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# Assessing project risks from a supply chain quality management (SCQM) perspective

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## Abstract

**Purpose** – Project-driven supply chain risks pose a significant threat to the success of complex development projects, in terms of achieving key performances such as quality, time and efficiency. The purpose of this paper is to adopt a supply chain quality perspective in order to explore and better understand the unique attributes of risks associated with project-driven supply chains for continuously improving the quality of both processes and products.

**Design/methodology/approach** – Theoretically grounded in the framework of Bayesian Belief Networks and Game theory, this paper develops a structured process for assessing and managing risks in project-driven supply chains. The application of the proposed approach is demonstrated through a simulation case study conducted on the development project of Boeing 787 aircraft.

**Findings** – The conflicting incentives amongst stakeholders in a supply chain can jeopardise the success of a project and therefore, assessment of this category of risks classified as "Game theoretic risks" needs special consideration. Project-driven supply chain risks pose a significant threat to the success of complex projects. The results of the study clearly revealed that without mitigating the game theoretic risks, the main objective of timely completion of the Boeing 787 project was not materialised. Further, the lack of management expertise was the major factor contributing to the overall project costs including cost of quality.

**Originality/value** – The proposed process and analyses present a significant and original insight in terms of capturing the key determinants of both product and service quality such as product performance, convenience and reliability of service, timeliness, ease of maintenance, flexibility, and customer satisfaction and comfort. Propositions are developed for ascertaining the significance of information sharing in a project-driven supply chain, and a fair sharing partnership is introduced to help supply chain managers in managing game theoretic risks in order to achieve the goals of quality, time and efficiency.

**Keywords** Supply chain risks, Continuous improvement, Supply chain quality, Process and product quality, Bayesian belief networks, Game theory

**Paper type** Research paper

## 1. Introduction

Supply chains have become more complex and vulnerable due to trends such as globalisation, increased outsourcing, global sourcing, and focus on efficiency (Son and Orchard, 2013). These trends generate the need to create more resilient supply chains (Das, 2018), identifying vulnerabilities and risks within functions and processes, and their impacts on supply chain performances (Mhatre *et al.*, 2017).

Non-linear interactions between risks make it a daunting task to understand and properly manage these risks (Ackermann *et al.*, 2014) and therefore, a number of frameworks and tools have been introduced to the literature on supply chain risk management (SCRM)

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(Christopher and Peck, 2004) and supply chain quality management (SCQM) (Foster, 2008) to better address the increasing interdependency among supply chain actors, processes and risks. Amongst these approaches, there are, for example, scenario-based analyses (Das, 2018), interpretive structural modelling (Haleem *et al.*, 2012), fuzzy techniques (Nieto-Morote and Ruz-Vila, 2011), Bayesian Belief Networks (BBNs) (Qazi *et al.*, 2018), and the Analytic Hierarchy Process (AHP) (Gaudenzi and Borghesi, 2006).

In SCRM and SCQM frameworks, an interesting area of investigation is project management. According to Mhatre *et al.* (2017), long-term projects present a high level of complexity, typically emphasising the key role of an effective risk management to achieve the project and supply chain objectives (Doloi *et al.*, 2012; Chapman and Ward, 2004). In the specific case of a new product development (NPD) project, key risks are major delays and cost overruns, which are influenced by significant and complex interdependency between risks, involving different stakeholders and decision-makers (Ackermann *et al.*, 2006, 2014).

Conventional supply chains (involving routine processes) and project-driven supply chains (involving unique processes specific to NPD) are reported to have different characteristics and therefore, there is a need to tailor the risk management process in accordance with the characteristics and objectives of the supply chain. A well-known case in this sense is Boeing, which outsourced 70% of the development and production tasks in the development project of Boeing 787 aircraft (Tang *et al.*, 2009; Zhao *et al.*, 2013). More than 50% of the fuselage was planned to be made of composite material. In order to mitigate the key risks, a strategic partnership was developed with Tier-1 suppliers passing to them the responsibility to control quality and risks associated with the development project. Despite Boeing adopting an unconventional supply chain composed of several partners, the project was delayed incurring major financial penalties in millions of dollars because the project team did not realise the importance of assessing and managing risks before the commencement of the project (Tang *et al.*, 2009). The Boeing management had not planned for managing the interdependency between risks.

BBNs provide an effective modelling framework for capturing interdependency between risks (Qazi *et al.*, 2018). Game theory is a technique, which allows to model situations in which stakeholders have conflicting incentives, and can effectively support risk management decisions (Osborne, 2003). Game theory can be integrated with BBNs in order to capture causal interdependency across risk factors. However, these tools have not been applied together with the scope to modelling and managing risks in complex supply chains where key supply chain stakeholders might have conflicting incentives regarding the key performance attributes. For example, time might not be the top priority for a supplier specific to a supply chain, who is involved in providing supplies to multiple supply chains with different associated contracts and incentivisation schemes. In addition, while interdependency modelling has been extensively explored in other research areas, such as the reliability and safety of engineering systems, there are fewer applications in the area of SCRM, SCQM and complex projects.

The present paper has therefore the scope to propose a framework for capturing interdependency between risks and modelling the risk appetite of a decision maker (Aven, 2015), using the lens of BBNs and Game theory. The framework will be validated through a simulation model (Badurdeen *et al.*, 2014) for the case study of Boeing 787 (Tang *et al.*, 2009). The case study was used to construct cognitive maps followed by the development of BBN and Game theory-based models. This paper also attempts to narrow the aforementioned research gap and aims to extend the research of Mhatre *et al.* (2017). The remainder of the paper is organised as follows. A brief overview of the relevant literature is presented in Section 2. The proposed methodology is described in Section 3 and demonstrated through a simulation case study in Section 4. We discuss the implications of our study in Section 5 and conclude the article and present future research directions in Section 6.

## 2. Literature review

There are different perceptions of risk in the context of SCRM and SCQM, and the literature has offered significant theoretical and empirical advancements in the investigation of risk and uncertainty in supply chain operations (Tang and Nurmaya Musa, 2011). For example, researchers highlighted that certifications in Quality Management System, particularly the ISO 9000 and ISO 9001 certifications, represent for organizations a first essential step in order to reach a comprehensive understanding of risks and vulnerabilities amongst companies' processes, and to achieve better performance (Bevilacqua *et al.*, 2013). In particular, these standards might contribute to improving the effectiveness and efficiency of process management within the company and along the network (Su *et al.*, 2020). In parallel, these standards lead organizations to extensively adopt quality tools and techniques (Castello *et al.*, 2020), which can improve the measurement of performances and risks.

Two important aspects in SCRM are the assessment of the probability of risk event and the measurement of its final impact (Colicchia and Strozzi, 2012). SCRM researchers typically focus on the negative consequences of risk (Christopher and Peck, 2004; Wagner and Bode, 2008), which are generally characterised as events with small/medium probability and the potentiality of severe consequences in terms of business continuity and profitability (Christopher and Peck, 2004). Sources of these risks have been addressed in SCQM studies (Das, 2018; Moeinedini *et al.*, 2018; Das, 2018; Roy *et al.*, 2016; Knemeyer *et al.*, 2009) as – for example – natural calamity, terrorism, political instability or labour disputes, and vulnerabilities in single/global sourcing, which can generate cascading effects such as supplier failures, delays and other negative impacts in SC operations.

A review of articles focussing on supply chain risks reveals the need for conducting extensive research in the area of both SCRM and SCQM in order to explore holistic methods for capturing the interdependency between risks (Tang and Nurmaya Musa, 2011; Colicchia and Strozzi, 2012; Ghadge *et al.*, 2012). Existing risk analysis methods assign risks to independent categories and fail to capture the interdependency between causal chains of vulnerabilities, risk sources, risk events and resulting losses; disruptions are unpredictable and in order to safeguard a supply chain from the adverse effects of these disruptions, managers need to have complete visibility across the entire network; and there is a need to explore the synergy of SCRM and quality management for the continuous improvement of supply chain operations (Qazi *et al.*, 2018; Abuazza *et al.*, 2020).

Researchers have been using different techniques for capturing the interdependency between project/supply chain risks. Well-cited techniques include BBNs (Badurdeen *et al.*, 2014; Lockamy, 2014; Garvey *et al.*, 2015; Nepal and Yadav, 2015); Failure Modes and Effects Analysis (FMEA) (Sinha *et al.*, 2004); Network Theory (Squire, 2010; Fang *et al.*, 2012); Monte Carlo Simulation (Lee *et al.*, 2012); AHP (Gaudenzi and Borghesi, 2006); Analytic Network Process (ANP) (Boateng *et al.*, 2015); Causal Mapping (Ackermann *et al.*, 2014); Systems Thinking (Williams, 2005); Graph Theory (Wagner and Neshat, 2010) and ISM (Pfohl *et al.*, 2011). The tools that can significantly contribute to the integration of SCRM and SCQM and to the continuous improvement of processes in SCM are BBNs, FMEA, Causal Mapping and ISM because all these tools help in visualising the causal interdependency among different factors influencing the quality and key performance indicators of a supply chain. BBNs provide a unique opportunity in terms of integrating numerous tools of total quality management such as cause and effect diagrams, pareto analysis, scatter diagrams, and process flow charts.

Strategic risks can result among supply chain stakeholders due to their conflicting incentives such as their unique preferences (utility) across supply chain performance indicators (Wakolbinger and Cruz, 2010; Lutz *et al.*, 2012; Zhao *et al.*, 2012; Zhao, 2013; Xin and Zhao, 2013). Game theory is an effective technique for mitigating such risks (Osborne, 2003). Risk sharing-based contracts can be designed for aligning conflicting incentives of stakeholders to maintain high reliability and profitability of a supply network. According to Qazi *et al.* (2015), strategic

risks have not been fully explored in the literature on SCRM and project risk management and, therefore, there is a need to model opportunistic behaviour of stakeholders while modelling and assessing supply chain risks.

Limited articles have explored supply chain risks associated with projects involving NPD and the literature on project risk management only partially includes risk management frameworks to manage risks related to such mega projects (Kardes *et al.*, 2013). For example, in the construction industry, Aloini *et al.* (2012) highlighted that none of the 140 research articles on supply chain management in construction projects dealt with the risk management. In the aviation industry, Tang *et al.* (2009) used secondary data to establish why the Boeing 787 project incurred a substantial financial loss despite Boeing having introduced a fair-sharing partnership with its Tier-1 suppliers. The undermining of the supply chain risks associated with the project was adjudged as the main underlying cause; however, the assessment of risks in isolation might not represent the systemic behaviour of risks (Ackermann *et al.*, 2014). As opposed to utilising secondary data, efforts have been made to conduct case studies in industry and explore the nature of SCRM processes adopted in such projects; however, such studies have either focussed on the conventional risk matrix-based tools thereby assuming independence of risks (Khan *et al.*, 2008) or reported on a single stage of the risk management process without integrating all the stages involved (Lin and Zhou, 2011).

Badurdeen *et al.* (2014) also conducted a case study in Boeing related to the development project of a missile guidance system. Their proposed model establishes the link between supply chain risks but instead of integrating the network-wide risks, the model captures the risks specific to a Tier-1 supplier and aids in ranking the suppliers as does the model proposed by Hosseini and Barker (2016). It seems that there are two major limitations of the existing studies: first, these studies focus on few stages of the risk management process without establishing and validating a comprehensive risk management process in such projects; and secondly, the interdependency modelling of risks in general and strategic risks in particular is ignored in entirety. As highlighted by Moeinedini *et al.* (2018), due to the non-repetitive nature of the projects, often characterised by a lack of historical data and domino-effects amongst risks, more investigations and frameworks about project risk assessment are needed. To fill this gap, Qazi *et al.* (2016) initially introduced a process, namely Project Complexity and Risk Management (ProCRiM) capturing interdependencies among project characteristics, risks and project objectives. In this additional study, authors propose a new methodology grounded in the theoretical framework of BBNs and Game theory, which is presented in the following section. The scope of this study is also to start filling a wider gap, highlighted by Huo *et al.* (2019), in that the majority of studies on SCQM have considered SCM and QM as different practices without investigating the association between them.

## 3. Proposed methodology

BBNs with their background in statistics and artificial intelligence were first introduced in the 1980*s* for dealing with uncertainty in knowledge-based systems (Sigurdsson *et al.*, 2001). They have been successfully used in addressing problems related to a number of diverse specialities including reliability modelling, medical diagnosis, geographical information systems and aviation safety management, among others. (Jensen and Nielsen, 2007; Kjaerulff and Anders, 2008). BBNs facilitate capturing the interdependency between uncertain variables and a number of studies specific to SCRM have substantiated the efficacy of BBNs in modelling supply chain risks (Badurdeen *et al.*, 2014; Garvey *et al.*, 2015).

Game theory was developed to explain the rationale for taking economic decisions that would not have occurred on the basis of a simple cost-benefit analysis. Game theory can help the operations managers take appropriate decisions within the supply chain context. A game

in a business setting has four basic elements: players (supply chain stakeholders); rules of the game (policies and constraints); a complete set of actions or decisions for each player; and the outcomes or pay-offs resulting from each set of decisions. For understanding the mechanics of Game theory, interested readers may consult Osborne, 2003 and Zhao *et al.*, 2012.

The proposed process integrating the two techniques of BBNs and Game theory is shown in Figure 1. The process involves identifying key risks, strategies and performance criteria specific to the project-driven supply chain. This step is followed by the qualitative modelling of the BBN model. Game theoretic modelling of the conflicting incentives is carried out

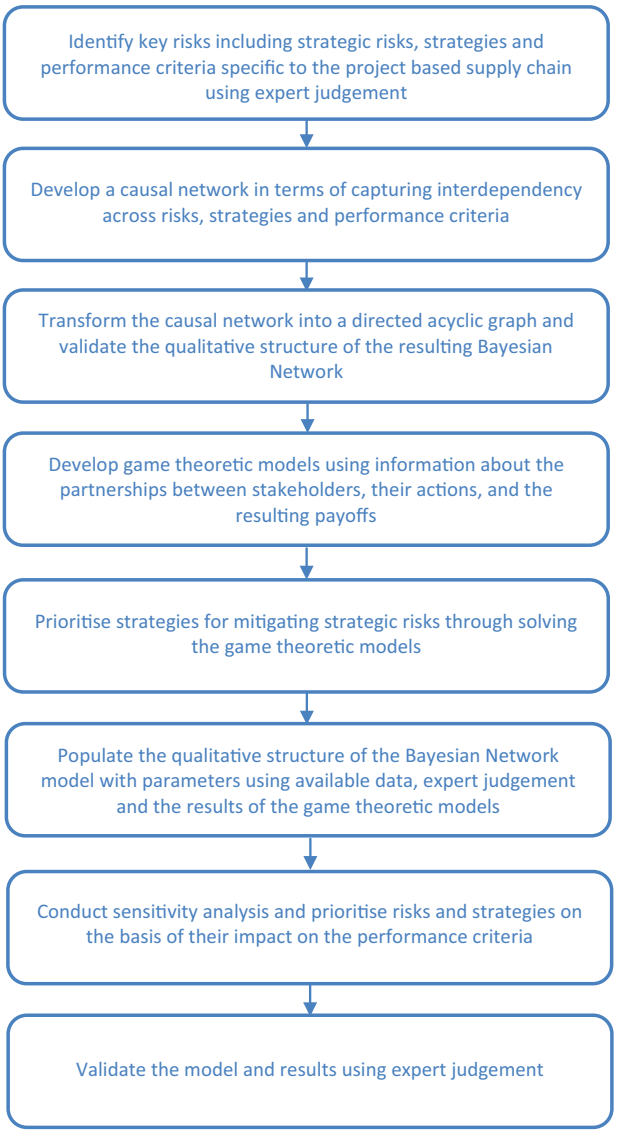



**Figure 1.**
Proposed process for assessing project risks in supply chains

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. Subsequently, game theoretic analysis is performed and optimal strategies are established. The results are incorporated in the BBN model in the form of a small network of "Game theoretic risks". The "Game theoretic risks" node is connected to the relevant impact node. The entire BBN model is populated with parameters using expert judgement, available data and the results of the game theoretic analysis. Sensitivity analysis of the entire model is performed, and key risks and strategies are established. This analysis helps in validating the quantitative part of the model through involving experts and stakeholders in the validation process.

## 4. Demonstrative case study

The proposed methodology is demonstrated using secondary data related to the development project of Boeing 787 aircraft (Tang *et al.*, 2009). The Game theory and BBN-based models are presented and analysed in the following sections using the information and data related to the case of Boeing as provided by Tang *et al.* (2009); Zhao *et al.* (2013); Xin and Zhao (2013); Denning (2013a, b) and Greising and Johnsson (2007).

### *4.1 Game theoretic models and analysis*

The discrete time-based Game theoretic analysis concerning the development project of Boeing 787 aircraft revealed that there were conflicting incentives amongst the strategic partners (Xin and Zhao, 2013). Developing on this analysis, we propose new game models incorporating uncertainty and the 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 labour, 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.

The direct cost of a task reduces with the duration representing a convex function as shown in Figure 2. "$X_i$" indicates the scheduled timeframe of the task. If either Boeing or a Tier-1 supplier delays its task, it gets a saving represented by "$s_i$". In the 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 2. "$X_s$" indicates the scheduled timeframe of the suppliers' tasks while "$X_m$" indicates the scheduled timeframe of the Boeing's task. If the resultant time of the two tasks exceeds the scheduled time, there is a penalty "$p_i$", whereas expediting the project results in the reward "$r_i$" 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 the completion of tasks by the suppliers, Boeing performs the final assembling phase.

*4.1.1 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 the 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 penalised 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 a "moral hazard". There were misaligned objectives as every supplier would consider the possibility of other partner delaying their

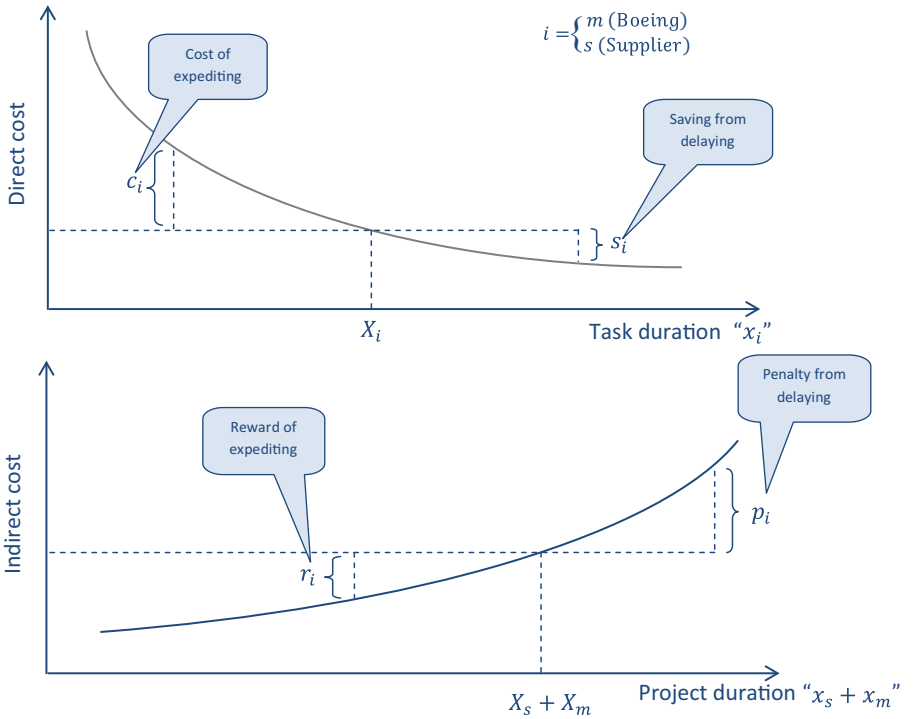



**Figure 2.**
Variation of direct and indirect costs with task and project duration, respectively (source: Qazi *et al.*, 2014)

respective task and in the 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 analyse the game theoretic perspective of Boeing's partnership.

4.1.1.1 Game between two suppliers with an uncertainty regarding the project completion time. In this game, we consider a situation in which both the suppliers are uncertain about the response of Boeing keeping in view the delay incurred by one of the suppliers (or both). Therefore, in the case of any delay, a node representing "Nature" is introduced having probability "$q$" denoting the chance of Boeing expediting the project for timely completion as shown in Figure 3. It is evident that "$E$" is a dominated strategy for both the suppliers.

*Lemma 1.* In a loss-sharing partnership between two suppliers and an OEM, the suppliers may either delay or keep their tasks in time under the following conditions:

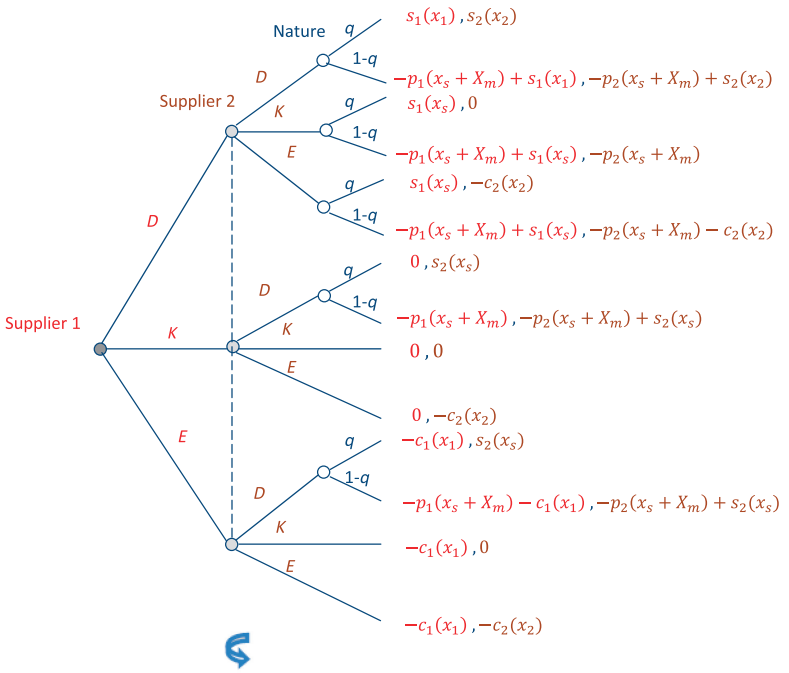
(1) All the players having complete knowledge of the cost functions of each other

(2) The amount of penalty being greater than the saving resulting from delaying the task

(3) An uncertainty "$q$" related to the timely completion of the project

*DD* is the unique Nash equilibrium;

$$iff\ 1 - q \leq \frac{s_i(x_s)}{p_i(x_s + X_m)} \tag{1}$$




| Supplier 1 \ Supplier 2 | D | K | E |
|---|---|---|---|
| D | $s_1(x_1) - \{1-q\}\{p_1(x_s + X_m)\}$, $s_2(x_2) - \{1-q\}\{p_2(x_s + X_m)\}$ | $s_1(x_s) - \{1-q\}\{p_1(x_s + X_m)\}$, $-\{1-q\}\{p_2(x_s + X_m)\}$ | $s_1(x_s) - \{1-q\}\{p_1(x_s + X_m)\}$, $-c_2(x_2) - \{1-q\}\{p_2(x_s + X_m)\}$ |
| K | $-\{1-q\}\{p_1(x_s + X_m)\}$, $s_2(x_s) - \{1-q\}\{p_2(x_s + X_m)\}$ | $0, 0$ | $0, -c_2(x_2)$ |
| E | $-c_1(x_1) - \{1-q\}\{p_1(x_s + X_m)\}$, $s_2(x_s) - \{1-q\}\{p_2(x_s + X_m)\}$ | $-c_1(x_1), 0$ | $-c_1(x_1), -c_2(x_2)$ |

**Figure 3.**
A game between two suppliers with uncertainty about the project completion time

*KK* is the pareto-optimal solution;

$$iff\ 1 - q > \frac{s_i(x_s)}{p_i(x_s + X_m)} \tag{2}$$

4.1.1.2 Game between two suppliers with an uncertainty about the cost function of Supplier 2. In this game, we incorporate the uncertainty about the cost function of a supplier. Supplier 1 knows about its pay-offs but cannot differentiate between the two types of Supplier 2; one having the penalty function greater than the saving function (Type *L*) while the other having converse of it (Type *H*). Supplier 2 knows about the pay-offs of both of them. The matrix form of the game between Supplier 1 and each of the two types of Supplier 2 is presented in Table 1. For this situation, a pure strategy Nash equilibrium is defined as a triple of actions (Osborne, 2003), one for Supplier 1 and one for each type of Supplier 2, with the property that:

(1) the action of Supplier 1 is optimal, given the actions of the two types of Supplier 2 (and Supplier 1's belief about the state), and

(2) the action of each type of Supplier 2 is optimal, given the action of Supplier 1.

Game between supplier 1 and type *L* of supplier 2.

$p: \; p_2(x_s + X_m) > s_2(x_s)$

| Supplier 1 \ Supplier 2 | K | D |
|---|---|---|
| K | 0 , 0 | $-p_1(x_s + X_m)$ , $-p_2(x_s + X_m) + s_2(x_2)$ |
| D | $-p_1(x_s + X_m) + s_1(x_1)$ , $-p_2(x_s + X_m)$ | $-p_1(x_s + X_m) + s_1(x_1)$ , $-p_2(x_s + X_m) + s_2(x_2)$ |

Game between supplier 1 and type *H* of supplier 2.

$1 - p: \; \bar{p}_2(x_s + X_m) < \bar{s}_2(x_s)$

| Supplier 1 \ Supplier 2 | K | D |
|---|---|---|
| K | 0 , 0 | $-p_1(x_s + X_m)$ , $\bar{s}_2(x_s) - \bar{p}_2(x_s + X_m)$ |
| D | $-p_1(x_s + X_m) + s_1(x_1)$ , $-\bar{p}_2(x_s + X_m)$ | $-p_1(x_s + X_m) + s_1(x_1)$ , $\bar{s}_2(x_2) - \bar{p}_2(x_s + X_m)$ |

Expected pay-off of supplier 1 for each pair of actions of two types of supplier 2.

| Supplier 1 \ Supplier 2 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | 0 | $\boldsymbol{-\{1-p\}p_1(x_s + X_m)}$ | $-pp_1(x_s + X_m)$ | $-p_1(x_s + X_m)$ |
| D | $-p_1(x_s + X_m) + s_1(x_1)$ | $-p_1(x_s + X_m) + s_1(x_1)$ | $-p_1(x_s + X_m) + s_1(x_1)$ | $\boldsymbol{-p_1(x_s + X_m) + s_1(x_1)}$ |

**Table 1.**
A game between two suppliers with uncertainty about the cost function of Supplier 2

*Lemma 2.* In a loss-sharing partnership between two suppliers and an OEM, the suppliers may either delay or keep their tasks in time under the following conditions:

(1) A supplier having an uncertainty about the cost function of other supplier

(2) The amount of penalty being greater than the saving resulting from delaying the task for the supplier having the incomplete information

$(K, (K, D))$ is the pareto-optimal solution;

$$iff \; p > \frac{s_1(x_1)}{p_1(x_s + X_m)} \tag{3}$$

$(K, (K, D))$ and $(D, (D, D))$ are the Nash equilibria;

$$iff \; p = \frac{s_1(x_1)}{p_1(x_s + X_m)} \tag{4}$$

$(D, (D, D))$ is the unique Nash equilibrium;

$$iff \; p < \frac{s_1(x_1)}{p_1(x_s + X_m)} \tag{5}$$

4.1.1.3 Game between two suppliers with an uncertainty about the cost function of each other. We analyse the game between two suppliers incorporating the uncertainty of both suppliers regarding the type of other one in terms of the relative functions of penalty and saving. Both suppliers are uncertain about the pay-offs of each other. Type "*L*" indicates the supplier having the penalty greater than the corresponding saving while type "*H*" represents the supplier whose saving is greater than the relative penalty associated with the delay. Supplier 1 has a common belief represented by "*p*" of being sure about the type "*L*" of Supplier 2 while the Supplier 2 has a common belief represented by "*q*" of being sure about the type "*L*" of Supplier 1. The game is shown in Figure 4. The expected pay-offs of type "*L*" and type "*H*" of Supplier 1 are given in Table 2. Each column represents actions of each type of Supplier 2; the first action representing the action of type "*L*" of Supplier 2 followed by that of type "*H*" of Supplier 2. For each of the columns, the greater value is selected out of the two actions of Supplier 1. The triple of actions corresponding to each greater value is checked for confirming the best action for each of the two types of Supplier 2. The same procedure is repeated for each of the types of Supplier 2 having expected pay-offs tabulated in Table 2. After considering the results of all four expected pay-off tables, it is revealed that ((*D*,*D*),(*D*,*D*)) and ((*K*,*D*),(*K*,*D*)) are the Bayesian Nash equilibria of this game.

*Lemma 3.* In a loss-sharing partnership between two suppliers and an OEM, both suppliers will either delay or keep their tasks (in time) under the following conditions:

(1) Both suppliers being uncertain about the cost function of each other

(2) OEM completing its task within the stipulated timeframe

$((K,D),(K,D))$ and $((D,D),(D,D))$ are the Bayes Nash equilibria;

$$iff\ p \geq \frac{s_1(x_1)}{p_1(x_s + X_m)} \text{ and } q \geq \frac{s_2(x_2)}{p_2(x_s + X_m)} \tag{6}$$

$((K,D),(K,D))$ is the pareto-optimal solution;

$$iff\ p > \frac{s_1(x_1)}{p_1(x_s + X_m)} \text{ and } q > \frac{s_2(x_2)}{p_2(x_s + X_m)} \tag{7}$$

$((K,D),(K,D))$ is the unique Bayes Nash equilibrium in all other cases.

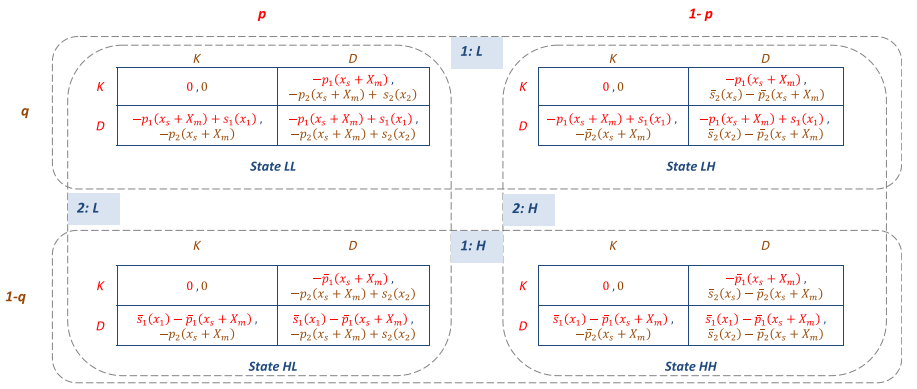



**Figure 4.** A game between two suppliers with an uncertainty about the cost function of each other

Expected pay-offs of type *L* of supplier 1.

| Supplier 1 \ Supplier 2 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | $0$ | $\boldsymbol{-\{1-p\}p_1(x_s+X_m)}$ | $-pp_1(x_s+X_m)$ | $-p_1(x_s+X_m)$ |
| D | $-p_1(x_s+X_m)+s_1(x_1)$ | $-p_1(x_s+X_m)+s_1(x_1)$ | $-p_1(x_s+X_m)+s_1(x_1)$ | $\boldsymbol{-p_1(x_s+X_m)+s_1(x_1)}$ |

Expected pay-offs of type *H* of supplier 1.

| Supplier 1 \ Supplier 2 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | $0$ | $-\{1-p\}\bar{p}_1(x_s+X_m)$ | $-p\bar{p}_1(x_s+X_m)$ | $-\bar{p}_1(x_s+X_m)$ |
| D | $\bar{s}_1(x_1)-\bar{p}_1(x_s+X_m)$ | $\bar{s}_1(x_1)-\bar{p}_1(x_s+X_m)$ | $\bar{s}_1(x_1)-\bar{p}_1(x_s+X_m)$ | $\boldsymbol{\bar{s}_1(x_1)-\bar{p}_1(x_s+X_m)}$ |

Expected pay-offs of type *L* of supplier 2.

| Supplier 2 \ Supplier 1 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | $0$ | $\boldsymbol{-\{1-q\}p_2(x_s+X_m)}$ | $-qp_2(x_s+X_m)$ | $-p_2(x_s+X_m)$ |
| D | $-p_2(x_s+X_m)+s_2(x_2)$ | $-p_2(x_s+X_m)+s_2(x_2)$ | $-p_2(x_s+X_m)+s_2(x_2)$ | $\boldsymbol{-p_2(x_s+X_m)+s_2(x_2)}$ |

Expected pay-offs of type *H* of supplier 2.

| Supplier 2 \ Supplier 1 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | $0$ | $-\{1-q\}\bar{p}_2(x_s+X_m)$ | $-q\bar{p}_2(x_s+X_m)$ | $-\bar{p}_2(x_s+X_m)$ |
| D | $\bar{s}_2(x_2)-\bar{p}_2(x_s+X_m)$ | $\bar{s}_2(x_2)-\bar{p}_2(x_s+X_m)$ | $\bar{s}_2(x_2)-\bar{p}_2(x_s+X_m)$ | $\boldsymbol{\bar{s}_2(x_2)-\bar{p}_2(x_s+X_m)}$ |

**Table 2.** Solution of the game between two suppliers with an uncertainty about the cost function of Supplier 2

4.1.1.4 Game between two suppliers with an uncertainty about the cost function of each other and Boeing's response. The previous game assumed that Boeing would complete its task in time. Now, we incorporate a possibility of Boeing expediting its task (*E*) but there is an uncertainty associated with the possibility of the project not getting completed in time. The common belief about this uncertainty is represented by "$r$" as each supplier will have a prior belief that the project would not be completed in time because of the delay in the first phase of the project. The game is presented in Figure 5 with the pay-off matrix shown in Table 3. The Bayesian Nash equilibria of this game are again ((*K*,*D*),(*K*,*D*)) and ((*D*,*D*),(*D*,*D*)).

*Lemma 4.* In a loss-sharing partnership between two suppliers and an OEM, both suppliers will either delay or keep their tasks under the following conditions:

(1) Both suppliers being uncertain about the cost function of each other

(2) An uncertainty associated with the possibility of OEM expediting its task to cover up the delay caused by the suppliers

$((K,D),(K,D))$ and $((D,D),(D,D))$ are the Bayes Nash equilibria;

$$iff\ pr \geq \frac{s_1(x_1)}{p_1(x_s+X_m)} \text{ and } qr \geq \frac{s_2(x_2)}{p_2(x_s+X_m)} \tag{8}$$

$((K,D),(K,D))$ is the pareto-optimal solution;

$$iff\ pr > \frac{s_1(x_1)}{p_1(x_s+X_m)} \text{ and } qr > \frac{s_2(x_2)}{p_2(x_s+X_m)} \tag{9}$$

$((D,D),(D,D))$ is the unique Bayes Nash equilibrium in all other cases.

*Theorem 1.* In the case of a loss-sharing partnership (between an OEM and Tier-1 suppliers) within a supply chain, all Tier-1 suppliers will either delay or keep their tasks in the case of an uncertainty about the cost functions of one another but the possibility of timely completion of the project is very rare because of the requirement of meeting a very strong probabilistic condition on the part of each supplier. This theorem is valid under the following assumptions:

(1) All Tier-1 Suppliers perform their tasks simultaneously (Phase I).

(2) The OEM undertakes its task after the completion of all the tasks of Tier-1 Suppliers (Phase II).

(3) The project duration is the summation of the two phases.

Let $r$ represent the common belief of the suppliers about the possibility of OEM not expediting its task in order to cover up the delay of Phase I and $p_{ij}$ represent the belief of a supplier $i$ about the cost function of other supplier "$j$" being of the form "$p_j(x_s+X_m)>s_j(x_j)$" (type "$L$") with $p$ and $s$ indicating the penalty and cost saving functions, respectively.

*Corollary 1.* Each supplier "$i$" of type "$L$" will keep their task:

$$iff \prod_{j=1}^{N-1} rp_{ij} \geq \frac{s_i(x_i)}{p_i(x_s+X_m)} \tag{10}$$

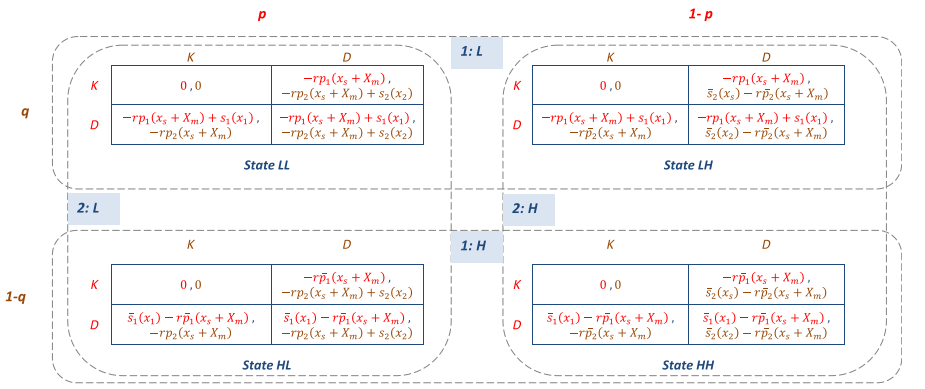



**Figure 5.** A game between two suppliers with an uncertainty about the cost function of each other and the OEM's response

Expected pay-offs of type "$L$" of supplier 1.

| Supplier 1 \ Supplier 2 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | 0 | $\boldsymbol{-r\{1-p\}p_1(x_s+X_m)}$ | $-rpp_1(x_s+X_m)$ | $-rp_1(x_s+X_m)$ |
| D | $-rp_1(x_s+X_m)+s_1(x_1)$ | $-rp_1(x_s+X_m)+s_1(x_1)$ | $-rp_1(x_s+X_m)+s_1(x_1)$ | $\boldsymbol{-rp_1(x_s+X_m)+s_1(x_1)}$ |

Expected pay-offs of type "$H$" of supplier 1.

| Supplier 1 \ Supplier 2 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | 0 | $-r\{1-p\}\bar{p}_1(x_s+X_m)$ | $-rp\bar{p}_1(x_s+X_m)$ | $-r\bar{p}_1(x_s+X_m)$ |
| D | $\bar{s}_1(x_1)-r\bar{p}_1(x_s+X_m)$ | $\bar{s}_1(x_1)-r\bar{p}_1(x_s+X_m)$ | $\bar{s}_1(x_1)-r\bar{p}_1(x_s+X_m)$ | $\boldsymbol{\bar{s}_1(x_1)-r\bar{p}_1(x_s+X_m)}$ |

Expected pay-offs of type "$L$" of supplier 2.

| Supplier 2 \ Supplier 1 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | 0 | $\boldsymbol{-r\{1-q\}p_2(x_s+X_m)}$ | $-rqp_2(x_s+X_m)$ | $-rp_2(x_s+X_m)$ |
| D | $-rp_2(x_s+X_m)+s_2(x_2)$ | $-rp_2(x_s+X_m)+s_2(x_2)$ | $-rp_2(x_s+X_m)+s_2(x_2)$ | $\boldsymbol{-rp_2(x_s+X_m)+s_2(x_2)}$ |

Expected pay-offs of type "$H$" of supplier 2.

| Supplier 2 \ Supplier 1 | (K,K) | (K,D) | (D,K) | (D,D) |
|---|---|---|---|---|
| K | 0 | $-r\{1-q\}\bar{p}_2(x_s+X_m)$ | $-rq\bar{p}_2(x_s+X_m)$ | $-r\bar{p}_2(x_s+X_m)$ |
| D | $\bar{s}_2(x_2)-r\bar{p}_2(x_s+X_m)$ | $\bar{s}_2(x_2)-r\bar{p}_2(x_s+X_m)$ | $\bar{s}_2(x_2)-r\bar{p}_2(x_s+X_m)$ | $\boldsymbol{\bar{s}_2(x_2)-r\bar{p}_2(x_s+X_m)}$ |

**Table 3.** Solution of the game between two suppliers with an uncertainty about the cost function of each other and the OEM's response

*Corollary 2.* $((K,D),(K,D),\ldots(K,D)_N)$ and $((D,D),(D,D),\ldots(D,D)_N)$ are Bayes Nash equilibria.

$$iff \prod_{j=1}^{N-1} rp_{ij} \geq \frac{s_i(x_i)}{p_i(x_s+X_m)} \text{ for every suppliers "}i\text{" of type "}L\text{"} \tag{11}$$

*Corollary 3.* $((D,D),(D,D),\ldots(D,D)_N)$ is the unique Bayes Nash equilibrium in all other cases meaning that the project will be delayed even if all suppliers are of type "$L$".

These results indicate that in the case of an uncertainty about the cost functions of other suppliers, each supplier might delay their task even knowing that the OEM might not expedite

its task in order to cover up the overall project duration. Thus, in a supply chain, an uncertainty about the information of other partners results in the worst selection of actions by all partners. The same phenomenon can be best described as a bullwhip effect. Uncertainty about the information is a major risk within a supply chain that can result into major losses as evident in the case of the Boeing 787 project. After analysing the strategic partnership, it is revealed that the partnership scheme engendered misaligned incentives amongst the stakeholders that finally contributed to the realisation of game theoretic risks. Therefore, there was a need to assess the impact of misaligned incentives classified as "game theoretic risks" on project performance and to introduce a "fair risk-sharing strategy" for mitigating game theoretic risks.

*4.2 Bayesian Belief Network models and analysis*

Based on the information retrieved from Tang *et al.* (2009), the perceived oversimplified cognitive map of the Boeing 787 project comprised 27 concepts and 38 links as shown in Figure 6. The model clearly reveals that Boeing was focussing on the opportunities resulting from the introduction of an unproven technology and an unconventional supply chain. After the inferencing stage, the probability of the development time being high was just 0.09 and that of the development cost was 0.22. These favourable results stem from 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 three years causing a 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 as shown in Figure 7. A BBN was modelled following the steps outlined in the proposed framework. Two nodes identified earlier as "fair risk-sharing strategy" (see concept 36 in Figure 7) and "game theoretic risks" (see concept 35 in Figure 7) were added to the BBN model. The output of "game theoretic risks" node was linked to the "development time" (see concept 20 in Figure 7) node. The impact of "game theoretic risks" node on the "development time" node was quantified based on the game theoretic analysis. 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 an increase in the exposure of game theoretic risks, being dominant on other factors affecting the development time.

The management involved in the project was lacking expertise in SCRM. 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 SCRM process does not focus on analysing the risks caused by misaligned incentives of the stakeholders. It also emphasises the importance of considering this unique category of risks within the project risk assessment stage and the management must possess the ability to apply Game theory to quantify such risks.

The initial updating of the model revealed that the probability of the development cost and time being high was 0.46 and 0.54, respectively. Different scenarios were generated and the impact of individual risk factors was determined as shown in Table 4. Management expertise was found to be the dominant factor influencing both development cost and time. Game theoretic risks were considered as the dominant factor influencing the development time across all scenarios. The proactive strategies of ensuring a team with SCRM expertise, devising a fair strategy, negotiating with the labour union, and adopting a thorough supplier selection process resulted in the probability of development cost and time overruns as 0.31 and 0.30, respectively.

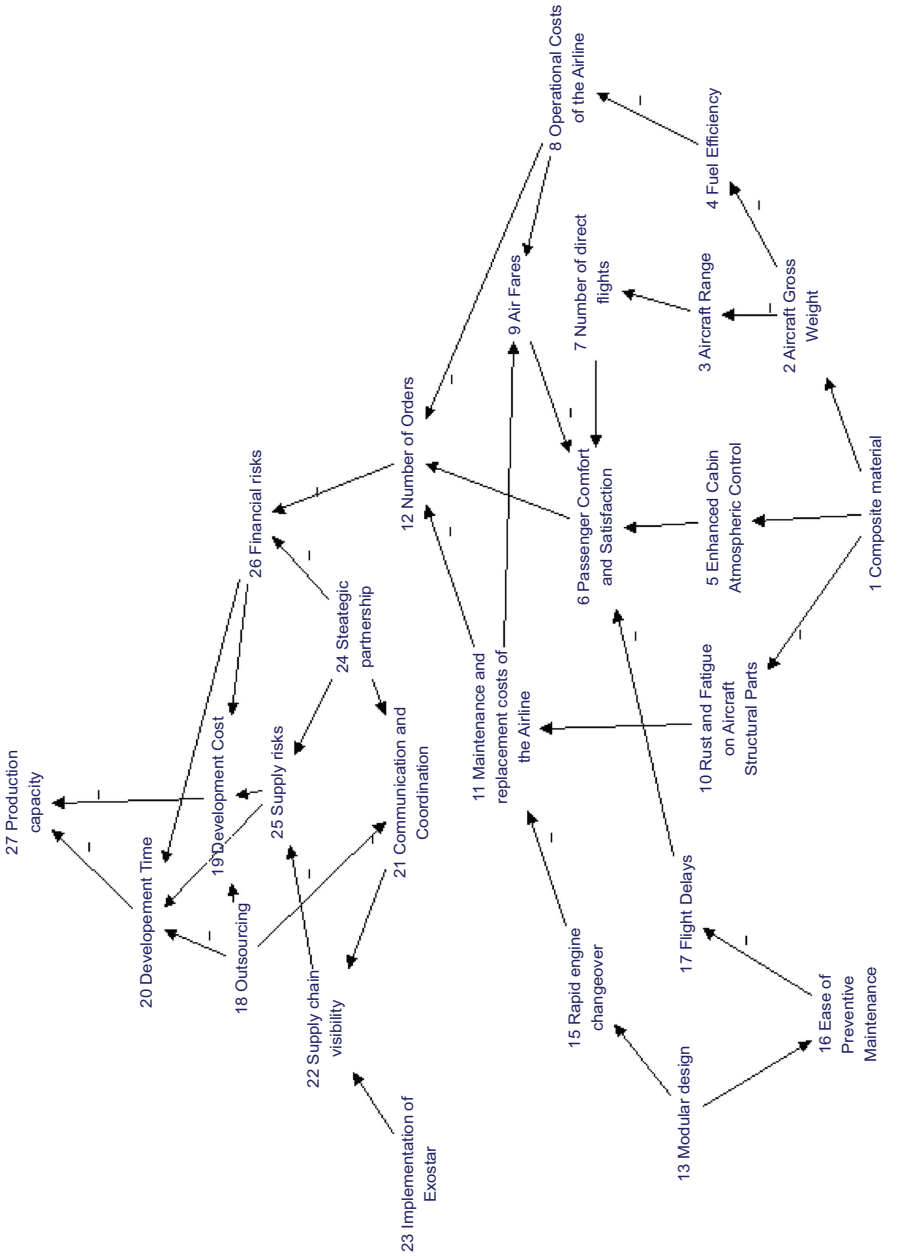



**Figure 6.**
Cognitive map based on Boeing's perception

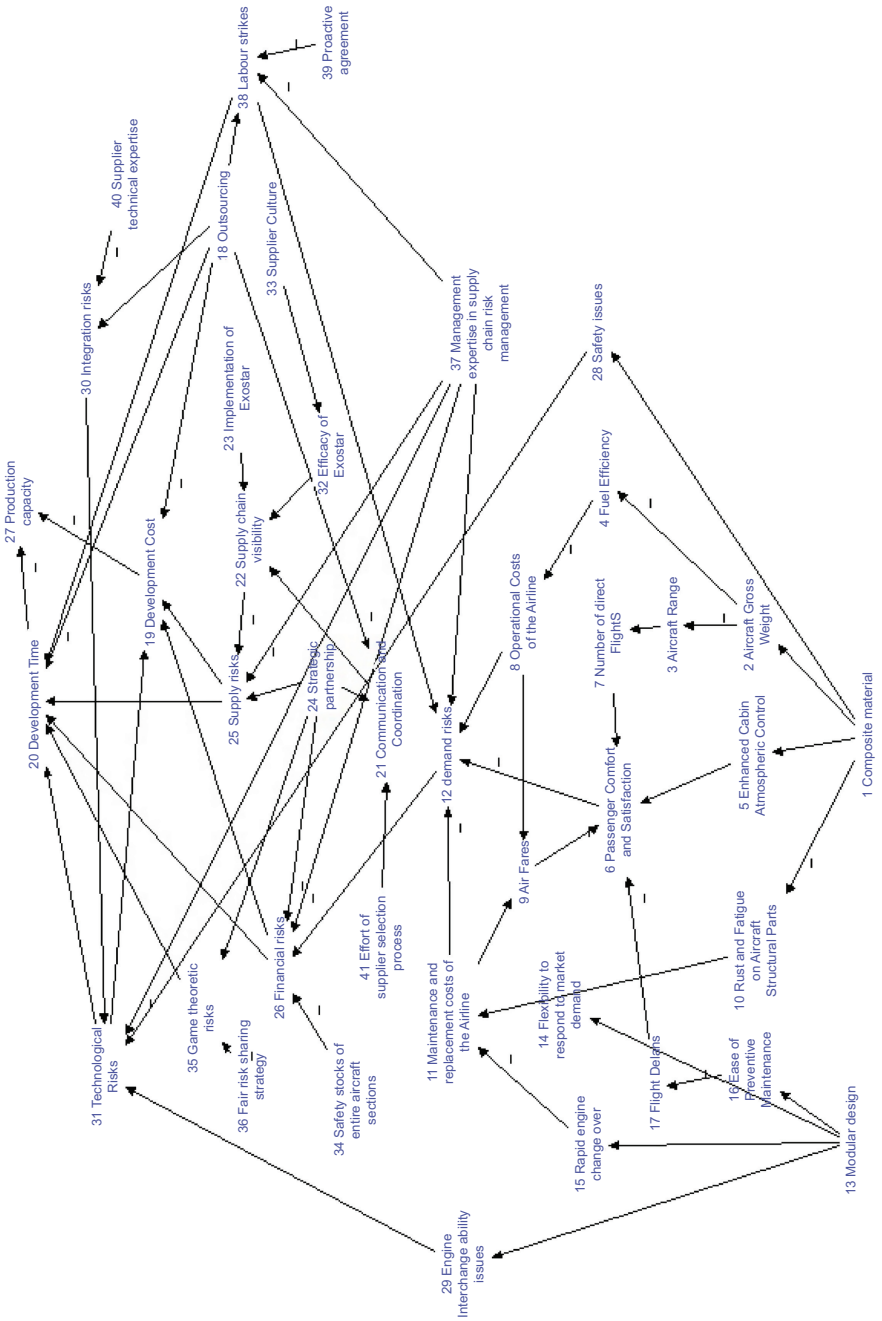



**Figure 7.**
Cognitive map based on real-time risks

**Table 4.** Summary of BBN results

| Management expertise | Supplier selection process | Outsourcing | Fair strategy | Probability of time overrun (in percentage) | Probability of cost overrun (in percentage) |
|---|---|---|---|---|---|
| High | Thorough | High | Yes | 30 | 31 |
| High | Thorough | High | No | 62 | 35 |
| High | Thorough | Low | Yes | 24 | 26 |
| High | Thorough | Low | No | 55 | 31 |
| High | Casual | High | Yes | 31 | 33 |
| High | Casual | High | No | 63 | 37 |
| High | Casual | Low | Yes | 25 | 29 |
| High | Casual | Low | No | 56 | 33 |
| Low | Thorough | High | Yes | 67 | 71 |
| Low | Thorough | High | No | 83 | 75 |
| Low | Thorough | Low | Yes | 49 | 66 |
| Low | Thorough | Low | No | 69 | 69 |
| Low | Casual | High | Yes | 67 | 75 |
| Low | Casual | High | No | 83 | 79 |
| Low | Casual | Low | Yes | 50 | 69 |
| Low | Casual | Low | No | 70 | 72 |

*4.3 Formulation of a fair strategy*

The sensitivity analysis of game theoretic risks revealed its major impact on the development time. Therefore, there is a 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 their own deeds. If the suppliers perform their tasks within the stipulated time, the 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 materialise because of its delay. Similarly, if a supplier is involved in the delay, it will be proportionately penalised for its part of the delay. In the case of a delay on the part of both the suppliers and Boeing, the penalty would be paid fairly.

Developing on the fair strategy proposed by Xin and Zhao (2013), we present a modified strategy incorporating the features of the time value of money and the continuous rate of interest. Boeing's and suppliers' pay-off functions considering the time value of money are tabulated in Table 5. Following are the various symbols used in the pay-off functions:

$$\alpha_m = \frac{X_m - x_m}{X_m + X_s - x_s - x_m} \tag{12}$$

$$\beta_m = \frac{x_m - X_m}{x_m + x_s - X_s - X_m} \tag{13}$$

$$\sum_{j=s,m} \alpha_j = 1 \tag{14}$$

$$\sum_{j=s,m} \beta_j = 1 \tag{15}$$

$$r_s(x_j) = \sum_{i=1}^{N} r_i(x_j) \text{ for } j = s, m \tag{16}$$

| Supplier's timeline | Boeing's response | Boeing's pay-off |
|---|---|---|
| $E: x_s < X_s$ | $E: x_m < X_m$ | $a_m\{r(x_s + x_m)\}e^{-\delta(x_s+x_m)} - c_m(x_m)e^{-\delta(x_m)}$ |
| | $K: x_m = X_m$ | $0$ |
| | $D: x_m > X_m$ | $-\{r(x_s + X_m) - r(x_s + x_m)\}e^{-\delta(x_s+x_m)} + s_m(x_m)e^{-\delta(x_m)}$ if $x_s + x_m \leq X_s + X_m$ |
| | | $-\{r(x_s + X_m) - p(x_s + x_m)\}e^{-\delta(x_s+x_m)} + s_m(x_m)e^{-\delta(x_m)}$ if $x_s + x_m > X_s + X_m$ |
| $K: x_s = X_s$ | $E: x_m < X_m$ | $r(X_s + x_m)e^{-\delta(x_s+x_m)} - c_m(x_m)e^{-\delta(x_m)}$ |
| | $K: x_m = X_m$ | $0$ |
| | $D: x_m > X_m$ | $-p(X_s + x_m)e^{-\delta(x_s+x_m)} + s_m(x_m)e^{-\delta(x_m)}$ |
| $D: x_s > X_s$ | $E: x_m < X_m$ | $\{p(x_s + X_m) + r(x_s + x_m)\}e^{-\delta(x_s+x_m)} - c_m(x_m)e^{-\delta(x_m)}$ if $x_s + x_m < X_s + X_m$ |
| | | $\{p(x_s + X_m) - p(x_s + x_m)\}e^{-\delta(x_s+x_m)} - c_m(x_m)e^{-\delta(x_m)}$ if $x_s + x_m \geq X_s + X_m$ |
| | $K: x_m = X_m$ | $0$ |
| | $D: x_m > X_m$ | $-\beta_m\{p(x_s + x_m)\}e^{-\delta(x_s+x_m)} + s(x_m)e^{-\delta(x_m)}$ |
| *Supplier's timeline* | *Supplier i* | *Pay-off of Supplier i* |
| $E: x_s < X_s$ | $E: x_i < X_s$ | $\alpha_i r(x_s + x_m)e^{-\delta(x_s+x_m)} - c_i(x_i)e^{-\delta(x_i)}$ if $x_s + x_m \leq X_s + X_m$ |
| | | $\frac{1}{N}\{r(x_s + X_m)\}e^{-\delta(x_s+x_m)} - c_i(x_i)e^{-\delta(x_i)}$ if $x_s + x_m > X_s + X_m$ |
| $K: x_s = X_s$ | $E: x_i < X_s$ | $-c_i(x_i)e^{-\delta(x_i)}$ |
| | $K: x_i = X_s$ | $0$ |
| $D: x_s > X_s$ | $E: x_i < X_s$ | $-c_i(x_i)e^{-\delta(x_i)}$ |
| | $K: x_i = X_s$ | $0$ |
| | $D: x_i > X_s$ | $-\beta_i p(x_s + X_m)e^{-\delta(x_s+x_m)} + s(x_i)e^{-\delta(x_i)}$ if $x_s + x_m < X_s + X_m$ |
| | | $-\beta_i\beta_s p(x_s + x_m)e^{-\delta(x_s+x_m)} + s(x_i)e^{-\delta(x_i)}$ if $x_s + x_m \geq X_s + X_m$ and $x_m > X_m$ |
| | | $-\beta_i[\{p(x_s + X_m)\} - \{p(x_s + X_M) - p(x_s + x_m)\}]e^{-\delta(x_s+x_m)} + s(x_i)e^{-\delta(x_i)}$ if $x_s + x_m \geq X_s + X_m$ and $x_m \leq X_m$ |

**Note(s)**: $\delta$ is the annual interest rate compounded continuously

**Table 5.** Pay-off functions based on a fair-sharing partnership

$$p_s(x_j) = \sum_{i=1}^{N} p_i(x_j) \text{ for } j = s, m \tag{17}$$

$$r(x_j) = r_s(x_j) + r_m(x_j) \text{ for } j = s, m \tag{18}$$

$$p(x_j) = p_s(x_j) + p_m(x_j) \text{ for } j = s, m \tag{19}$$

$$\alpha_i = \frac{\alpha_s}{\text{Number of suppliers } (N)} \tag{20}$$

$$\gamma_i = \frac{x_i - X_s}{x_s - X_s} \tag{21}$$

$$\beta_i = \frac{\gamma_i}{\sum \gamma_i} \tag{22}$$

In the presence of a fair strategy, no partner is incentivised 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 unchanged and therefore, there is no requirement of updating the BBN model. However, in other situations, the formulation of a policy may necessitate the addition of other nodes to the BBN model. After the introduction of a fair strategy, the game theoretic risks reduce to the minimum level resulting in a low probability of the development time being high.

## 5. Discussion

This paper provides a theoretical application of the BBNs and Game theory methods with the scope to assessing risks in complex projects within a supply chain network. This simulation, based on existing secondary data regarding the case of Boeing 787, offers an effective example of how to capture the interdependency between risks for a comprehensive risk assessment in complex contexts. The simulation also addresses the different influences that the decision-makers' risk appetite and conflicting incentives may have on the assessment of risks.

The theoretical and managerial implications are relevant. As suggested by several authors (Bevilacqua *et al.*, 2013; Su *et al.*, 2020), managers must achieve a thoughtful understanding of the end-to-end processes, in order to get better performance. To assess and monitor key processes, ISO 9000 and ISO 9001 standards stress the importance of effective measurement systems, based on the adoption of robust audit procedures (Abuazza *et al.*, 2020) and ad hoc quality and risk tools (Castello *et al.*, 2020). The paper offers an insight on how to practically develop a holistic risk analysis approach, in coherence with a process and project management strategy. In doing so, the paper responds to the need to integrate risk management systems and quality management systems, as advocated by recent papers (Samani *et al.*, 2019). According to Mhatre *et al.* (2017) and Aven (2015), the paper contributes to fill a research gap regarding the lack of studies that assess risks in complex projects, addressing their impacts on supply chain performances. In addition, the paper enriches the studies that apply the interdependence modelling tools in the fields of SCRM and SCQM (Roy *et al.*, 2016; Moeinedini *et al.*, 2018), as also advocated by Huo *et al.* (2019).

From a managerial perspective, decision-makers can benefit from theoretical simulations and demonstrative case studies, which propose clear examples about how to implement a holistic and comprehensive supply chain risk management process regarding complex projects, also considering the effects of opportunistic behaviours (Qazi *et al.*, 2015; Hosseini and Barker, 2016).

Another key implication for managers, is to offer a tool that could support the implementation of a quantitative "risk based-thinking" tool, as required by ISO 9001 standard and Quality Management System frameworks. In particular, the framework proposed in Figure 1 and the demonstrative case study, based on the secondary data from the Boeing 787 project, allow managers to gain interesting and original insights regarding the development of a strategy of efficiency and timeliness, according to SCRM and SCQM principles (Huo *et al.*, 2019; Das, 2018; Foster, 2008; Colicchia and Strozzi, 2012).

Firstly, managers can reflect on how to consider direct/indirect costs, the network of different suppliers, the loss-sharing and penalty-based contractual conditions, and the

overall relationship strategies. In particular, the simulation allows reflecting on the potential actions that suppliers can pursue in the case of a delay, providing three different scenarios, and considering the uncertainty level related to the cost function.

Secondly, thorough the application of a BBN model in the demonstrative case study, managers can find a useful example of the role of careful supplier selection, risk management and bargaining power in defining an effective cost and time strategy. The case allows, in fact, to address multiple factors and highlights that in the context of a fair strategy, where each player is responsible for their own deeds, the project is more likely to be completed in time depending on the other risk factors impacting the delay.

## 6. Conclusions

This paper has introduced and demonstrated the application of a new process for managing project-driven supply chains that combines two complementary techniques of Game theory and BBNs. The proposed process is capable of capturing the dynamics of interacting risk factors. BBNs provide a useful modelling technique for the quantification of interdependent risk factors, whereas Game theoretic modelling provides an opportunity to model the risks associated with conflicting incentives amongst stakeholders within a supply network. The results of the case study clearly revealed that without mitigating the game theoretic risks, the objective of timely completion of the Boeing 787 project was not accomplished. Furthermore, the lack of management expertise was the major factor contributing to the overall costs of the project. The application of the proposed process to other project-driven supply chains will help decision-makers to visualise a holistic view of interacting interdependent risk factors and identify key risk factors for establishing proactive risk mitigation strategies.

In future, the proposed process may be applied across different industries. Furthermore, empirical research needs to be conducted to investigate the best practices in managing complex interdependencies between project-driven supply chain risks. It will also be important to devise methods for reducing the effort involved in populating such models as when there are limited available data, experts will have to be consulted and the elicitation of the set of conditional probability values will be a real challenge. Methods other than BBNs can be explored to adapt the proposed process and investigate the trade-off between the effort involved in developing the model and the precision of the results.

The proposed process may be extended to involve different stakeholders across a supply chain and contracts can be designed to encourage the active participation of stakeholders within the risk management process. Risk networks may be developed across different industries and compared to establish common patterns in order to develop a generalised risk taxonomy. The cost and benefit analysis may be conducted to help practitioners understand the utility of interdependency-based frameworks. Once the framework gets established in its simplified form of risks and strategies with binary states, these can be modified as continuous variables. The framework may also be extended to capture the dynamic behaviour of risk over time.

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