A decision framework to mitigate supply chain risks: an application in the offshore-wind industry

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Abstract

Decision support systems for supply chain risk management benefit from a holistic approach for mitigating risks, which include identification and assessment of risks and evaluation and selection of measures to appease risks. However, previous studies in this area overlooked probability estimation, measure selection, and assessment of interdependence of risks and measures. We aim to fill these gaps in the literature by proposing a two-stage decision support systems that will assist managers to not only select mitigation strategies for supply chain risks but also mitigation tactics when risks occur. Our decision support system employs a novel matrix-formulation for decision-tree analysis which integrates expert judgements. We applied our models to the supply chain of a fast-expanding offshore-wind industry, which faces high levels of exposure to risks because of the associated complexities in this domain. The results demonstrate how to select mitigation strategies and mitigation tactics for managing supply chain risks within the offshore-wind industry.

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1. Introduction

In today's business environment, supply chains are often exposed to risks because of their complexity and global nature of operations. Given the emphasis on risk, both academicians and practitioners are advocating the development of decision support systems (DSS) to help companies in assessing their supply chain risks and choosing suitable mitigation strategies [1]. Because of the limited control and visibility ensuing from the complexity and globalization of supply chains, any DSS must employ a process that is holistic in nature by effectively identifying and assessing relevant supply chain risks and proposing appropriate mitigation strategies [2]. We call this process the supply chain risk management (SCRM) process.

Literature on DSS employing the SCRM process is still at an embryonic level. In particular, we identify potential gaps in the SCRM-process literature leading to the development of the DSS utilized in this study. First, previous studies have not often employed structured techniques for the assessment of risk probabilities [3, 4]. Second, extant literature in this domain has primarily considered risks as independent, an assumption rarely verified in practice [5, 6, 7, 8]. Third, most studies have mainly focused on the evaluation of the risk profile of a supply chain, but have not optimized the selection of effective mitigation measures to minimize such risk profile [3, 4, 5, 8].

To this end, the main contribution of this paper is to propose a DSS for supply chain risk management by addressing the aforementioned gaps in the literature. More specifically, we propose a two-stage DSS approach for supply-chain-risk reduction that is based on a matrix-based decision-tree model. The proposed DSS not only assists in selecting mitigation strategies but also focuses on specific tactics within each strategy, including contingency plans, with the aim of minimizing the impact of risks in the supply chain. The second contribution of this paper is in applying the proposed DSS to manage supply chain risks for the fast-expanding offshore-wind industry on which academic contributions are limited. In particular, we are interested in understanding if the predominant governance structure of offshore-wind supply chains, multi-contracting, is more effective in mitigating risks than project alliance and EPC (engineering, procurement and construction).

To achieve these goals, we represent the two-stage supply chain risk profile reduction method using a decision-tree structure. Next, we propose a matrix formulation of the decision tree model, which extends the matrix formulation of the Bayes' formula suggested by [9]. Our matrix formulation can be used not only to represent Bayes' formula probabilities as in [9], but also to calculate such probabilities. Subsequently, we apply the DSS to the offshore-wind supply chain. In this context, we collect expert judgments through a focus group . We demonstrate that for a supply chain characterized by medium exposure to risks, supplying a 630 MW farm, the risk-profile-minimizing strategy is EPC, followed by multi-contracting and project alliance. We chose to analyze the case of a 630 MW farm because many future offshore-wind farm projects will be of similar size. Finally, we conduct sensitivity analysis to understand whether these two strategies, multi-contracting and project alliance, could be more effective than EPC for different parameter values. In particular, we demonstrate that multi-contracting could be more effective than EPC for an offshore-wind supply chain characterized by low exposure to risks.

The rest of this article is organized as follows. We review related work in Section 2. We describe the methodology in Section 3. We discuss the application of the DSS to the offshore-wind supply chain in Section 4. Section 5 focuses includes the conclusions of this study and directions for future research.

2. Related work

First, we discuss the still prevalent 'traditional' approaches for developing DSS for supply chain risk management. These contributions consider specific problems in a supply chain, such as inventory and scheduling management. Then, we introduce the concept of supply chain risk management (SCRM) process, which calls for a holistic view of supply chains and relevant risks, given that this perspective is adopted in this article. The holistic view of the SCRM process requires the categorizations of risks and mitigation measures. Next, we provide an overview of the studies adopting the SCRM process and related DSS. Finally, we summarize the research gaps leading to the development of this article and subsequently present our DSS approach.

Academic literature shows growing interest to incorporate risks in DSSs, both for supplier-evaluation decisions [10] and for supply chain configuration problems [11]. Traditionally, supply chain management studies that account for risks mainly deal with specific problems in logistics and manufacturing. These include the optimization of inventory in presence of uncertain demand or lead times or the assessment of manufacturing scheduling systems performance when lead times are uncertain [12]. The methods used to solve these problems are generally stochastic in nature, including simulation. Few sourcing support systems adopt a similar approach by determining the order quantities to be allocated to various suppliers in the presence of risks. Given their narrow scope, these studies detail a series of operational constraints for the problem, including assumptions on the structure of the supply chain and tolerance on quality and delays set by decision makers. [13] and [14] employed multi-objective and goal programming, respectively, to solve this problem.

The complexity and globalization of modern supply chains often lead to lack of control and visibility. Therefore, recent contributions advocate the introduction of a structured risk-management process to help companies in assessing supply chain risks and identifying appropriate mitigation measures [1, 7]. The SCRM-process is this structured approach. It is derived from risk analysis and includes identifying and assessing risks and evaluating and selecting mitigation measures [2]. The SCRM-process calls for a holistic view of supply chains and their risks, a view that requires categorizing supply chain risks and their mitigation measures [15]. Therefore, before turning our attention to the studies adopting the SCRM-process and developing DSSs, we introduce theoretically-grounded categories for supply chain risks and mitigation measures.

Risk can be defined as the chance of danger, damage, loss, injury or any other undesired consequences [16]. Supply chain risk can be defined as the chance of financial or competitive disadvantage resulting from the failed implementation of supply chain best practices [17]. Supply chain risks emerge from risk sources. [18] classified risks based on risk sources into demand risks, supply risks, internal or process risks, control risks and environmental risks. [19] extended their classification by taking into account behavioral risks and by detailing environmental risks into intellectual property risks and political or social risks. Companies assess supply chain risks by their probability of occurrence and impact, typically a negative business impact on the supply chain. A disruption is a risk with low probability and high impact [20, 21]. A risk is referred to as recurrent or operational if it has high probability and low impact [22]. [23] further categorized recurrent risks into delays and distortions, which are also called forecast risks. The supply chain risk profile, commonly defined as the expected value of risks, captures the overall exposure of the supply chain to risks [6].

Companies employ a combination of mitigation measures, called mitigation policy, to improve their supply chain practices with the aim of reducing their supply chain risk profile [7]. [12] argued that the process of identifying mitigation measures is structured into two stages: 1) long-term planning, whose output is mitigation strategies, and 2) short-term planning, whose output is mitigation tactics, which include contingency plans. Mitigation strategies are measures taken by companies prior to the occurrence of risks with the aim of reducing the probability or the impact of risks or to transfer or eliminate the risks altogether [24]. [23] considered the general mitigation strategies that are increasing capacity, increasing inventory, increasing responsiveness, increasing flexibility, aggregating demand, increasing capability and employing more than one supplier. Mitigation tactics are measures taken by companies after the occurrence of risks with the aim of reducing their impact [12, 24]. Examples of mitigation tactics include contingent sourcing, expediting orders, rerouting deliveries and lateral- and vertical-emergency transshipments. [25] categorized mitigation measures into actions to increase the redundancy of the supply chain, such as dual sourcing, and actions to increase its flexibility, such as increased manufacturing responsiveness. [12] alternatively classified mitigation measures into supply, demand, product, and information management.

We review studies adopting the SCRM process and developing DSS. These contributions primarily estimated parameters from expert judgments by employing the Analytic Hierarchy Process (AHP). Some studies considered only sourcing risks and others a broader set of supply chain risks. These studies generally assessed risks for probability and/or impact, but they differ by the way they estimate these two parameters. Some studies developed a formal method to select suitable mitigation measures for supply chain risks and other considered mitigation measures in a more implicit manner. [5] proposed an AHP-model to estimate the impact of inbound supply risks on the supply chain. They estimated probability of risks through direct judgments and assessed supply managers' control level on each risk. [6] designed a goal-programming model to determine the supply-base configuration by considering both cost and risk measures. In their study, probability and impact of risks was assessed through an AHP-approach based on a case company. The impact in their work was captured through delivery, cost, and quality components that are influenced by suppliers' mitigation capabilities. [4] analyzed the impact of offshoring decisions on supply chain risks. They assessed supply chain risk factors and alternatives through action research and their relative importance through AHP. [3] proposed a process to identify supply chain risks in distribution, manufacturing, warehousing and procurement. Their work utilized AHP to assess the impact of risks for time and quality factors. In addition, they proposed a qualitative evaluation of mitigation measures for transport, manufacturing, order cycle, warehousing and procurement. [8] combined fuzzy-AHP and fuzzy-TOPSIS to estimate the influence of risks on the supply chain, which they captured through a risk index, representing the supply chain risk profile. In their analysis, they considered the following factors: risk type, probability of occurrence, risk impact, and how easily mitigation measures would be available for a risk. [7] proposed a linear-programming model to identify the combination of mitigation measures, or policy, leading to the lowest supply chain risk profile under budget constraints. They utilized direct judgments to assess the probability of risks and fuzzy-pairwise comparisons to assess the impact of risks for time, quality, and flexibility factors.

In summary, literature on DSS for SCRM is still at an embryonic level. Therefore, we identify some research gaps leading to the development of this paper. First, previous studies mostly focus on the assessment of the impact of risks, overlooking the assessment of their probability. Only [6] and [8] employed structured methods to assess risk probability using AHP and fuzzy-TOPSIS, respectively. However, the former study mostly focused on supplier selection while the latter determined a supply chain risk index, without identifying or assessing mitigation measures. Second, all previous studies in this domain considered risks, and consequently their impact and probability, as being independent. This assumption is rarely verified in practice, because risks are interrelated to each other and mitigation measures may affect likelihood and impact of more than one risk. Third, most studies focused on the estimation of the supply chain risk profile, overlooking the process of identifying and selecting mitigation measures. [6] and [7] proposed methods to optimize the selection of mitigation measures. However, the former study focused exclusively on sourcing risks and the latter did not employ a structured method to assess risk probabilities. Both studies also did not consider interrelationships among risks.

We address these gaps in the literature by proposing a DSS for SCRM, which employs pairwise comparisons for the estimation of probability and impact from expert judgments and uses a decision-tree model for selecting mitigation strategies and tactics. Our DSS approach addresses three gaps in extant literature in this domain, 1) by proposing a method to estimate probabilities from expert judgments, 2) by considering the relationships among risks and mitigation measures and 3) by modeling the selection of mitigation strategies and tactics that lead to the lowest supply chain risk profile.

3. Methodology

First, we introduce our assumptions on supply chain risks, mitigation strategies, and mitigation tactics. Then, we formulate a decision-tree problem to evaluate the choice of mitigation strategies and tactics. Next, we express this decision problem using a novel matrix formulation, which makes the process of incorporating expert judgments easier. We also highlight the connection between this matrix formulation and the Analytic

Network Process (ANP). Finally, we demonstrate how to translate expert judgments into numerical values populating the matrices by using pairwise comparisons with a geometric scale for judgments.

3.1. Assumptions

Mitigation strategies are long-term measures to reduce the probability of risk occurrence and to reduce their impact if they occur [24]. Because of their long-term orientation, the scope of intervention of mitigation strategies is broad, often enveloping the entire supply chain [12]. Because of their broad focus, we assume that decision makers prefer to formulate mitigation strategies as alternative mitigation plans rather than combinations of mitigation plans. Such plans often include different types of intervention, for example those related to supply network design and information systems adoption [12]. For this reason, we further assume that mitigation strategies, interpreted as mitigation plans, generally affect both the probability of risks occurring and their impact if they occur. Mitigation tactics are much narrow in focus and target actions to solve contingent supply chain problems [12]. For this reason, we assume decision makers can choose to employ many mitigation tactics simultaneously. Mitigation tactics assist in reducing the impact of a risk after it occurs. As decision-makers determine short-term interventions based on the constraints derived from long-term plans, we further assume that mitigation strategies affect which mitigation tactics are available to decision makers. Mitigation strategies and tactics could affect many supply chain risks. These risks arise from many risk sources [18]. Therefore, they are not generally mutually exclusive. Mitigation strategies and tactics have costs associated to them. We assume that the costs of mitigation strategies and tactics are independent. We summarize our assumptions in a conceptual entity-relationship model (Figure 1). In this model, rectangles are relevant entities, ellipses are entity attributes and arcs (employing crow's foot notation) are relationships among entities.

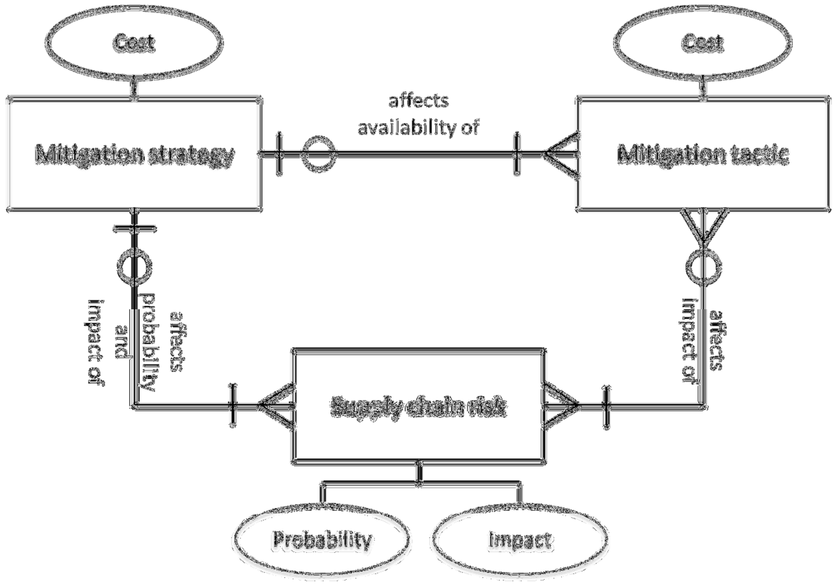

Figure 1: Conceptual model summarizing our assumptions on the relationships among relevant entities (mitigation strategies, tactics and supply chain risks) and on their attributes.

3.2. Decision-tree problem

A decision maker aims at identifying the combination of mitigation strategies and tactics, or policy, leading to the lowest supply chain risk profile. Figure 2 represents an example of such problem in a decision-tree form. The set of S alternative strategies available to the decision maker is $\mathcal{S} = \{1,2 \dots S\}$. We denote with s a strategy belonging to $\mathcal{S}$. In Figure 2, $\mathcal{S} = \{s_1, s_2\}$ and $S = 2$. The set of T tactics available to the decision maker is $\mathcal{T} = \{1,2 \dots T\}$. We denote with t a tactic belonging to $\mathcal{T}$. In Figure 2, $\mathcal{T} = \{t_1, t_2\}$ and $T = 2$. A policy $\pi \in \mathcal{P} = \{1,2 \dots \Pi\}$ is defined by the tuple including a tactic and its corresponding strategy, that is $\pi = (s, \mathcal{T}_s)$. In Figure 2, $\Pi = 5$. The set of R risks is $\mathcal{R} = \{1,2 \dots R\}$. We denote with r a risk belonging to $\mathcal{R}$. In Figure 2, $\mathcal{R} = \{r_1, r_2\}$ and $R = 2$. The set of all possible outcomes, which are risk combinations, is the sample space $\Omega = \{1,2 \dots O\}$. We denote with ω an outcome belonging to Ω. In Figure 2,

$\Omega = \{r_1 \cap r_2, r_1 \cap \bar{r}_2, \bar{r}_1 \cap r_2,\}$ and $O = 3$. If every risk combination was possible, the set Ω would have been the power set of $\mathcal{R}$. The chosen mitigation strategy affects the probability of risk occurence. The set $\mathcal{T}_s$ is the set of all the combinations of $\mathcal{T}$ available to the decision maker if she chooses s. In Figure 2, $\mathcal{T}_{s1} = \{(t_1), (t_2), (t_1, t_2)\}$ and $\mathcal{T}_{s2} = \{(t_1), (t_2)\}$. We denote with $\mathcal{T}_s$ a combination of tactics such that $\mathcal{T}_s \in \mathcal{T}_s$. For each final node, representing a policy π, we calculate the supply chain risk profile. This is the expected value of the total impact, which also includes the costs of the strategy and the tactics employed. To compute expectations, we employ probabilities calculated using Bayes' formula.

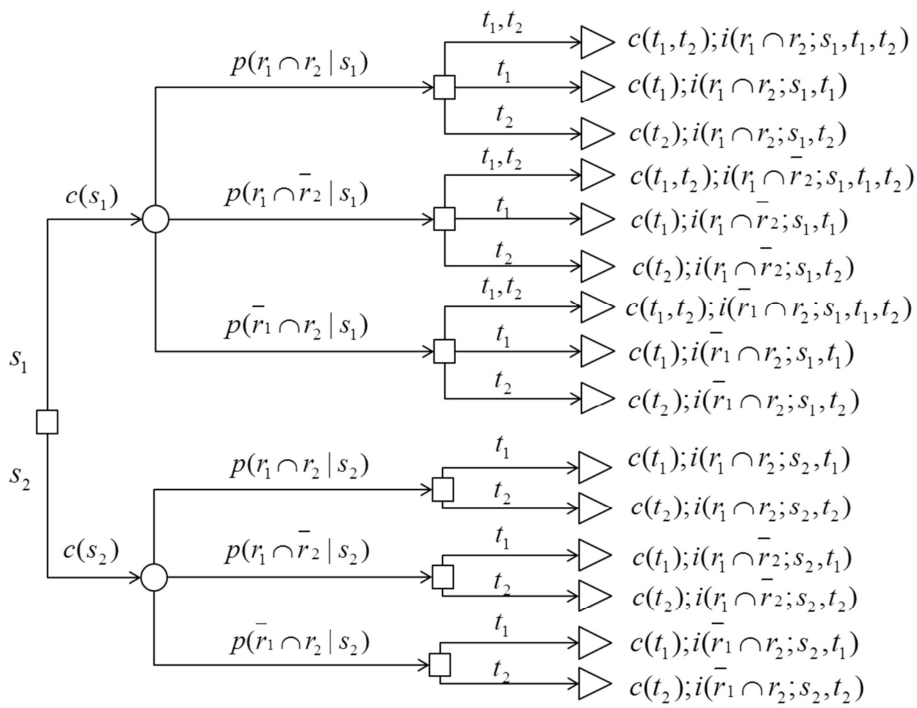

Figure 2: Example of a decision-tree problem.

3.3. Matrix formulation

The matrix formulation of the decision-tree problem requires the definition of the elements as follows: total impact for each event including policy costs, event probabilities, probabilities of strategies being successful in the presence of an event and event probabilities when a strategy is used. We now present the various parameters used in the matrix formulation:

- c_s is the cost of the strategy s and c_t is the cost of the tactic t.
- **cs** is the S-dimensional vector including the strategy costs c_s.
- **ct** is the T-dimensional vector including the tactic costs c_t.
- The cost of the combination of tactics τ_s is $c_{\mathcal{T}_s} = \sum_{t\in\mathcal{T}_s} c_t$.
- The cost of a policy $\pi = (s, \mathcal{T}_s)$ is $c_\pi = c_s + c_{\mathcal{T}_s}$.
- **c** is the Π-dimensional vector including the policy costs c_π.
- $i_{\omega,\pi}$ is the monetary impact of the outcome ω if the policy π is used.
- The Π-dimensional vectors $\mathbf{i}_\omega$ include the impact $i_{\omega,\pi}$.
- The Π-dimensional total-impact vectors $\mathbf{v}_\omega$ are defined as: $\mathbf{v}_\omega = \mathbf{i}_\omega + \mathbf{c}$.
- $p(\omega)$ is the probability of the outcome ω, with $\sum_{\omega\in\Omega} p(\omega) = 1$.
- $p(s|\omega)$ is the probability of strategy s being successful in presence of the outcome ω, with $\sum_{\omega\in\Omega} p(s|\omega) = 1$.
- **p** is the O-dimensional vector including the probabilities $p(\omega)$.
- The O-dimensional vectors $\mathbf{p}_\mathrm{s}$ include the probabilities $p(s|\omega)$.

In Paragraph 3.4, we explain how to obtain the vectors $\mathbf{cs}, \mathbf{ct}, \mathbf{i}_\omega$ for each ω, $\mathbf{p}$, and $\mathbf{p}_\mathrm{s}$ for each s, from expert judgments.

We now proceed with the matrix formulation. Our aim is to find the probability $p(\omega|s)$ for each ω, which is the probability of outcome ω when the strategy s is used. We define the $O \times S$ matrix $\mathbf{P}(\omega|s)$ as follows:

$$\mathbf{P}(\omega|s) = \begin{pmatrix} p(1|1) & p(1|2) & \cdots & p(1|S) \\ p(2|1) & p(2|2) & \cdots & p(2|S) \\ \vdots & \vdots & \ddots & \cdots \\ p(O|1) & p(O|2) & \cdots & p(O|S) \end{pmatrix}.$$

Similarly, we define the $O \times S$ matrix $\mathbf{P}(s|\omega)$ as follows:

$$\mathbf{P}(s|\omega) = \begin{pmatrix} p(1|1) & p(2|1) & \cdots & p(S|1) \\ p(1|2) & p(2|2) & \cdots & p(S|2) \\ \vdots & \vdots & \ddots & \cdots \\ p(1|O) & p(2|O) & \cdots & p(S|O) \end{pmatrix}.$$

We define the $O \times O$ diagonal matrix $\mathbf{P}(\omega)$ as follows:

$$\mathbf{P}(\omega) = \begin{pmatrix} p(1) & 0 & \cdots & 0 \\ 0 & p(2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & p(O) \end{pmatrix}.$$

We denoted with $\mathbf{p}$ the O-dimensional vector including the probabilities $p(\omega)$ and with $\mathbf{p_s}$ the O-dimensional vector including the probabilities $\mathbf{P}(s|\omega)$. We define the $S \times OS$ block-diagonal matrix $\widehat{\mathbf{P}}(s|\omega)$ as follows:

$$\widehat{\mathbf{P}}(s|\omega) = \begin{pmatrix} \mathbf{p}_1^{\boldsymbol{T}} & 0 & \cdots & 0 \\ 0 & \mathbf{p}_2^{\boldsymbol{T}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & \mathbf{p}_s^{\boldsymbol{T}} \end{pmatrix}.$$

We define the $OS \times S$ block diagonal matrix $\widehat{\mathbf{P}}(\omega)$ as follows:

$$\widehat{\mathbf{P}}(\omega) = \begin{pmatrix} \mathbf{p} & 0 & \cdots & 0 \\ 0 & \mathbf{p} & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & \mathbf{p} \end{pmatrix}.$$

We denote $p(s)$ as the probability of the policy s. We define the $S \times S$ diagonal matrix $\mathbf{P}(s)$ as follows:

$$\mathbf{P}(s) = \begin{pmatrix} \mathrm{p}(1) & 0 & \cdots & 0 \\ 0 & \mathrm{p}(2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & \mathrm{p}(S) \end{pmatrix}.$$

The matrix formulation allows us to find neat expressions to calculate $\mathbf{P}(\omega|s)$ from $\widehat{\mathbf{P}}(s|\omega), \widehat{\mathbf{P}}(\omega), \mathbf{P}(\omega) and\ \mathbf{P}(s|\omega)$ as we show in Proposition 1.

Proposition 1. *The Bayes' formula in matrix form is given by the relation as follows:*

$$\mathbf{P}(\omega|s)\mathbf{P}(s) = \mathbf{P}(\omega)\mathbf{P}(s|\omega)$$

$with\ \mathbf{P}(s) = \hat{\mathbf{P}}\ (s|\omega)\widehat{\mathbf{P}}(\omega). Furthermore, \mathbf{P}(\omega|s)\ can\ be\ calculated\ from\ \mathbf{P}(\omega|s) = \mathbf{P}(\omega)\mathbf{P}(s|\omega)\mathbf{P}^{-1}(s).$

Proof. The proposition can be proved by carrying matrix multiplication and by noting that as $\mathbf{P}(s)$ is diagonal, $\mathbf{P}^{-1}(s)$ is as follows:

$$\mathbf{P}^{-1}(s) = \begin{pmatrix} \frac{1}{p(1)} & 0 & \cdots & 0 \\ 0 & \frac{1}{p(2)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \cdots \\ 0 & 0 & \cdots & \frac{1}{p(S)} \end{pmatrix}.$$

[9] proposed a similar alternative matrix formulation of Bayes' formula that can be interpreted as an ANP super-matrix. The principal problem of their approach is that their matrix formulation can be used to represent the Bayes' formula probabilities once they are known but cannot be used to calculate such probabilities.

We can calculate the probabilities $p(\omega|\pi)$from $p(\omega|s)$ using the relation as follows: $p(\omega|\pi) = p(\omega|s)|s \in \pi$. We define the $O \times \Pi$ matrix $\mathbf{P}(\omega|\pi)$ including the probabilities $p(\omega|\pi)$ as follows:

$$\mathbf{P}(\omega|\pi) = \begin{pmatrix} p(1|1) & p(1|2) & \cdots & p(1|\Pi) \\ p(2|1) & p(2|2) & \cdots & p(2|\Pi) \\ \vdots & \vdots & \ddots & \cdots \\ p(O|1) & p(O|2) & \cdots & p(O|\Pi) \end{pmatrix}.$$

We denote with $\mathbf{P}(\omega|\pi)_{*,\mathbf{j}}$ the columns of such matrix, which are O-dimensional column vectors. The Π-dimensional vector $\mathbf{v}_\omega$ contains the values of the total impact including the cost of the policy if event ω happens. We define the $\Pi \times O$ matrix $\mathbf{V}$ as follows:

$$\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \ldots \mathbf{v}_O].$$

We denote with $\mathbf{V}_{i,*}$the rows of such matrix, which are O-dimensional row vectors. We find the policy π_{min}minimizing the supply chain risk profile using the relation as follows:

$$\pi_{min} = \arg\min(\boldsymbol{V}_{1,*}\boldsymbol{P}(\omega|\pi)_{*,1}, \boldsymbol{V}_{2,*}\boldsymbol{P}(\omega|\pi)_{*,2}, \ldots\ \boldsymbol{V}_{R,*}\boldsymbol{P}(\omega|\pi)_{*,R}).$$

3.4. Pairwise comparisons

We obtain the vectors $\boldsymbol{cs}$, $\boldsymbol{ct}$, $\boldsymbol{i}_\omega$ for each ω, $\boldsymbol{p}$ and $\boldsymbol{p}_s$ for each s, using pairwise-comparison matrices including expert judgments. $\boldsymbol{cs}$, $\boldsymbol{ct}$, and $\boldsymbol{i}_\omega$ have dimensions S, T, and Π, respectively. $\boldsymbol{p}$ and $\boldsymbol{p}_s$ have both dimension O. We illustrate our method for a generic vector of dimension n. As recommended by [26], who introduced pairwise comparisons for estimating decision-tree parameters, we use a geometric space of judgments to compare factor f_1 to factor f_2, defined as follows:

$$\mathcal{g} = \{1, 2, 4, 8, 16, 1/2, 1/4, 1/8,\ 1/16\}.$$

In our DSS, the factors are probabilities, costs and impact. When comparing f_1 to f_2, the values 1, 2, 4, 8, 16 indicate 'as probable or costly', 'somewhat more probable or costly', 'more probable or costly', 'much more probable or costly' and 'vastly more probable or costly', respectively. The reciprocal values 1/2, 1/4, 1/8, and 1/16 take the same meaning when comparing f_2 to f_1. [26] argued that such scale is suitable to convert verbal quantifiers into numbers, especially for probabilities.

We use the eigenvector method to obtain the weight vectors $\boldsymbol{w} = [w_1 \ldots w_n]^T$ from the $n \times n$ pairwise comparison matrix $\boldsymbol{A}$. If λ_{max} is the largest eigenvalue of $\boldsymbol{A}$, we calculate the weight vector from the expression as follows:

$$\boldsymbol{A}\boldsymbol{w} = \lambda_{max}\boldsymbol{w}.$$

If $\boldsymbol{w}$ is a weight vector for probability judgments, we normalize the weights to one. We use this process to estimate the vectors $\boldsymbol{p}$ and $\boldsymbol{p_s}$, that is, if pr_i is an element of such vectors:

$$pr_i = \frac{w_i}{\sum_{j=1}^{n} w_j}, i = 1 \ldots n.$$

If $\boldsymbol{w}$ is a weight vector for cost or impact judgments, we scale the weights using the value b estimated from previous projects. We use this process to estimate the vectors $\boldsymbol{cs}$, $\boldsymbol{ct}$ and $\boldsymbol{i}_\rho$. We denote co_j as an element of such vectors. The value b is the cost or the impact of a strategy, a tactic or a policy k, that is $co_k = b$. We estimate the cost and impact vectors from scaling the elements of the vector $\boldsymbol{w}$ using b, that is:

$$co_i = \frac{bw_i}{w_k}, i = 1 \dots n.$$

4. Case application

We apply the DSS, described in Section 3, to an expanding industry, offshore wind, for which academic contributions on its supply chain are still limited [27]. First, we introduce the industry and its supply chain. Second, we describe the validation and data collection phases for the case application. Third, we present the case application by describing the strategies, tactics and risks employed. Fourth, we present and discuss the results obtained from applying the DSS to the case. Finally, we present a sensitivity analysis, by interpreting how changes in parameters could affect the results.

4.1. Introduction to the offshore-wind supply chain

Offshore wind is one of the most promising renewable energy sources. The offshore-wind power generated globally is forecasted to increase dramatically in the next few years [28]. Building wind farms offshore allow the development of large-size plants, which are efficient in generating energy, without the concerns for local population and land availability that inshore plants raise. In comparison with onshore-wind plants, offshore-wind farms also lead to better energy generation because sea winds are stronger and more stable.

Schematically, the components of an offshore-wind farm include turbines, foundations, cables and substations. Turbine components can be further categorized in hubs, blades, nacelles, and towers, with transition pieces linking turbines to foundations. The offshore-wind supply chain revolves around three principal phases, not strictly sequential: supply, construction and management. [29, pp. 79-81] used similar phases to categorize risks in large engineering projects. Companies involved in these phases can be more than forty [30, 31]. The principal suppliers are turbine, foundation, cable and substation suppliers. The principal companies involved in construction are port operators, installers, and vessel suppliers. The wind-farm operator and the transmission operator share the management of the offshore-wind farm. Developers and consultants offer their support throughout the three phases.

Managing offshore-wind supply chains efficiently and effectively is a key success factor for the industry [27]. However, because of the complexity of offshore-wind projects, supply chain risks are many. In particular, offshore-wind supply chains are sensitive to disruptions and delays. Disruptions could be caused by quality problems. Delays could be caused for example by inclement weather coupled with resource availability issues. For these reasons, the application of suitable DSS to mitigate the risks in the offshore-wind industry is a priority for the industry. The application of a DSS employing the SCRM-process is particularly useful for this supply chain, because its holistic view helps decision-makers to recognize relationships among risks and mitigation measures which could be difficult to identify and interpret.

4.2. Validation and data collection

We applied the DSS described in Section 3 to the offshore-wind supply chain. Industrial experts validated the case application by commenting on the suitability of the strategies, risks, and tactics used in the DSS. They also provided judgments for probabilities, impact, and costs.

We carried out the case-application validation and the data collection in three stages. In the first stage, an industrial expert validated the case application and helped the researchers in estimating costs and base values of impact based on previous offshore-wind farm projects. In the second stage, we organized a focus group involving four industrial experts to further validate the case application and to provide judgments for probabilities and impact. The focus group, conducted in accordance to the guidelines of [32] was held at EDF Energy in London on the 21st of January 2015 and lasted over two hours. The focus group facilitator was one of the researchers. The focus group was audio recorded and subsequently transcribed for analysis. In the third stage, we contacted eight industrial experts with varied backgrounds and at least five-year experience in the industry requiring their written feedback to reach consensus on the judgments and values collected in the first two stages.

4.3. Case description

We applied the DSS described in Section 3 to the offshore-wind supply chain with the aim of finding the best policy, which is a combination of a strategy and tactics, to mitigate delays and disruptions. In particular, we are interested in understanding which governance structure is the most effective strategy in mitigating supply chain risks. Our scope concerns the supply and construction of offshore-wind farms. We refer the reader to [33] for an analysis of the risks arising in the management of offshore-wind farms. We assume that the supply chain is characterized by medium exposure to risks and supplies a farm of the size of London Array, whose capacity is 630 MW, because many future offshore-wind farm projects will be of similar size. We assume that the user of the DSS is the owner or the developer of the farm.

[34] identified the most used governance structures in offshore projects for the oil and gas industry. Based on their analysis, in the case application we included the

three supply chain strategies as follows: EPC, which is engineering, procurement and construction, multi-contracting, and project alliance. In the EPC strategy, denoted as s_1, a contractor manages all the suppliers on behalf of the farm owner and also bears most of the construction-project risks. For example, Fluor acted as contractor for the construction of the British offshore-wind farm Greater Gabbard [35]. In the multi-contracting strategy, denoted as s_2, the owner manages the construction project directly and stipulates individual contracts with all the suppliers. Multi-contracting is the predominant governance structure for offshore-wind projects [36]. Project alliance, denoted as $s_{3,}$ is a governance structure designed in a way that both the owner and the suppliers share both risks and rewards. This governance structure is employed in offshore oil and gas projects but it is not commonly used in the offshore-wind industry. A case of partial project alliance is the Dutch offshore-wind farm Gemini. In this project, some of the suppliers also act as the farm shareholders [37].

[23] categorized risks into disruptions, delays and distortions. When supply and construction of an offshore-wind farm start, the number and the type of components required are known. Therefore, in the supply and construction phases, offshore-wind supply chains are not subject to forecast risks, or distortions. The sources of disruptions could be quality problems and lack of synchronization in the supply chain, the latter mostly caused by its complexity. In particular, the impact of quality problems on the offshore-wind supply chain can be severe. For example, the foundations supplied for the Greater Gabbard offshore-wind farm, once transported to the site, were found to be faulty. They had to be replaced, creating relevant disruptions to the project [38]. The sources of delays, besides the lack of synchronization, could be inclement weather coupled with resource availability issues. Resource availability issues mostly concern vessels, which are custom-built ships employed to transfer crew during construction

activities. Because of the scarcity of such vessels, their scheduling to the construction of an offshore-wind farm needs to be planned well in advance. If the project is delayed because of inclement weather, rescheduling construction activities could incur further delays because of the vessels' limited availability. Delays account for a large amount of the risk impact. For the London Array offshore-wind farm, two months of delay were estimated to cause € 47 million loss to the owners [39]. In the case application, we included quality and delay risks, denoted as r_1 and r_2, whose source could be the relationship with a specific supplier.

We identified four tactics that could be used to mitigate quality and delay risks. The first tactic, t_1, involves finding a solution to the problem collaboratively with the supplier. The second tactic, t_2, involves requesting the supplier a compensation for the quality or delay problems. The third tactic, t_3, involves requesting more funds from the investors to mitigate the impact of risks. The fourth tactic, t_4, involves delaying the payment to the supplier until the quality or delay problems are solved. Tactics t_1 and t_3 require a collaborative approach with the supplier to mitigate risks. Tactics t_2 and t_4, if employed, denote an adversarial relationship with the supplier. The sample space in the case application is $\Omega = \{r_1 \cap \bar{r}_2, \bar{r}_1 \cap r_2, r_1 \cap r_2, \bar{r}_1 \cap \bar{r}_2\}$. In Section 2, we discussed how mitigation tactics are available to decision makers. We defined $\mathcal{T}_s$ as the set of all tactic combinations available to the decision maker if she chooses the strategy s. In the case application $\mathcal{T}_{s_1} = \{\emptyset, (t_2), (t_4)\}$, $\mathcal{T}_{s_2} = \{(t_1), (t_2), (t_1, t_3), (t_2, t_3), (t_4)\}$ and $\mathcal{T}_{s_3} = \{(t_1), (t_1, t_3)\}$. If the decision maker chooses s_1, which is EPC, she could choose to take no mitigation tactics, exercise the compensation clause or delay payments to the supplier. The impact when the decision maker chooses EPC and does not choose any mitigation tactic, referred to as π_0, is an upper bound for the other policies and is only taken into account for the estimation of the impact of such policy from previous projects. Under EPC, the contractor often bears the construction risks and stipulates contracts with the suppliers governed by strict regulations that define penalties if the suppliers are found to be at fault. As EPC is often associated with project financing, investors may partially impose such regulations as conditions to fund the project [29, p.182]. If risks occur, the EPC contractor will employ an adversarial approach contacting the supplier at fault through her legal department, choosing either to exercise the compensation clause or to delay payments to the supplier. It is unrealistic for the contractor to employ both tactics at the same time. If the decision maker chooses s_3, which is project alliance, she will decide to co-find solutions with the supplier, also in conjunction with requesting more funds from the investors, if necessary. In project alliance, the companies will choose a collaborative approach to tactics because they are partners in ownership, sharing the project risks and rewards [29, p.182]. In multi-contracting, the role of each supplier is more important than under EPC, because the contracts stipulated among the owner and the suppliers are intertwined. Therefore, more than one supplier can affect the risk-mitigation process. However, multi-contracting is less democratic than project alliance. Although the owner could consult the suppliers on the decisions to be made, the decisional power resides exclusively with the owner. Therefore, the owner could take an adversarial approach to tactics, a collaborative approach, or even a mix of both.

4.4. Results

We present the results obtained by applying the DSS described in Section 3 to the offshore-wind supply chain. Before discussing the ranking of the mitigation policies (Table 1), we describe some intermediate results obtained from the data collection for the parameters of Figure 1, which are probabilities, costs, and impact.

Considering the probabilities, the most probable event is 'neither of the two risks happening'. The industrial experts remarked that strict quality procedures and project tracking in real time reduce the probability of occurrence for quality and delay risks, respectively. However, because of the complexity of offshore-wind projects, delay risks are rather frequent. A quality issue is almost always associated to a delay as the former trigger the latter. The experts also argued that strategies such as multi-contracting but especially project alliance, by fostering a collaborative environment, could reduce the probability of occurrence of quality problems. The experts remarked that all the three strategies are comparable in reducing the occurrence of delays.

Examining the costs, the cost of setting up a project alliance is by far the most expensive, followed by EPC and multi-contracting. Tactics are comparable for costs, with the most expensive options being the combination of t_3, which involves requesting more funds from investors, with either t_1, which is 'co-finding solutions' or t_2, which is 'exercising the compensation clause'. The least expensive tactic is t_4, which involves delaying payments to the supplier.

Considering the impact, quality risks occurring without ensuing delays are minor for impact. Delay risks result in high impact because they require supply chain managers to contract extremely expensive resources, such as vessels, for longer than expected. The combination of quality and delay risks occurring at the same time put relevant strains on the supply chain. Therefore, the impact of the combination of delay and quality risks is higher than the sum of their impact if these risks occur separately. Adversarial tactics, such as t_2, which is 'exercising the compensation clause' and t_4, which involves delaying payments to the supplier, are more effective in mitigating the impact ensuing from quality risks. Collaborative tactics, such as t_1, which is 'co-finding solutions' and t_3, which involves requesting more funds from investors, are similarly effective in mitigating the impact ensuing from delay and quality risks.

Proposition 1 greatly simplifies the conversion of expert judgements into a decision making objective, the supply chain risk profile, defined as the expected total impact of risks including the cost of the policy employed. In the Appendix to this paper, we provide details on the estimation of numerical values from expert judgements. These numerical values populate the matrices described in Paragraph 3.3. By carrying out matrix multiplication using Proposition 1 we obtain supply chain risk profiles for each mitigation policy (Table 1).

Policy	Strategy	Tactics	Supply chain risk profile	Percentage Increase
π_1	s_1: EPC	t_2 : Exercising the compensation clause	*£ 4,152,679*	*0%*
π_6	s_2 : Multi-contracting	t_2 : Exercising the compensation clause <u>and</u> t_3: Request more funds from investors	*£ 4,268,586*	*3%*
π_2	s_1: EPC	t_4: Delay payments to the supplier	*£ 4,278,067*	*3%*
π_5	s_2 : Multi-contracting	t_1: Co-founding solutions <u>and</u> t_3: Request more funds from investors	*£ 4,784,568*	*15%*
π_9	s_3 : Project alliance	t_1: Co-founding solutions <u>and</u> t_3: Request more funds from investors	*£ 5,188,169*	*25%*
π_4	s_2 : Multi-contracting	t_2 : Exercising the compensation clause	*£ 5,375,500*	*29%*
π_8	s_3 : Project alliance	t_1: Co-founding solutions	*£ 5,696,338*	*37%*
π_7	s_2 : Multi-contracting	t_4: Delay payments to the supplier	*£ 6,281,211*	*51%*
π_3	s_2 : Multi-contracting	t_1: Co-founding solutions	*£ 8,097,591*	*95%*

Table 1: Ranking of mitigation policies for increasing values of supply chain risk profile.

The results suggest implementing π_1, which is EPC, followed by exercising the compensation clause. An alternative policy, π_6, involves implementing multi-contracting followed by exercising the compensation clause and request more funds from investors.

Such policy results in a percentage increase of only 3% from the risk-profile minimizing policy π_1. Policies including project alliance lead to a relevant increase in the risk profile. Policy π_9 involves implementing project alliance followed by co-finding solutions and request more funds from investors. Such policy results in a percentage increase of 25% from the risk-profile minimizing policy π_1.

The experts suggested that adversarial tactics are more effective in mitigating quality risks than collaborative tactics and their effectiveness in mitigating delay risks is similar to the one of collaborative tactics. Therefore, adversarial tactics are generally more effective in mitigating the impact of risks. As these tactics work better with EPC than with multi-contracting and project alliance, policies combining EPC with adversarial tactics perform well in reducing the supply chain risk profile, with π_1 and π_2 ranked first-best and third-best, respectively. Multi-contracting is less effective than EPC if in conjunction with adversarial tactics and less effective than project alliance if in conjunction with collaborative tactics, leading to high level of impact. Nevertheless, the cost for setting up multi-contracting is lower than the ones for setting up EPC or project alliance. For this reason, multi-contracting leads to a modest percentage increase of the risk profile, which includes the cost of strategies, in comparison to EPC. Project alliance, by fostering a more collaborative environment, reduces the probability of quality risks from happening. However, such benefit does not offset the advantages of employing the adversarial tactics in mitigating quality risks, especially if in conjunction with EPC.

4.5. Sensitivity analysis

Policy, π_1, which minimizes the risk profile, employs EPC as a governance structure. We compare it against π_6, the best policy using multi-contracting, and π_9, the best policy using project alliance. The supply chain risk profile for π_1 is £ 4,152,679. We change the parameters of policies π_6 and π_9 with the aim of obtaining the same value of risk profile, therefore making the decision maker indifferent between such policies and π_1. Having a matrix formulation for this problem as a result of Proposition 1 greatly simplifies this sensitivity analysis.

First, we change the values of the probabilities $p(\rho|s_2)$ and $p(\rho|s_3)$ under the constraint that their sum over ρ is equal to one with the aim of obtaining the value of the risk profile of π_1 for π_6 and π_9, respectively. A solution to this problem for $p(\rho|s_2)$ is depicted in Table 2. There is no feasible solution to this problem for $p(\rho|s_3)$ as the risk profile of π_9 cannot be reduced to the risk profile π_1 with any probability combination.

Probabilities	Original value	New value	Percentage difference
$p(\rho_1 = r_1 \cap r_2 \vert s_2)$	*0.0606*	*0.0577*	*-5%*
$p(\rho_2 = r_1 \cap \bar{r}_2 \vert s_2)$	*0.1036*	*0.0916*	*-12%*
$p(\rho_3 = \bar{r}_1 \cap r_2 \vert s_2)$	*0.0107*	*0.0106*	*-1%*
$p(\rho_4 = \bar{r}_1 \cap \bar{r}_2 \vert s_2)$	*0.8251*	*0.8401*	*+2%*

Table 2: A probability combination leading to multi-contracting to have the same supply chain risk profile of EPC with the original probability combination.

The probability of event ρ_4, with neither risks occurring, needs to be increased for π_6 to be comparable to π_1, because in this case the risk profile is given by the cost of the strategies, which for π_6 is less than for π_1. This suggests that multi-contracting could be more effective than EPC for an offshore-wind supply chain characterized by low exposure to risks. The probability of event ρ_2, with only the quality risk occurring, needs to be relevantly reduced for π_6 to be comparable to π_1. This is because quality risks are more effectively mitigated by adversarial tactics, which are more effective in conjunction with EPC, as in π_1, than with multi-contracting, as in π_6.

Second, we change the values of impacts i_{ϱ,π_6} and i_{ϱ,π_9} with the aim of obtaining the value of the supply chain risk profile of π_1 for π_6 and π_9, respectively. There is no feasible solution to this problem for i_{ϱ,π_9} as the risk profile of π_9 cannot be reduced to the risk profile of π_1 by changing the impact for policy π_9. Policy π_6 could be made comparable to policy π_1 by either reducing i_{ϱ_1,π_6} from £7,670,253 to £6,551,903 or by reducing i_{ϱ_3,π_6} from £5,369,177 to £3,456,507.

Finally, we changed the values of costs c_{s_2} and c_{s_3} with the aim of obtaining the risk profile of π_1 for π_6 and π_9, respectively. This could be obtained by reducing c_{s_2} from £3,000,269 to £2,884,363 and by reducing c_{s_3} from £4,762,461 to £3,726,972. Therefore, the only feasible option to make project alliance comparable to EPC is to relevantly reduce the cost of setting up a project alliance.

5. Conclusions

In this study, we proposed a DSS to mitigate supply chain risks and applied it to the offshore-wind supply chain. The decision support system employs the SCRM process, which calls for a holistic view of the supply chain and its risks. Our DSS improves and extends previous DSSs employing the SCRM process by 1) proposing a method for estimating probabilities from expert judgments, 2) considering the relationships among risks and mitigation measures and 3) modelling the selection of mitigation measures leading to the lowest supply chain risk profile. To our knowledge, this research study is the first to propose a two-stage DSS for mitigating supply chain risks, which takes into account not only mitigation strategies but also mitigation tactics. Our principal methodological contribution is the extension of the decision-tree approach to a matrix formulation that can be used to calculate posterior probabilities. This formulation improves the matrix formulation of the Bayes' formula suggested by [9].

By applying the DSS to the offshore-wind supply chain, we contributed to the limited literature available on the supply chain of this expanding industry. For a supply chain characterized by medium exposure to risks, supplying a farm with capacity of 630 MW, the risk-profile-minimizing governance structure is EPC, followed by multi-contracting and project alliance. The sensitivity analysis suggests that multi-contracting could be more effective than EPC for an offshore-wind farm characterized by low exposure to risks. Project alliance could be more effective than EPC only if the cost to set up this structure is relevantly reduced. These results should be extended with care to other offshore-wind projects. We asked the experts to formulate judgments without an offshore-wind farm in mind. Therefore, results could be different from those obtained in here if experts formulate judgments for a specific farm.

The study lends itself to three possible extensions. First, fuzzy numbers could be used in the pairwise-comparison matrices employed for determining parameters from expert judgments in Paragraph 3.4. However, this extension could be considered after the problems concerning fuzzy-pairwise comparisons are resolved [40]. Second, real options could be used to model the case in which the decision maker delays the mitigation measure choice with the aim of gaining more information on the risks. As real options could also be described using decision trees [41], this extension should be relatively straightforward. Third, contracting decisions in offshore-wind supply chains could be studied using game theory as in [42] and [43], which propose game-theory models for supply chains subject to disruptions.

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