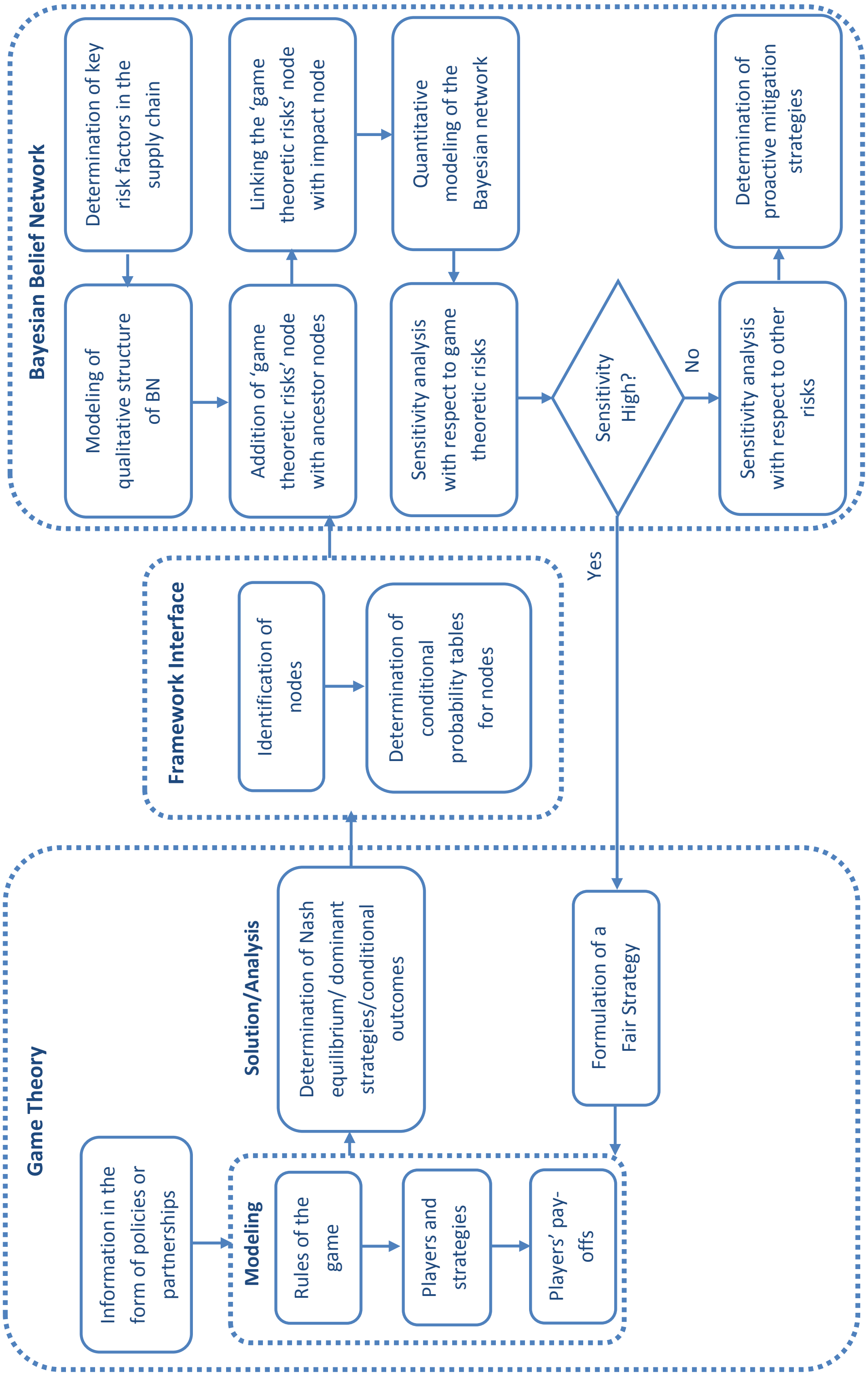


Figure 3 A novel framework for quantification of supply chain risks.

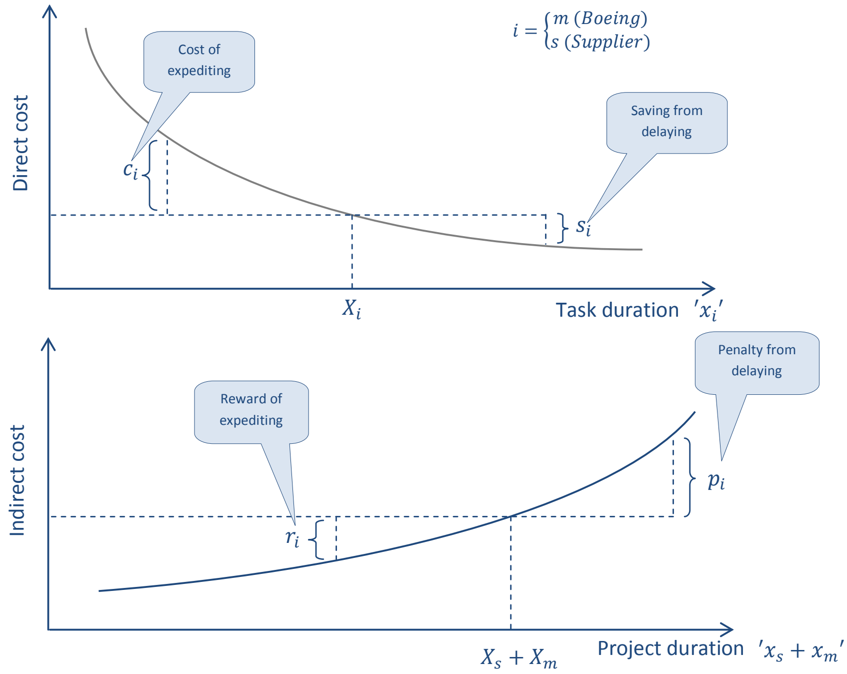


Figure 4 Variation of direct and indirect costs with task and project duration respectively.

of the Boeing's task. If the resultant time of the two tasks exceeds the scheduled time, there is a penalty '$\mathrm{p_i}$' whereas expediting the project results in the reward '$\mathrm{r_i}$' for each partner.

It is assumed that all the Tier-1 suppliers perform their tasks in parallel and the overall time taken by the suppliers is determined by the supplier completing its task at the end. After completion of tasks by the suppliers, Boeing performs the final assembling phase.

7.1.1 Strategic Loss Sharing Partnership

The strategic partnership was introduced by Boeing in order to reduce its financial risks. Each firm was supposed to bear the direct and indirect costs whereas final payment was to be made only after the successful culmination of the project. If a firm delays its task and the project gets delayed, all the firms incur additional indirect costs but the delaying firm saves from its direct costs. The firms having completed the tasks in time, are unfairly penalized because of the project delay caused by the delaying firm. As the firms were not made responsible exclusively for their specific actions, this type of partnership resulted into 'moral hazard' [20]. There were misaligned objectives as every supplier would consider the possibility of other partner delaying the respective task and in case of delivering the task in time, the supplier would lose the amount contrary to the delaying suppliers gaining the same. We will present various forms of games in order to analyze the game theoretic perspective of Boeing's partnership.

- In the first form of game, we consider only one Tier-1 supplier and Boeing. Each player can either delay (D) or keep (K) the task schedule. The extensive form of this sequential-move game is presented in Figure 5. Assuming the marginal benefits being lower than the marginal costs for delaying, Boeing's best strategy is to keep the project in time while the supplier also completes the task in time.

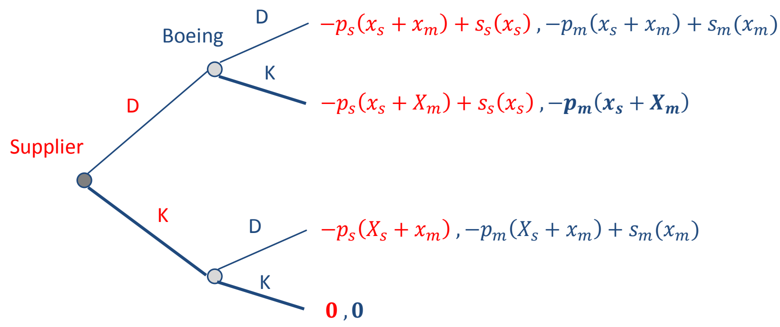
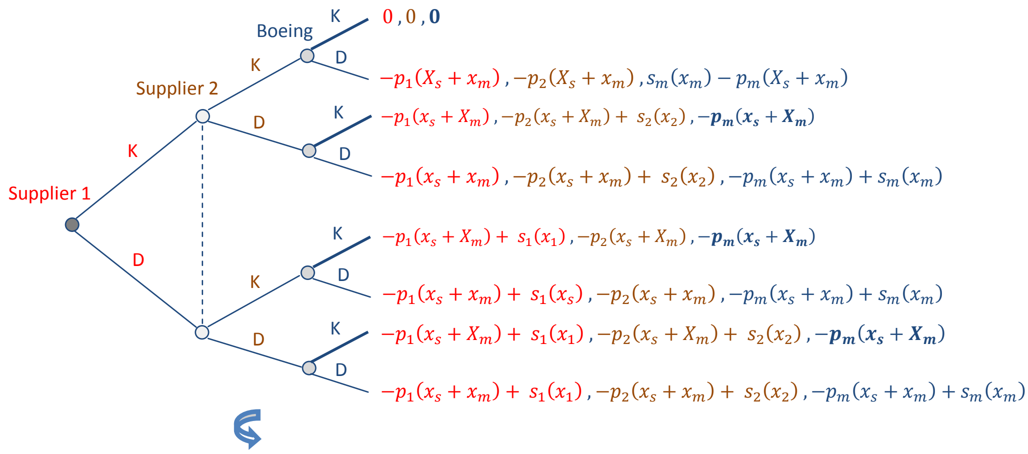


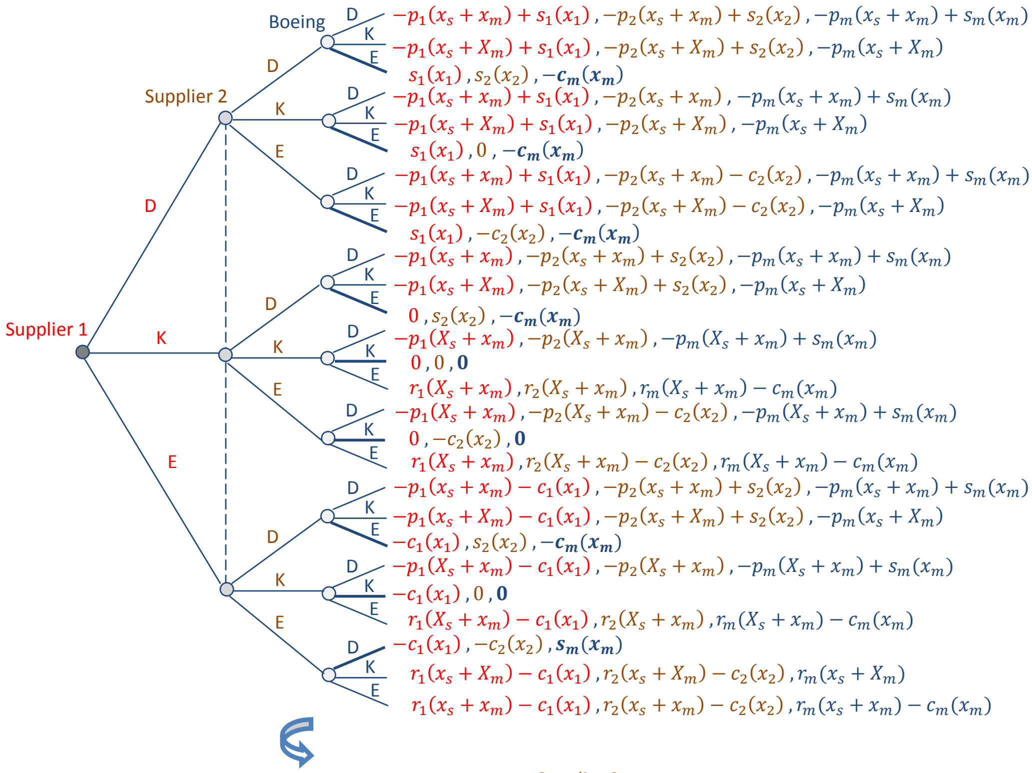
Figure 5 A game between one supplier and Boeing (two actions for each player).



	Supplier 2: K	Supplier 2: D
Supplier 1: K	$\mathbf{0}\,,\mathbf{0}$	$-p_1(x_s+X_m)\,,$ $-p_2(x_s+X_m)+\ s_2(x_2)$
Supplier 1: D	$-p_1(x_s+X_m)+\ s_1(x_1)\,,$ $-p_2(x_s+X_m)$	$\boldsymbol{-p_1(x_s+X_m)+\ s_1(x_1)\,,}$ $\boldsymbol{-p_2(x_s+X_m)+\ s_2(x_2)}$

Figure 6 A game between two suppliers and Boeing (two actions for each player).

- Now, we extend the game to two suppliers and Boeing. The three players' game is presented in Figure 6. The dotted line represents simultaneous game between the two suppliers as they are assumed to perform the tasks in parallel. Assuming the marginal penalty being higher than the marginal saving from delaying, the Boeing's best strategy is to keep the schedule. Having established this fact from the extensive form of the game, the game between suppliers can be modeled in matrix form. From the matrix form, it is clear that the two Nash equilibria are (K,K) and (D,D). Therefore, the strategies of the stakeholders are not aligned and there is a chance that project would be delayed as each supplier considers the possibility of other supplier delaying the task.
- Now, we extend our model to incorporate the option of expediting a task. The extensive form of the game is presented in Figure 7. Based on the technique of backward induction, we can determine the best response of Boeing at each of the terminal nodes. As there is no other sub-game because of the simultaneous game between two suppliers, the solution is determined through matrix form of the game. It is easy to interpret that there is



		Supplier 2		
		D	K	E
Supplier 1	D	$s_1(x_1), s_2(x_2)$	$s_1(x_1), 0$	$s_1(x_1), -c_2(x_2)$
	K	$0, s_2(x_2)$	$0, 0$	$0, -c_2(x_2)$
	E	$-c_1(x_1), s_2(x_2)$	$-c_1(x_1), 0$	$-c_1(x_1), -c_2(x_2)$

Figure 7 A game between two suppliers and Boeing (three actions for each player).

only one subgame perfect equilibrium that is the decision to delay on the part of both the suppliers because Boeing would have to expedite in order to save the heavy penalty resulting from the project delay. The consideration of present value of money does not affect the outcome if it is assumed that Boeing would always prefer completing the task in time even at the cost of expediting.

7.2 Framework Interface

After analyzing the strategic partnership, it is revealed that the partnership engendered misaligned objectives among the stakeholders that finally contributed to the game theoretic risks. As a result of this analysis, three nodes are identified namely ‘fair strategy’, ‘misaligned objectives’ and ‘game theoretic risks’. The qualitative and quantitative parts of the structure are determined for subsequent incorporation into the Bayesian network.

7.3 Bayesian Network Analysis

The perceived oversimplified cognitive map of the Boeing 787 Project comprised 27 concepts and 38 links. The Bayesian belief network based on the cognitive map is depicted in Figure 8. The model clearly reveals that Boeing was focusing on the opportunities resulting from the introduction of unproven technology and unconventional supply chain. After the inferencing stage, the probability of development time being high was just 0.09 and that of development cost was 0.22. These favorable results represent the fact that the Boeing management had ignored the interdependency between risk factors and assumed the events of development cost and time being high as unlikely. Contrary to the expectations, the project was delayed by almost 3 years causing major financial penalty to the Boeing.

There were a number of risks associated with the decisions taken by the Boeing management. The cognitive map of the actual supply chain risks comprised 41 concepts and 63 links. A Bayesian network was modeled following the steps outlined in the framework. Three nodes identified earlier as 'fair strategy', 'misaligned objectives' and 'game theoretic risks' were added to the BN. The output of 'game theoretic risks' node was linked to the 'development time' node. The impact of 'game theoretic risks' node on the 'development time' node was quantified based on the game theoretic analysis. The resulting Bayesian network is presented in Figure 9. The unproven technology resulted in major technological risks that further affected the intended outcomes. Outsourcing was considered to be a means of reducing development cost and time; however, it resulted in integration issues as the Tier-1 suppliers were not proficient in selecting their suppliers. Furthermore, the strategic partnership was not a fair strategy as it did not provide due incentives to the stakeholders to keep the schedule in time. This caused increase in the game theoretic risks, being dominant on other factors affecting the development time.

The management involved in the project was lacking expertise in supply chain risk management. The expertise would have provided a guard against all the risks in terms of adopting suitable mitigation strategies. Game theoretic risks are assumed to be independent of the management expertise as the conventional supply chain risk management does not focus on analyzing the risks caused by misaligned objectives of the stakeholders. It also emphasizes the importance of considering unique category of risks within the project risk assessment and the management must possess the ability to apply Game theory to quantify such risks.

The initial updating reveals that the probabilities of development cost and time being high were 0.46 and 0.54 respectively. Different scenarios were generated and the impact of individual risk factor was determined as shown in Table 1. Management expertise was found to be the dominant factor influencing development cost as it lowered its probability being high by 37 % in relation to the case with no management expertise in supply chain risk management.

Game theoretic risks were considered as the dominant factor influencing development time. Introduction of a fair strategy lowered its probability by 26 % in relation to the case with no fair strategy. Once all the facts were entered in the model, the probabilities of development cost and time being high were 0.81 and 0.98 respectively indicating high likelihood of the events. The proactive strategies of ensuring a team with supply chain risk management expertise, devising a fair strategy, negotiating with the labor union and adopting a thorough supplier selection process resulted in the probabilities of development cost and time being high as 0.31 and 0.24 respectively.

7.4 Formulation of a Fair Strategy

The sensitivity analysis of game theoretic risks revealed its major impact on the development time. Therefore, there is requirement of designing a fair strategy in order to reduce the game theoretic risks. The main purpose of a fair strategy is to make each player responsible for one's own deeds [3]. If the suppliers perform their tasks within stipulated time then

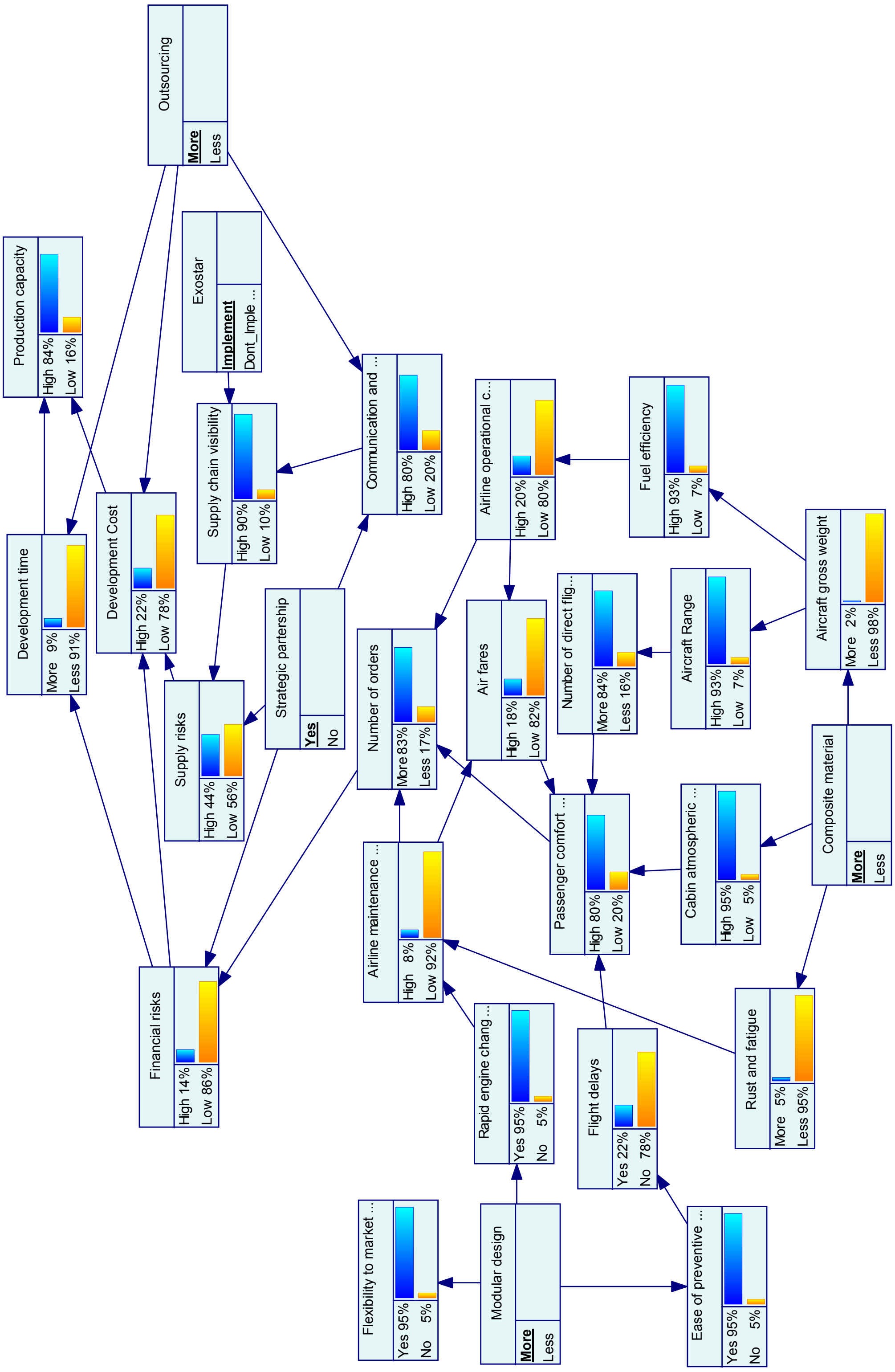


Figure 8 Bayesian belief network based on Boeing's perception.

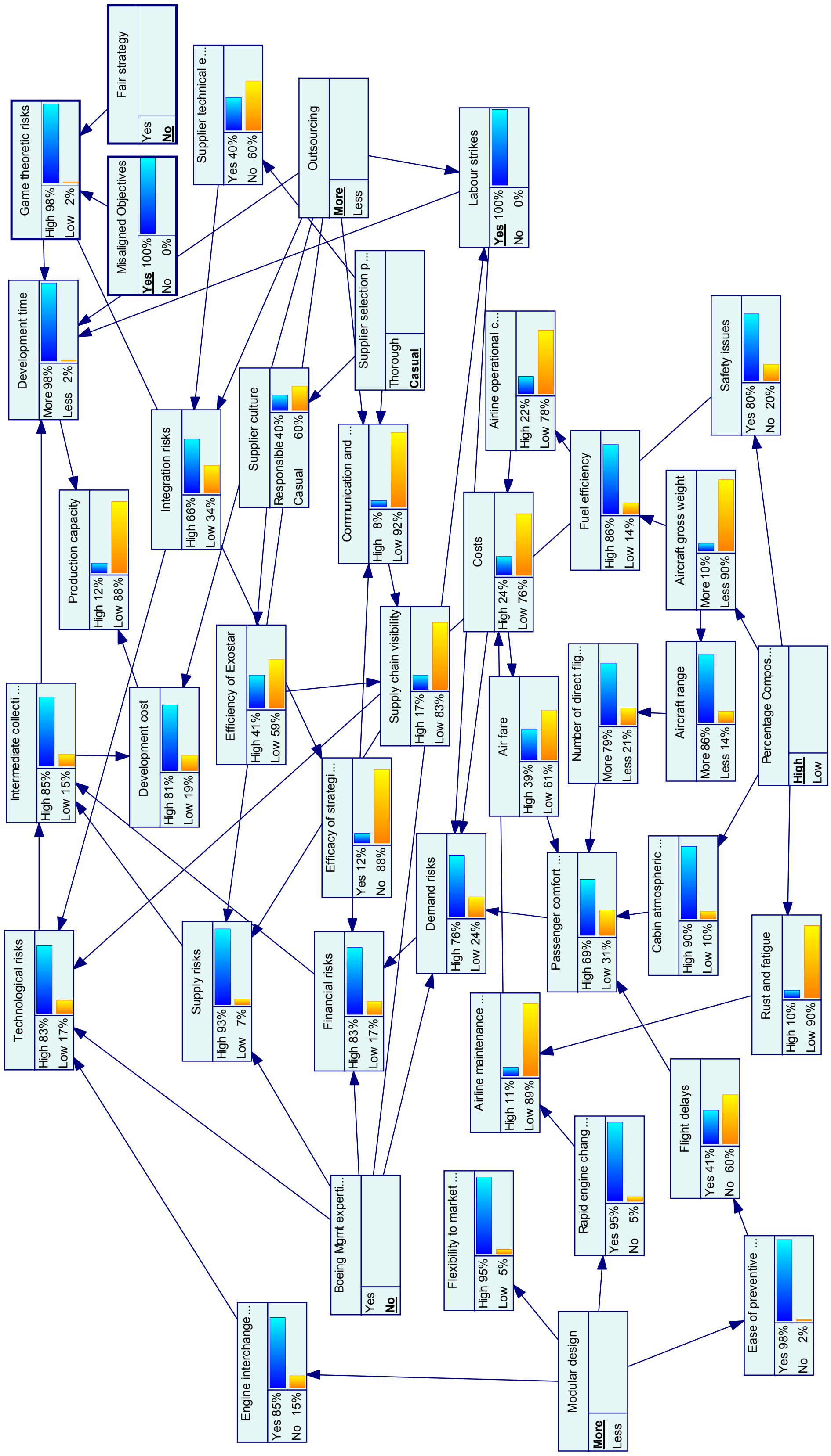


Figure 9 Bayesian belief network based on real time risks.

Table 1 Summary of BBN results.

Scenario	Probability of development time (more)	Probability of development cost (high)
Initial updating	0.54	0.46
Management expertise 'Yes'	0.42	0.28
Management expertise 'No'	0.66	0.65
Fair strategy 'Yes'	0.41	0.44
Fair strategy 'No'	0.67	0.49
Outsourcing 'More'	0.60	0.50
Outsourcing 'Less'	0.48	0.43
Composite material 'More'	0.54	0.48
Composite material 'Less'	0.53	0.45
Modular design 'More'	0.55	0.49
Modular design 'Less'	0.53	0.44
Supplier selection process 'Thorough'	0.53	0.43
Supplier selection process 'Casual'	0.55	0.49
Updating of all facts	0.98	0.81
Fair strategy 'No' and Management expertise 'Yes'	0.93	0.44
Fair strategy 'Yes' and Management expertise 'Yes'	0.33	0.35
Implementation of proactive strategies	0.24	0.31

consequences of any delay on the part of Boeing would be completely compensated by the Boeing and in case of suppliers having expedited their tasks, Boeing would have to pay the reward that did not materialize because of its delay. Similarly, if a supplier is involved in the delay, it will be proportionately penalized for its part of delay. In case of delay on the part of both the suppliers and Boeing, the penalty would be paid fairly.

In the presence of a fair strategy, no partner is incentivized to delay the task; therefore, the project is more likely to be completed in time depending on the other risk factors impacting the delay. After devising the fair strategy, it is revealed that the already existing variables pertaining to game theoretic risks remain same and therefore, there is no requirement of updating the Bayesian network. However, in other situations, the formulation of a policy may necessitate addition of other nodes into the BN requiring some changes as depicted in the framework. After introduction of the fair strategy, the game theoretic risks decrease to the minimum level resulting in lower probability of development time being high.

8 Conclusion

The paper has demonstrated development of a novel framework that combines two complementary techniques of Game theory and Bayesian belief network. The rationale for development of the framework is based on bridging the research gap in the field of supply chain risk management. The developed framework has been successfully applied on the development project of Boeing 787 aircraft. The novel framework captured the dynamics of interacting risk factors. Bayesian belief network is a useful modeling technique for quantification of interdependent risk factors. Game theoretic modeling provides an opportunity to model the risks associated with conflicting incentives among the stakeholders within a supply network. The Game theoretic results were fed in the Bayesian network as inputs. The results of the study clearly revealed that without mitigating the game theoretic risks, the objective of timely completion of the project was not materialized. Furthermore, lack of management expertise was the major factor contributing to overall costs of the project. The application of this novel risk modeling framework in other supply chain risk projects will help decision makers visualize holistic view of interdependent risk factors and identify key risk factors for establishing proactive risk mitigation strategies.

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