Real options approach to evaluate postponement as supply chain disruptions mitigation strategy

Real-options Approach to Evaluate Postponement as Supply Chain Disruptions Mitigation Strategy

The purpose of this paper is to assess the value of postponement as strategy for mitigating supply chain disruptions. To accomplish this objective, we develop a real option computational model that quantifies the value of postponement in mitigating both supply and demand disruptions by taking into account the value of managerial flexibility to decide whether exploiting or not the strategy, if and when disruptions occur, and whenever product differentiation proves valuable based on information available at that time. Numerical experiments show the importance of incorporating an option valuation method when pricing the value of postponement. This ensures managers implement postponement only when it is valuable, thus avoiding burdening the company with its initial sunk costs. By modelling the postponement implementation under different conditions, we identify the situations in which postponement performs better as supply chain disruption mitigation strategy. We derive the operational configurations, in terms of decoupling point position, and external conditions, in terms of riskiness of the environment, which make the postponement an effective mitigation strategy.

Keywords: Postponement, Real options, Supply Chain Risk Management, Supply Chain Disruptions, Mitigation Strategies

1. Introduction

In the past years, supply chain risk management literature has fixed academics and practitioners' attention on a specific source of supply chain risk, namely the supply chain disruptions due to unplanned and unanticipated events that radically disturb a supply chain by hampering the normal flow of goods and materials (see for example Hendricks and Singhal, 2005; Jain et al., 2017; Talluri et al., 2013; Tang, 2006b; Tang and Tomlin, 2008; Wagner and Bode, 2008). Disruptions may occur upstream, as consequences of interruptions in the supply of specific items due to disruptive incidents in the supplier's internal operations, supplier bankruptcy, opportunistic behavior, or shortages in the supply market, etc. (Norrman and Jansson, 2004). Several cases can be mentioned as examples of

supply disruptions, such as the bankruptcy of the Land Rover branches' suppliers in 2002 (Sheffi, 2007) and the supply problems at one of the Boeing sources in 2008 that impeded the introduction of the Boeing 787 (Asian and Nie, 2014). On the other hand, disruptions may occur downstream, caused by unexpected changes in the market scale due to, for instance, financial crisis, trade restrictions, etc. (Tang, 2006b). Examples of demand disruptions are the slump of sales of Japanese commodities and vehicles in 2012 due to strained relationships between China and Japan (Li et al., 2014), and the abrupt house demand reduction in US due to the mortgage crisis in 2008 (Goetzmann et al., 2012).

Supply chain disruptions may have tremendous impact on a firm's business performance and its ability to survive (Hendricks and Singhal, 2005; Ivanov et al., 2014). Hence, appropriate strategies are needed to proactively manage these uncertain events, also for maintaining profitability and enhancing the competitive position of the firm (Namdar et al., 2017; Tomlin, 2006; 2009).

Studies that have considered how to properly manage and reduce companies' exposure to supply chain disruptions have recognized the combination of both operational and strategic flexibility and redundancy as effective practices to cope with such risks (Daultani et al., 2015; Ho et al., 2015; Namdar et al., 2017; Yu et al., 2015). While the concept of redundancy essentially refers to maintaining excess resources such as inventory and capacity, the concept of flexibility is broader and varies from one context to another (Choi, 2016; Daultani et al., 2015; Paul et al., 2014 ; Paul et al., 2017; Rezaei Somarin et al., 2017). In its general formulation, flexibility is defined as the firm's ability to change or react to environmental changes with little or negligible penalty and sacrifice in time, operational efforts, costs or performance (Lu et al., 2017; Pérez et al., 2016; Upton, 1994).

Among practices that build on flexibility for reducing the impact of risks (Paul et al., 2017; Rezaei Somarin et al., 2017), previous literature has frequently cited postponement (Gupta and Somers, 1992; Lee, 2004; Reichhart and Holweg, 2009; Swaminathan and Lee, 2003; Tang and Tomlin, 2008). Postponement consists of delaying activities in the supply chain until customer order information becomes available (Yang and Yang, 2010), thus being able to cope with changing circumstances or instability caused by the environment. Postponement is enabled by some product and process features,

including product customization (MacCarthy, 2013), product and process redesign, decouplability, standardization, and modularity (Brun and Zorzini, 2009; Skipworth and Harrison, 2004; Swaminathan and Lee, 2003; Yang et al., 2004). Successful applications of postponement have been experienced in industries and markets featured by those postponement enablers, such as textile and apparel, consumer electronics, and medical devices (Chaudhry and Hodge, 2012; Gualandris and Kalchschmidt, 2013; Venkatesh and Swaminathan, 2004).

Thanks to the possibility of reconfiguring the product to quickly respond to sudden changes in demand and/or to shortages in supply, recently, postponement has been mentioned as practice to manage disruptions along the entire supply chain (Lee, 2004; Sheffi, 2001; Tang 2006a; 2006b; Yang and Yang, 2010). Such a strategy is not free, because it is built on product and process modularity, standardization, commonality, and versatile management and organizational systems to accommodate last minute changes. Besides, through the postponement a manufacturer can take actions to increase revenues, avoid losses or take advantages (i.e., differentiating the product), depending on the resolved uncertainties along time, rather than passively accept all the consequences. For example, the opportunity to use different components in case of supply disruption or to alter the product design making it suitable for other customers in case of demand disruptions open an option (i.e. flexibility) to reconfigure the product when such a differentiation proves valuable.

Postponement capability to mitigate supply chain disruptions has to be assessed against the cost of implementing it. Hence, in making decisions about postponement adoption, the key questions for the managers are: Is postponement valuable in mitigating supply chain disruptions? Does its value justify its costs? How do the operational configuration of postponement and external conditions affect the postponement performance? In other words, in which conditions does postponement perform better? The conventional approaches for cost-benefit analysis are not able to give answers to these questions since they cannot capture the flexibility mechanism of postponement to decide whether to differentiate the product, when disruptions occur, and whenever such a differentiation proves valuable according to the information available at the disruption time. For estimating the value of flexibility

given by postponement to change the configuration of one product at the last possible moment in case of disruptions in demand or in supply of a component, we adopt a real option approach, as an alternative valuation method (see Mun (2002), Copeland and Antikarov (2001) for a comprehensive review on the use of "real-option valuation (ROV)" in different fields), where a real option is the "right but not the obligation" to choose a course of action and obtain an associated payoff (Dixit and Pindyck, 1995; Leslie and Michaels, 1997).

Our research aims at answering to the above questions by developing a ROV computational model for evaluating postponement as supply chain disruption risks mitigation strategy. In particular, the model quantifies the value associated to postponement, which comes at certain costs, but has uncertain potential benefits that will be gained at a future date if and when disruptions occur, and whenever product differentiation proves valuable based on information available at that time. The proposed ROV model allows for capturing the value of the managerial flexibility of taking the action of product differentiation (i.e., postponement exercise), since each time a disruption occurs the model assesses the net benefits associated with the product differentiation and decides whether making such a differentiation or not.

This paper is related to the recent literature on postponement as supply chain risk mitigation strategy and serves, as target audience, industries and production systems with product and process features enabling postponement, e.g., product and process decouplability, standardization, and modularity. The paper provides some new contributions. Firstly, we extend the existing literature on postponement by considering the implication of a postponement response in case of supply and demand disruptions, rather than in case of changeable demand. Furthermore, to the best of our knowledge, the proposed model differentiates from previous ones since it quantifies the benefits of postponement by explicitly modelling the flexibility mechanism of postponement to decide whether to differentiate the product when disruptions occur and if this differentiation proves valuable.

The rest of the paper is organized as follows. In Section 2 we firstly provide an overview of studies on postponement, and a brief literature review on the ROV method. Section 3 presents the ROV

computational model for evaluating postponement as supply chain disruptions mitigation strategy. Section 4 reports the results of the numerical experiments and sensitivity analysis carried out in order to investigate the value of postponement in mitigating supply chain disruptions and in which conditions postponement performs better. Section 5 draws our conclusions and suggests the directions of future studies.

2. Literature Review

2.1 Postponement practice in supply chain

The concept of postponement has a long history not only in academic literature (Alderson, 1950; Bucklin, 1965), but also in practical applications (e.g. Brewer and Rosenzweig, 1961; Cox and Goodman, 1956); and it is considered one of the lean manufacturing best practices along with Just in Time and Kanban (Mistry, 2005; Wadhwa et al., 2006). Over the years researchers changed their perspective on postponement, understood once mainly as a strategy that changes the differentiation of goods in terms of their form, identity, and inventory location, to as late as possible. Nowadays postponement is perceived as an organizational concept whereby some of the supply chain activities are not executed until precise customer order information becomes available (van Hoek, 2001; Yang and Yang, 2010). Following this definition, different forms of postponement exist, including purchasing postponement, manufacturing postponement, assembly postponement, packaging/labelling postponement, logistic postponement, and the price postponement (Van Mieghem and Dada, 2001; Yang and Burns, 2003).

This study focuses on manufacturing postponement practice, which is, from an operational standpoint, a hybrid strategy between Make-To-Stock (MTS) and Make-To-Order (MTO) mode of production, i.e., a combined MTO/MTS system. In case of manufacturing postponement, in fact, a common product platform is firstly built to stock and then is differentiated, through customer-specific features, when demand is realized. Hence, manufacturing postponement occurs in two stages: (i) a MTS stage, where one or more undifferentiated platforms are produced and stocked; and (ii) a MTO stage, where

product differentiation takes place in response to specific customer orders (Forza et al., 2008; Gupta and Benjaafar, 2004; Lee, 2004; Swaminathan and Lee, 2003; Tang and Tomlin, 2008). The point in the production chain where MTO/MTS segregation occurs depends on the decoupling point (DP), defined as "the point that indicates how deeply the customer order penetrates into the goods flow" (Hoekstra and Romme, 1992). The DP separates elements in the production chain oriented towards activities for customer orders (MTO) from those based on forecasting and planning (MTS) (Van Donk, 2001).

Technically, manufacturing postponement is enabled by product modularity and process modularity (Gualandris and Kalchschmidt, 2013). Product modularity relies on standardizing some key components, or introducing parts commonality in the product structure. Process modularity is based on (1) process standardization, i.e., making some part of the process standard so that the different product variants share that process; (2) process re-sequencing, i.e., changing the sequence of customization steps in which the product attains distinct functionalities and characteristics; and (3) process postponement, i.e., postponing customization steps until a customer order is received.

Postponement carries several benefits, as largely reported by the literature that has extensively looked at postponement as a means to directly improve operational performance in terms of inventory order costs, delivery lead times, processing costs, transportation costs, quality conformance, service level (Johnson and Anderson, 2000; Lee and Whang, 1998; Pagh and Cooper, 1998). Such benefits are influenced by the operational configuration of postponement, specifically by the location of the DP. For example, more downwards the DP location, i.e. towards the MTO position, shorter the delivery time (van Donk, 2001).

More recent studies are investigating the effectiveness of the postponement strategy in mitigating supply chain risks and the conditions in which postponement performs better (e.g. Bulgak and Pawar, 2006; Cvsa and Gilbert, 2002; Gualandris and Kalchschmidt, 2013; 2015; Zheng and Mesghouni, 2011).

Literature on this topic is not without gaps. First, the existing studies assess the postponement benefits in terms of operational performance, but they neglect the benefits provided by the inner mechanism of postponement to change the product configuration at the last possible moment, thus giving the company the flexibility to quickly respond to sudden environmental changes and allowing managers to proactively manage uncertain events, which is the core of postponement. This area of research is crucial for supporting managers' decision-making process on the postponement adoption. In fact, while there are undoubtedly several benefits associated to postponement, it carries several additional costs, such as the additional investment for acquiring the appropriate technologies and related designing skills enabling that modularity (Baldwin and Clark, 2000; Mukhopadhyay and Setoputro, 2005; Sanchez and Mahoney, 1996). Therefore, a careful assessment of benefits, incorporating the postponement mechanism to alter the configuration of the product at the last possible moment according to uncertainty evolution, is needed before engaging in higher expenses.

Second, most of the existing studies dealing with the postponement as a risk mitigation strategy focus on the ability of postponement as a marketing strategy to cope with highly changeable demands, showing its benefits in terms of inventory cost, service level, compared to the performances of other production modes such as MTS or MTO (Ogawa and Piller, 2006). Other studies investigate the benefit of postponing ordering decisions to a later time point in order to improve demand forecast and reduce demand uncertainty (Choi et al., 2017), or to handle regular demand fluctuation under normal circumstances at companies such as Xilinx, Hewlett Packard, and Benetton (Tang, 2006b). Some real cases reveal the potentially of postponement to recover both demand and supply disruptions. When postponement is undertaken, in fact, even companies facing a relatively stable demand (e.g., open orders) are able to reconfigure the product quickly in the event of demand disruption, making it saleable to other customers. For example, in industries with rapid technological innovations, such as computer industry, companies adopting postponement can achieve responsiveness to changing requirements, thus rapidly recovering the shift of the demand towards new products. This is the case of Dell, which, under a postponement strategy, catches up with the

latest technological trends by quickly introducing new product lines as they are unencumbered by final goods inventories (Yang and Yang, 2010). At the same way, in case of disruption in the supply of a component, the company may deploy a contingency plan by quickly reconfiguring its generic product so that the reconfigured product could integrate a slightly different component from other available suppliers. For example, when the Philips's semiconductor plant in New Mexico was shut down for a fire, the postponement strategy enabled Nokia to respond immediately by reconfiguring the design of its basic cell phone so that the reconfigured generic phone could accept a slightly different component from other suppliers in the USA and Japan. Contrarily, Ericsson, lacking of a robust contingency plan for facing a disruption, reacted slowly to this disruption and lost hundreds of millions of euros in sales (Hopkins, 2005). Despite of the postponement adoption in practice to recover supply chain disruptions, to our knowledge, very few studies investigate the full implications of a postponement response in case of demand or supply disruptions. In particular, Yang and Yang (2010) explore the role of postponement in mitigating supply chain disruptions from a complexity perspective arguing that, before seeking to implement postponement to protect themselves against disruptions, companies should examine the degree of complexity they are adding through this protective measure. Tang (2006b) mentions the postponement as one of the robust strategies for mitigating supply chain disruptions, since it enables a firm to change the configurations of different products quickly after a major disruption.

Third, from the existing literature it is hard to derive rules for locating or changing the position of the DP on the base of the postponement response in case of supply or demand disruptions. Few attempts have been made in this direction. For example, van Donk (2001) proposes a theoretical framework for making MTO/MTS decisions and locating the DP. The framework builds on balancing the factors and characteristics of market and processes, such as predictability of demand, lead-time, delivery time, etc.. Wong et al. (2011) develop a numerical methodology for identifying possible locations of the DP. These studies, however, do not provide rules for locating or changing the DP position in presence of supply chain disruptions.

These gaps of the literature offer motivation for our work. With the aim of filling these gaps, we develop a model that investigates the value of postponement in coping with both supply and demand disruptions. Respect to the discussed gaps of the literature, the novel contribution of our study stands in:

- The development of a model that includes in the evaluation of the postponement benefits those due to the inner flexibility mechanism of postponement that allows for changing the product configuration at the last possible moment on the basis of the information available time to time. In other words, our model operationalizes the managerial flexibility in taking decisions about postponement. In fact, once such a strategy has been implemented (i.e., a flexible production system enabling delaying differentiation is created), the decision whether to differentiate the product or not when a disruption occurs is left to the manager, who assesses whether the product differentiation proves valuable based on information available at that time and decides accordingly. In so doing, we enhance the existing models that evaluate the benefits of postponement in terms of operational performance (Forza et al., 2008; Nair, 2005) without considering the managerial flexibility of postponement to react to supply chain disruptions. We adopt Real Option Valuation methods for modeling such managerial flexibility, as justified in the next section.
- The assessment of the value of postponement in coping with both supply and demand disruptions. By providing a model that quantitatively measures the ability of postponement in mitigating supply and demand disruptions, we advance the previous studies that have investigated postponement response to supply chain disruptions adopting qualitative approaches (Tang, 2006b; Yang and Yang, 2010).
- The modelling of postponement response to supply and demand disruptions by taking into account its configuration, defined by the DP position. Hence, we put forward the existing studies by investigating the position of the DP on the base of the postponement response to supply disruption. This allows us to analyze how the value of postponement as supply and

demand disruption mitigation strategy is influenced by the DP, so as deriving rules on DP location.

2.2 Real Option Valuation

Real option valuation (ROV) methods are based on the concept of real option (Dixit and Pindyck, 1995; Leslie and Michaels, 1997), which has its roots in the theory of financial options. A financial option is a contract that gives the holder the right (not the obligation) to buy (call option) or sell (put option) a predefined quantity of an underlying asset at a fixed price (exercise price), at or before the expiration date of the option (maturity). The holder (buyer) pays a price for this right (option premium). The call option will be exercised only if the value of the underlying asset is greater than the exercise price; otherwise, the option will never be exercised and will expire worthless. Oppositely, the put option will be exercised only if the value of the underlying asset is lower than the exercise price (Damodaran, 2001). A real option is – similarly to that of the financial market – an option on a "real asset" (Myers, 1984) that consists, in the context of this research, in the opportunity to take actions in the future, whenever they prove valuable, by paying a predefined cost to maintain such a right.

ROV methods have been widely used on project/asset valuations, to capture the potential value of the managerial flexibility (i.e. option) to expand, abandon, or contract a project, based on different statues realized during the process of the project in future. Compared to traditional techniques adopted for project/asset valuations, such as Net Present Value (NPV) or Cost-Benefit analysis, ROV methods are more suitable since they are able to capture the value of projects/assets when further options exist, whose exercise is not certain and depends on the evolution of uncertainty, but which come at a certain initial cost (Damodaran, 2001).

Common ROV applications include the valuation of projects in energy sector innovation and R&D projects, real estate development, competition and corporate strategies, among others. For overviews on the application areas of real option analysis, the interested readers can refer to Trigeorgis (1995)

and Smit and Trigeorgis (2012), just to mention a few; specifically, for applications in industrial engineering/production management contexts, we suggest to see Bengtsson (2001).

ROV is a powerful valuation/decision-making tool in supply chain management, where the flexibility of the management behavior or organizational and production systems is important to cope with the prominent risks occurring within the supply chain. The application of real option theory to the field of supply chain risk management is not new (Costantino and Pellegrino, 2010; Cucchiella and Gastaldi, 2006; Kamrad and Siddique, 2001; Nembhard et al., 2001; 2005). Studies have focused on some specific supply chain decisions, such as estimating the flexibility to select different suppliers plant locations (Nembhard et al., 2005), assessing the option value of outsourcing (Nembhard et al., 2003), valuing multiple sourcing versus single sourcing strategy (Costantino and Pellegrino, 2010). To the best of our knowledge, the existing literature does not record uses of ROV method for the valuation of postponement as a supply chain risk mitigation strategy.

Our research develops a ROV computational model to evaluate the real benefits created by the managerial flexibility of postponement to react to supply chain disruptions. We adopt a simulation-based approach as option pricing method, namely the Monte Carlo simulation (MCS), which is a powerful numerical method in option pricing theory for dealing with complicated cases since analytical methods are applicable in limited cases (Wei and Tang, 2015). MCS is particularly suitable to the reality we face in our problem. In fact, the circumstances surrounding the supply chain problem we are modelling require methods able to model several uncertainties of different types (not only price uncertainty but also technical, engineering uncertainty; e.g. disruption, availability of suppliers/customers, etc.), that need subjective and objective information. Furthermore, simulation-based approaches are simple, intuitive, and do not require the making of all the strict assumptions normally required, when stochastic processes are used, and can easily be used for almost any kind of decision situation (Collan et al., 2016).

3. The real options-based computational model of Postponement

Postponement gives a manufacturer the ability but not the necessity – the right not the obligation – to reconfigure the product depending on the resolved uncertainties along time. When postponement is undertaken, even companies that face a relatively stable demand coming from, for example, open orders with their main customers, are able to reconfigure the product quickly in the event of demand disruption, making it saleable to other customers. At the same way, in case of disruption in the supply of a component, the company may deploy a contingency plan by reconfiguring its generic product quickly so that the reconfigured generic product could integrate a slightly different component from other available suppliers (Tang, 2006b; Yang and Yang, 2010).

The manufacturer, therefore, has the option to use different components in case of supply disruption or to alter the product design making it suitable for other customers in case of demand disruption. Coherently with a rational behavior, the manufacturer will decide to reconfigure the product to cope with the disruption only when such a differentiation proves valuable. Otherwise, the option will expire worthless.

The decisional process associated to the postponement is, therefore, characterized by two key decisions. First, the decision of implementing such a strategy made at very beginning. This is the decision to have a flexible production system, which will eventually enable delaying differentiation. Such a decision, in turns, involves making decisions on how to operationally implement the postponement, namely define the point in the production chain where MTO/MTS segregation occurs (i.e., the decoupling point). The cost associated to the decision of implementing postponement is the sunk cost of creating the flexibility, i.e., the cost of creating standardization, commonality, and modularity. Once the flexible system has been implemented, the second key decision is about the postponement exercise, namely the decision to differentiate or not differentiate the product when a disruption occurs. Such a decision depends on the convenience of doing it, that is, on the value of the net benefits associated to the product differentiation measured on the basis of the information

available at that time. As such, the decisional process characterizing the postponement exercise when a disruption occurs can be described as a call option. At the time a disruption occurs, the postponement will be exercised on the base of the actual conditions operating at that time; such a decision will not affect the decision of exercising postponement to cope with a new disruption occurring in next periods[1]. Hence, if more than one disruption occurs during the considered time horizon, the decisional process becomes a set of sequential independent call options. In analogy to financial options, the switching cost, measured by time or cost required to differentiate the product, is the exercise price K of the option, while the net benefits created by this differentiation are the stock price S_T. At each decisional time t, the (call) option will be exercised only if these net benefits S_T overcome the exercise price K, and the associated payoff is $\max(S_T - K,0)$. The value created by all these options is the sum of these payoffs throughout the time horizon considered, net of the initial cost of creating the flexible production system.

In this section, we present the ROV model for evaluating postponement when a hypothetic firm has to manage a supply and/or a demand shortage due to a supply/demand disruption. The ROV model reflects some commonly occurring supply chain configurations where postponement is adopted. It is deliberately kept simple so that the results of selected experiments may support some generalizations in mitigating supply chain disruptions through postponement. At the same time, the simplicity and ease of implementation of the model make it useful for operations managers who are called to make decisions on the postponement adoption when facing supply chain disruptions.

Specifically, as depicted in Figure 1, the model considers a three stages supply chain consisting of: the supplier stage, the manufacturer, and the client stage.

[Insert Figure 1]

[1] For example, in the apparel and fashion industries, the postponement can be done by cutting and potentially even sewing fabrics according to garment specifications, but delaying any additional activities that add details to the garment so as customizing its visual appeal. Hence, when a disruption of the main customer occurs, the decision to finish the design to accommodate the requirements of another customer will not affect the decision of exercising postponement in the next to deal with new disruptions. This is because of the fact that postponement allows apparel manufacturers to operate with pre-customized products to be later customized as per new customer requirements (Chaudhry and Hodge, 2012).

For the sake of simplicity, we have considered the supplier stage as consisting of the preferential supplier and all the other suppliers that do not have a preferential relationship with the manufacturer, namely the non-preferential suppliers. Modelling all the non-preferential suppliers as a whole is a realistic assumption in contexts where the manufacturer has a preferential relationship with one supplier, as for example in the case of a single sourcing strategy, and it is reasonable to assume a prevailing behavior of all the other suppliers, for example, in terms of average price, reliability, quality, etc. (Cox, 2001; Li, 2002). Similarly, we have considered the client stage as consisting of the preferential client and all the non-preferential clients modelled as a whole. The non-preferential suppliers and non-preferential clients represent the supply and demand markets, where the manufacturer sources and/or sells in alternative to the preferential supplier/client in case of disruption. Two different scenarios of supply chain disruption may happen: 1) supply disruption and 2) demand disruption.

Notice that the number of supply chain stages does not obviously correspond to a real supply chain, but this modeling choice coheres with the common approach used in the supply chain management literature to study supply chain dynamics (Cakravastia et al., 2002; Hishamuddin et al., 2014; Lee et al., 2000; Thomas and Griffin, 1996), although there are few studies that consider multi-stage supply chain network (Goh et al., 2007). Three supply chain stages permit representation of the main supply chain dynamics even if the destabilizing effects, due to the existence of multiple supply chain stages, cannot be taken into account (Albino et al., 2007).

3.1 Supply disruption

Let us assume that during a total time of T months the manufacturer expects a periodical demand d every N months, for a total demand in T equal to $D = n \cdot d$, where $n = T/N$. Accordingly, in T, the manufacturer places an open order Q ($Q = D$) to his/her preferential supplier. Over T, the open order is split in n periodical reorders of an amount equal to q (Q/n).

Let p_f be the price of the final product, c_A be the unit cost of purchasing from the preferential supplier, and c_m be the unit variable manufacturing cost.

At each order time j=1,…n, the model considers whether there is a supply disruption. The supply disruption can be due to a "global" default in the supply market or a supply shortage by the preferential supplier.

The global default in the supply market is modeled with a dummy variable (ω_j), which assumes value 1 (i.e., global default) with a very low probability p_ω and value 0 (no global default) with a probability (1-p_ω). The global default may cover m scheduled orders, where m is a random variable following a discrete geometric distribution (Eq. 1), since we assume that the probability that a global default by all the suppliers covers longer period is generally lower than the probability that a global default lasts for a while.

$$P(m) = k(1- k)^{m-1} \quad (1)$$

When the entire sector/market has a default (e.g., a sector strike that blocks the delivery of the considered product from all the suppliers), the manufacturer cannot receive the quantity q for the next m scheduled orders and, consequently, cannot exploit postponement.

As for the supply shortage by the preferential supplier, it can be partial or total, and the share of total quantity expected in each order q that is disrupted is α_j, where $\alpha_j \in [0,1]$. Therefore, $\alpha_j \cdot q$ is the supply shortage in each order, while $(1-\alpha_j)\cdot q$ is the quantity actually supplied from the preferential supplier in each order.

The shares of total disrupted quantity α_j is a random variable with an exponential probability distribution with parameter λ_1, since we assume that the probability that the preferential supplier defaults on a small quantity is high, whereas the probability of a total disruption is low. λ_1 measures the buyer's expectation of the preferential supplier reliability: when λ_1 is high the buyer expects to have more frequent small defaults than big ones, while when λ_1 is low the buyer expects to have the

same probability of small and big defaults. In other words, the higher the value of λ_1, the higher the reliability of the supplier.

$$f(x) = \lambda_1 e^{-\lambda_1 x} \tag{2}$$

If this occurs, the model estimates the disrupted quantity $\alpha_j \cdot q$. Postponement enables the manufacturer to turn to the supply market (i.e., switch supplier) and ask for the shortage so as continuing to produce and sell the quantity *d.* The alternative is to decrease the production and sale by the amount $\alpha_j \cdot q$, paying a unit penalty c_p on the unsatisfied demand.

Let $\delta_j \in [0,1]$ be the share of the disrupted quantity $\alpha_j \cdot q$ which is supplied by non-preferential suppliers (i.e., supply market) at a unit cost $c_B(j)$, that is the prevailing price given by the supply market at the time j and is normally uncertain. δ_j is assumed variable according to an exponential probability distribution function with parameter λ_2, since it is expected that the probability that supply market is able to suddenly respond to the requirements is higher when the required quantity is lower. We assume that the probability distributions of the random variables δ_j and α_j are correlated by a Pearson coefficient r, in order to take into account the fact that when the share of the disrupted quantity $\alpha_j \cdot q$ by the preferential supplier increases it is more difficult to find all the required quantity in the market. Therefore, there is a negative correlation between the two variables: the higher the supply shortage by the preferential supplier the lower the share provided by the supply market.

The quantity supplied by non-preferential suppliers is also influenced by the position of the DP. Positioning the DP downward (towards a MTS configuration) entails producing a more defined semi-finished product with less elements of flexibility, and hence reduces the possibility to find compatible alternative supplies in the supply market. *Vice-versa*, a more upward DP shifts the differentiation point at the beginning of the production chain (towards a MTO configuration), where the product is configured from the outset, that is, from raw materials, and just a small amount of the whole

production cost is sustained up to the differentiation point (van Donk, 2001). This configuration increases the possibility to find alternative suppliers able to supply the required quantity.

In order to consider such effect, given that the amount of the production cost sustained until the differentiation point denotes the position of the DP, higher is the cost more downward is the DP, we assume that the quantity that can be potentially supplied by the supply market $\delta_j \cdot \alpha_j q$ decreases by a share μ_j that is directly proportional to the share of the cost of production sustained until the differentiation point. In formula:

$$\mu_j \propto \frac{\text{production cost until the differentiation point}}{\text{total production cost}} \tag{3}$$

According to the actual costs and benefits, the model assesses whether it is really advantageous to exploit postponement and exercise the option of differentiating the product.

The option will be exercised only if its benefits overcome the costs. Operationally, the model considers the difference between the net actual benefits of exercising the option (*Sj*) and the exercise price (*K*), due to the switching costs that are sustained to adjust the production mode immediately when the disruption occurs, and calculates the payoff. Of course, if there is an overall default of suppliers in the industry (that is, the dummy variable ω in the model is 1), the exercise of the option (i.e., the exploitation of the postponement strategy though product differentiation) is not possible since no suppliers can deliver the required amount:

$$max\{[(p_f - c_B(j) - c_m) \cdot \delta_j \cdot \alpha_j q \cdot (1 - \mu_j) + c_p \cdot \delta_j \cdot \alpha_j q \cdot (1 - \mu_j) - K] \cdot (1 - \omega_j); 0\} \tag{4}$$

with j=1,2…n

The postponement value is the sum of the payoffs due to the exercise the option at each time j (with j = 1, 2..., n) net of the fixed cost associated to the implementation of postponement (C_S), discounted with an annual discount rate i, as follows:

$$Postponement\_value = \sum_{j=1}^{n} \frac{[(p_f - c_B(j) - c_m)\cdot\delta_j\cdot\alpha_j q\cdot(1-\mu_j) + c_p\cdot\delta_j\cdot\alpha_j q\cdot(1-\mu_j) - K]\cdot(1-\omega_j)\cdot Opt_j^1}{(1-i_p)^j} - C_S \quad (5)$$

Where:

- i_p is the discount rate that depends on the length of the time interval between orders;

- Opt_j^1 is a dummy variable indicating whether the option is exercised (Opt_j^1 =1) or not (Opt_j^1 =0) according to the payoff computed by equation 3.

The definition of the discount rate is an open issue in the real options literature. The main concern is that in real option valuation the decision on exercising the option changes the risk profile of the project. Since the discount rate takes into account the project risk, it should change accordingly. The definition of the 'new' discount rate is not an easy issue. However, Monte Carlo simulation has the advantage of taking into consideration risks and uncertainties in the probability distribution definition. Thus, when Monte Carlo simulation is used, the appropriate discount rate is risk free (Brealey and Myers, 2000), otherwise risk is counted twice because it is already included in the cash flows that depend on the randomly chosen values of the input parameters. The risk-free discount rate can be taken as the interest rate on government bonds (Carbonara et al., 2014).

Flowchart in Figure 2 depicts the managerial decision-making process in the first scenario (supply disruption).

[Insert Figure 2]

As reflected in Eq. (5) the cash flows associated to postponement strongly depends on the occurrence of a disruption as well as on other connected events. In fact, if the disruption does not occur (α_j =0), the postponement does not provide any additional benefits, but produces only the sunk cost for implementing such flexibility (C_S). When the disruption occurs ($\alpha_j \neq 0$), the advantages created by

the postponement depend on the ability of the supply market to suddenly respond to the requirements (δ_j).

3.2 Demand disruption

Let us assume that every N months the manufacturer expects to receive a demand d of the final product and, accordingly, places an order of q to produce a fixed production volume ($q=d$). Let $p_A(j)$ be the stochastic price of the final product charged to the preferential client, c_A is the unit cost of purchasing, and c_m is the unit variable manufacturing cost. At each order time j, it can be a disruption of the demand d by the preferential client. The share of the demand that is disrupted is β_j, where β_j Є[0,1]. Hence, the demand shortage in each time j is $\beta_j \cdot d$, while $(1-\beta_j)\cdot d$ is the quantity actually purchased by the preferential client. The share of total disrupted demand β_j is modelled as a random variable with an exponential probability distribution with parameter λ_3, since we assume that the probability that the preferential client defaults on a small quantity is high, whereas the probability of a total disruption is low. Therefore, λ_3 measures the manufacturer's expectation on the preferential client demand stability (the higher λ_3, the higher the stability of the preferential client).

In case of demand disruption, postponement enables the manufacturer to customize and differentiate the products so as react to the demand shortage and offer to other non-preferential clients, forming the potential market, the quantity not purchased by the preferential client. The alternative is to hold the unsold products in stock bearing an inventory cost per unit c_i. Let $p_B(j)$ be the price expressed the market (non-preferential clients) at the time of the transaction j, that is uncertain and fluctuates around an average value, and γ_j Є[0,1] be the share of the total disrupted demand $\beta_j \cdot d$ sold to the non-preferential clients. γ_j is assumed variable according to an exponential probability distribution function with parameter λ_4, since it is expected that the probability that the market is able to absorb the offer is higher when the exceeded quantity is lower. We assume that the probability distributions of the random variables γ_j and β_j are correlated by a Pearson coefficient r_1, in order to take into account the fact that when the share of the total disrupted demand $\beta_j \cdot d$ by the preferential client increases, it

is more difficult to sell all the exceed quantity to the market. Therefore there is a negative correlation between the two variables: the higher the disrupted demand by the preferential client the lower the capability of the market to take on all the exceeded quantity.

The quantity absorbed by the market is also influenced by the position of the DP. A more upward decoupling point shifts the differentiation point at the beginning of the production chain (towards a MTO configuration), where the product is configured from the outset, that is, from raw materials. This configuration, in turn, increases the lead-time and, therefore, reduces the quantity absorbed by the share of the market that is not willing to accept long lead-times (van Donk, 2001). *Vice-versa*, locating the decoupling point downwards (towards a MTS configuration) reduces the lead-time and increases the possibility to find more customers willing to accept such a short lead-time.

In order to consider such effect, given that the lead-time denotes the position of the DP, higher is the lead-time more upward is the DP, we assume that the quantity of demand that can be potentially sold to the market $d \cdot \beta_j \cdot \gamma_j$ decreases by a share ε_j that is directly proportional to the lead-time (T_{LT}), which, depends on the DP position. In formula:

$$\varepsilon_j \propto \frac{T_{LT}}{12} \tag{6}$$

According to the actual costs and benefits the model assesses whether it is really advantageous to exploit postponement (i.e., differentiate the product) and exercise the option.

The option will be exercised only if its benefits overcome the costs, according to the following equation:

$$max\left[(p_B(j) - c_A - c_m) \cdot d \cdot \beta_j \cdot \gamma_j \cdot (1 - \varepsilon_j) + c_i \cdot d \cdot \beta_j \cdot \gamma_j \cdot (1 - \varepsilon_j) - K; 0\right] \tag{7}$$

with j=1,2…n

Where K is the switching costs that are sustained to adjust the production mode immediately when the disruption occurs.

The postponement value is the sum of the differential benefits due to the exercise the option at each time j (with $j = 1, 2,..., n$) compared with the case of no postponement, net of the fixed cost associated to the implementation of postponement (C_S), discounted with an annual discount rate i. The differential benefits of postponement are operatively calculated by taking into account that postponement affects the inventory level. In fact, since the manufacturer has the flexibility to sell the share of the production volume not purchased by the preferential client, postponement allows for a potential reduction of the inventory level I_j at each time j by a quantity $d \cdot \beta_j \cdot \gamma_j \cdot (1 - \varepsilon_j)$, as computed by the following equation:

$$I_j^P = I_{j-1}^P + d \cdot \beta_j \cdot \left[1 - \gamma_j \cdot Opt_j^2 \cdot (1 - \varepsilon_j)\right] \qquad \text{with } I_0=0 \tag{8}$$

Where Opt^2_j is a dummy variable indicating whether the option is exercised ($Opt^2_j = 1$) or not ($Opt^2_j = 0$), according to the payoff computed by equation 7.

Contrarily, without postponement strategy the level of inventory would be:

$$I_j = I_{j-1} + d \cdot \beta_j \qquad \text{with } I_0=0 \tag{9}$$

Hence, the postponement value is computed by the following:

$$Postponement\_value = \sum_{j=1}^{n} \frac{\left[(p_B(j) - c_A - c_m) \cdot \gamma_j \cdot \beta_j \cdot d \cdot (1 - \varepsilon_j) + c_i\left(I_j - I_j^{PP}\right) - K\right] \cdot Opt_j^2}{(1 - i_p)^j} - C_S \tag{10}$$

Where i_p is the discount rate that depends on the length of the time interval between orders. As discussed in the previous section, the appropriate discount rate is risk free (Brealey and Myers, 2000). Flowchart in Figure 3 depicts the managerial decision-making process in the second scenario (demand disruption).

[Insert Figure 3]

As reflected in Eq. (10) the cash flows associated to postponement strongly depends on the occurrence of a disruption as well as on other connected events. In fact, if the disruption does not occur (β_j =0), the postponement does not provide any additional benefits, but produces only the sunk cost for implementing such flexibility. When the disruption occurs ($\beta_j \neq 0$), the advantages created by the postponement depend on the ability of the market to absorb the excess capacity (γ_j and ε_j).

4. Numerical experiments

Numerical experiments are carried out in order to investigate the value of postponement in mitigating supply chain disruptions and in which conditions postponement performs better.

We begin by examining a basic setting and then we focus attention on the effects of changing values of input parameters. An overview of the basic parameter settings can be found in Table 1, where values for deterministic and probabilistic input variables are reported.

[Insert Table 1]

As shown in Table 1, we have assumed that the unit cost of purchasing from the not preferential suppliers c_B, final product price charged to the preferential buyer p_A, and the price applied to the differentiated and customized final product sold to the no-preferential buyer p_B will vary stochastically in time following a Mean Reverting (MR) process. This assumption reflects the real behavior of such prices/costs that can vary but gravitate towards a "normal" equilibrium level that is usually governed by the cost of production and the level of demand (Haksöz and Seshadri, 2007; Seifert et al., 2004). Thus, if the price/cost is above the mean, the price/cost goes down, while if the price/cost is below the mean, the price/cost raises. Notice that the Mean reverting process overcomes the limitation of the Geometric Brownian motion (GBM) in modeling the stochastic price process as a “random walk”. In fact, the ‘random walk’ used to model prices under GBM is based on the assumption that price changes are independent of one another. In other words, the historical path the

price followed to achieve its current price is irrelevant for predicting the future price path (prices follow a Markov process). Mean reversion can be thought of as a modification of the random walk, where price changes are not completely independent of one another but rather are related. Mathematically, the stochastic evolution of a variable that follows a mean reverting process can be modeled in each period *j* as a function of the value in previous period according to the following equation:

$$s_{j+1} - s_j = \alpha (s^* - s_j) + \sigma\varepsilon_j \tag{11}$$

Where:

- s^* is the mean reversion level or long run equilibrium price
- s_j is the spot price
- α is the mean reversion rate
- σ is the volatility;
- ε is the random shock to price from *t* to *t+1*

The parameters, long run mean (s^*) and volatility (σ), for each variable modelled as MR, have been derived by using historical series of monthly data.

A Monte Carlo simulation with 10.000 trials was done. The model was implemented on a spreadsheet and the Crystal Ball software was used to run the simulation.

4.1 Results and discussion

The results of the numerical example are presented in this section. Results obtained by running the basic setting are reported in Figures 4a and 4b, where the probabilistic net differential benefits of implementing postponement as strategy to mitigate a supply disruption and a demand disruption are depicted, respectively.

[Insert Figures 4]

Figure 4a shows that the net differential benefit of the postponement strategy in the case of supply disruption is positive with a probability of about 40%. In other words, in 40 out of 100 cases the postponement strategy is advantageous, and is able to create value for the manufacturer.

The postponement value ranges between a minimum of -€ 15,000 and a maximum of € 176,888. The lower bound corresponds to the situation where postponement is not exercised (i.e., no differentiation of the product during the time horizon), thus no benefits are gained and only the sunk costs are borne.

Figure 4b shows that net differential benefits of the postponement strategy in the case of demand disruption is positive with a probability of about 70%. In other words, in 70 out of 100 cases the postponement strategy is advantageous and creates a value for the manufacturer. The median of the distribution is € 13,235, i.e., with a probability of 50%, the net benefits of postponement are higher than € 13,235, up to a maximum value of € 427,741.

Even in the case of demand disruptions the lower bound of the distribution corresponds to the value of the postponement strategy cost (*Cs*), thus confirming that the maximum loss by the manufacturer when all the things go wrong is the cost due to the implementation of the strategy.

The statistics of both distributions depend on the specific input data adopted for the simulation. However, besides these specific values, results show the value of postponement in mitigating supply and demand disruptions, thus providing answers to the first two research questions.

These results not only confirm the recent literature insights on the potential value of postponement in mitigating supply chain disruptions but also suggest more robust indications on this issue by extending the existing literature. Our findings, in fact, are based on the quantitative assessment of the value of postponement in mitigating supply chain disruptions that takes into account the value of the managerial flexibility of deciding whether exercising postponement when a disruption occurs or not, that is, from an operational point of view, deciding whether to differentiate the product or not.

In order to investigate how the operational configuration of postponement, namely the decoupling point position, and external conditions, namely the riskiness of the environment, affect the

postponement performance, so as responding to the third research question, a sensitivity analysis is conducted to identify the impact that possible variations of the input parameters have on the postponement value.

To address this issue, we conduct the following numerical experiments by setting different values of parameters ε_j, μ_j, λ_1, λ_2, λ_3, λ_4, p_ω, r and r_1 and by assuming as basic setting the previous scenario.

The analysis on the parameters ε_j and μ_j allows measuring how the DP position affects the postponement performance in mitigating demand and supply disruptions. In particular, we conduct a sensitivity analysis by changing the value of the parameter ε_j from 0, which is the value assumed in the basic setting, up to 0.9. Increasing the ε_j value means increasing the lead-time that in turn lowers the possibility to find customers willing to accept products with long lead-times. We found that the value of postponement in mitigating demand disruptions decreases when ε_j increases, in terms of either mean value or probability of being positive (Table 2). This implies that positioning the decoupling point upwards (towards a MTO configuration) reduces the value of postponement as demand disruption mitigation strategy: the drawback of postponement, namely longer lead-times, prevails on its capability to make production chains more responsive to changeable customer requirements. This is exacerbated when the alternative market is characterized by a time-sensitive demand, as for the case of perishable products which cannot be profitable after a certain day (Leung and Ng, 2007) or short lifecycle products (Chaudhry and Hodge, 2012).

[Insert Table 2]

We perform a sensitivity analysis by changing the value of μ_j, starting from μ_j= 0.1 up to μ_j = 0.9. The increase of the parameter μ_j stands for a shift of the decoupling point towards a MTS configuration (downwards). We found that when μ_j increases, the value of postponement in mitigating supply disruption decreases, both in terms of its mean and its probability of being positive (Table 2). This finding implies that locating the decoupling point downwards reduces the value of postponement as supply disruption mitigation strategy: in such configuration of the production chain, towards a MTS

configuration, the product is so well-defined that is not possible to use alternative components when a supply disruption by the main supplier occurs.

Beyond the specific numerical outcomes resulting from the sensitivity analysis on ε_j and μ_j, it is worth to compare the different performance of postponement in mitigating demand and supply disruptions when the DP position changes. As shown by Figure 5 (where the trends of the postponement value respect to the DP position are depicted), the performance of postponement in mitigating supply disruption is positive when μ_j is low and only for a small range of μ_j. This means that in case of supply disruption the postponement delivers value only when the DP position is pulled towards a MTO configuration. *Vice-versa* in case of demand disruption the value of postponement is positive for a wide range of ε_j, thus giving a higher degree of freedom in deciding about the DP position.

[Insert Figure 5]

To sum up, the findings of the sensitivity analysis on ε_j and μ_j reveal that the decision on the DP location is crucial to maximize the performance of postponement as mitigation strategy of supply and demand disruptions. Figure 5 suggests that such a decision should be based on the trade-off between the benefits of postponement in mitigating supply and demand disruptions and should be driven by the need of the company to protect itself against a demand or supply disruption, where such a need depends on the characteristics of the context in which the company operates. For instance, in a market with high obsolescence risks, typical of industries with rapid technological innovations, as computer industry, the concern about the demand disruption prevails over that one about the supply disruption, hence the decision should be to postpone the decoupling point as late as possible and customize the product when the orders are "pulled" by the customers (Naim et al., 1999).

The analysis on the parameters λ_1 and λ_2 allows us to measure the sensitivity of the postponement value to changes of the preferential supplier's reliability and the supply market's capacity to respond to the manufacturer's requirement, respectively.

The variation of the parameter p_ω lets us measure the impact that the global default by the entire sector may have on the postponement value, when its probability of occurrence changes.

Results shown in Figure 6 (a and b) report the effect that the variation of the parameters λ_1, λ_2, and p_ω, respect to the base case, has on the postponement value, in terms of variation of the mean value and the probability of being positive, respect to the base case. For example, Figure 6b depicts that a variation of the 20% of λ_1 determines a -30% variation of the probability that the postponement value is positive.

[Insert Figure 6]

The figures show that the reliability of the main supplier and the availability of the supply market seem to have the same impact on the value of postponement, either in terms of mean value created by the strategy (Figure 6a) or in terms of probability of being positive (Figure 6b). Actually, it is important to specify that the meaning of these two parameters (λ_1 and λ_2), and therefore their impacts, is different.

Two main managerial implications can be drawn from this analysis. As a first implication, results highlight that postponement is a valid strategy for mitigating the supply disruption due to the preferred supplier: when λ_1 decreases (the preferred supplier is less reliable), the value of the strategy increases very rapidly. Vice versa, where suppliers are more reliable and, accordingly, λ_1 is higher, the postponement loses its value in mitigating supply disruptions. This observation is intuitive, since the higher riskiness of the supply context, the higher value of postponement. This finding is consistent with the nascent literature proposing postponement as supply disruption mitigation strategy.

The other less intuitive observation is that when λ_2 decreases the postponement value increases. This means that the postponement strategy creates more benefits when the supply market delivers with the same probability high and small shares of the manufacturer's requirements (i.e., lower values of λ_2). On the contrary, when λ_2 increases there is higher probability that the supply market delivers small shares of the requirement than high shares, thus the strategy value decreases and it becomes no more convenient. A possible explanation of this result is: when markets have less capacity to fulfill the entire requirements, but only small shares, as may be the case of oversaturated markets, the postponement proves less valuable in mitigating supply disruptions. Oppositely, the value of

postponement increases when markets are able to fulfill either small or high shares of the requirements, as may be the case of supply industry with low product differentiation, low concentration, and large number of suppliers.

The sensitivity analysis on the parameter p_ω (that is, the probability of the global default by the entire sector) shows that when p_ω ranges in an interval of low values, the postponement strategy value does not vary so much. However, letting p_ω span within the entire definition interval (0, 1) we found that both the mean of postponement value and the probability of being positive decrease, showing that postponement strategy is not a way for hedging the disruption risks when the supply system collapses, as Figure 7 depicts. A possible explanation is: when a global default happens all suppliers are unable to fulfill the manufacturer's requirements. This means that postponement strategy is not the optimal "contingency plan" for mitigating catastrophic risks that put all suppliers down simultaneously.

[Insert Figure 7]

In case of demand disruption, the sensitivity analysis on the parameters λ_3 and λ_4 allows us to measure how postponement value changes when the preferential client's demand stability and the capacity of the market to absorb the offer change, respectively. The results of the sensitivity analysis are shown in Figure 8 (a and b), which depicts the effect that the variation of the parameters λ_3 and λ_4, respect to the base case, has on the postponement value, in terms of variation of the mean value and the probability of being positive, respect to the base case. For example, Figure 8a shows that a variation of the 20% of λ_3 determines a -50% variation of the mean value of the postponement. The figures highlight that the variations of both the preferential client demand stability (measured by λ_3) and the capacity of the market to absorb the offer (measured by λ_4) have the same impact on the value of the postponement strategy, either in terms of mean value created by the strategy or in terms of probability of its value being positive, although the meaning of these two parameters (λ_3 and λ_4), and therefore their impacts, is different.

Two main managerial implications can be drawn from this analysis. As a first implication, results highlight that postponement is a valid strategy for mitigating the demand risk: when λ_3 decreases the

value of the strategy quickly increases. On the contrary, when client demand is more stable and, accordingly, λ_3 is higher, the postponement loses its value in mitigating risks. This observation is intuitive, since the higher demand risk, the higher value of postponement. The finding is in line with the insights provided by previous research on this subject, proposing the postponement as a valid strategy to cope with demand disruption.

[Insert Figure 8]

Another observation is that when λ_4 decreases the postponement value increases. This means that markets characterized by higher capacity to absorb with the same probability high and small shares of the disrupted demand (i.e., lower values of λ_4) make postponement more valuable in demand risk mitigation. In contrast, when there is higher probability that the market absorbs small shares of the disrupted demand than high shares (i.e., higher values of λ_4), the strategy value decreases.

A possible explanation of this result is: when markets are able to absorb either small or high shares of the offer, as may be the case of sectors with excess demand, the postponement proves more valuable in mitigating demand disruptions. Oppositely, the value of postponement decreases when markets are less able to absorb the entire offers, as may be the case of sectors with declining demand, high clients' price sensitivity and/or small size of clients.

The analysis on the parameters r and r_1 allows us to measure the effect that the correlation between the preferential supplier disruption (α_j) and the supply market capacity (δ_j), as well the correlation between the preferential client disruption (β_j) and the market absorptive capacity (γ_j), has on the postponement value.

We conduct the analysis considering two values of r and r_1, namely -0.2 and -0.8, which stand for a weak and strong negative correlation, respectively. Strong correlation means that higher is the supply/demand shortage by the preferential supplier/client lower is the share provided by the supply market or absorbed by the market, weak correlation represents the opposite case. Results reported in Table 3 show that in case of strong negative correlation, the value of postponement in mitigating supply and demand disruptions is negative. This means that the postponement loses its value in

mitigating supply disruption when, in the face of a given amount of the supply shortage by the preferential supplier, it is more and more difficult to find all the required quantity in the market. It can be the case of supply industry with high product customization or exclusive and dedicated buyer-supplier relationships.

5. Conclusions

The paper provides a ROV computational model for assessing the value of postponement as strategy for mitigating supply chain disruptions for a three stages supply chain.

The novelty of our model lies in assessing the value of postponement in mitigating both demand and supply disruptions by taking into account the value of the managerial flexibility to decide whether exploiting or not the strategy if and when disruptions occur, and whenever product differentiation proves valuable based on information available at that time.

The paper offers three main contributions to the literature on postponement. First, we fill the gap of the literature that, focusing on the postponement advantages in terms of operational performance (such as inventory order costs and delivery lead times), lacks of models assessing the value of the flexibility to reconfigure the product to quickly respond to sudden environmental changes, as in case of supply chain disruptions. Second, we assess the postponement value considering the implications of a postponement response not only in case of demand disruptions, but also in case of disruptions in supply of a component, issue that is not exhaustively elaborated by the existing studies. Third, we develop a model that can be used to better implement the postponement strategy from an operational perspective (DP location), thus contributing to the literature by which it is not possible to derive rules for locating or changing the DP position in presence of supply disruption. We confirm the value of postponement in mitigating demand disruptions, in line with the insights provided by the previous research. We also enrich the existing literature by founding how and to what extent certain operational configurations of postponement, namely the position of the decoupling point, and the external

conditions, namely the riskiness of the environment, might undermine the value of postponement in mitigating demand disruptions. Furthermore, we enrich the nascent literature proposing postponement as a supply disruption mitigation strategy by investigating the full implications of a postponement response in case of supply disruption under different operational and external conditions. As significant insight, we found that the performance of postponement in mitigating supply disruptions is strongly related to the DP position.

Our research has also practical consequences. Addressing the target audience embracing all industries and production systems characterized by product and process features enabling postponement, namely, product and process decouplability, standardization, and modularity, product customization, and product and process redesign, we provide a model that supports managers' decision-making process on the postponement adoption. The application of the model via numerical experiments show the importance of incorporating an option valuation method when pricing the value of postponement. This ensures managers implement postponement only when it is valuable, thus avoiding burdening the company with its initial sunk costs. For our target industries, such as the textile and apparel, consumer electronics, and medical devices industries, by analyzing the postponement implementation under different conditions, we identify the operational configurations, in terms of DP position, and external conditions, in terms of riskiness of the environment, which make the postponement an effective supply chain disruption mitigation strategy. In particular, we found that the decision on the DP location is crucial to maximize the performance of postponement, since positioning the DP more upward or downward along the production chain has opposite effects on the ability of postponement in mitigating supply and demand disruptions.

Furthermore, we have shown that postponement reveals more valuable in more risky contexts, where the likelihood of supply and demand disruptions increases. However, as another remarkable result, we found that postponement value as supply chain disruptions mitigation strategy depends not only on the probability of having a disruption, but also on the characteristics of the supply chain and, specifically, on the upstream and downstream echelons.

For further research, one may consider a new complex scenario that envisages the possibility to have simultaneously supply and demand disruptions and a more complex network of supply chain players. This paper considers only two suppliers and two demand markets, reflecting the situation where a prevailing behavior characterizes the supplier and demand market. A more complex model could be developed by considering a number of actors, either in the upstream and in the downstream stage, that show different behaviors in terms of price, reliability, and capacity to fulfill the manufacturer's requirements or to absorb the manufacturer's offer. Such a model will be used to analyze situations where the decision to exercise the postponement is made by taking into account that the supply shortage may be fulfilled by fragmenting the manufacturer's order on more than one supplier at different costs and conditions, and the demand shortage may be absorbed by more than one client at different prices and conditions. Such situations may affect the postponement value and need future explorations. New insights about the postponement application as supply chain disruption mitigation strategy will be derived for those markets characterized by not-homogeneous behaviors of suppliers and clients.

Furthermore, one may find challenging to implement the model in the target manufacturing systems, because of difficulties in the estimation of some input parameters when historical data lack. Such a constraint could be overcome by using experts' judgments. Finally, it would be interesting the model application to a real case. This is an important step ahead for our study and we relegate it to future research.

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Figure 1. Three stages supply chain model and related disruption scenarios.

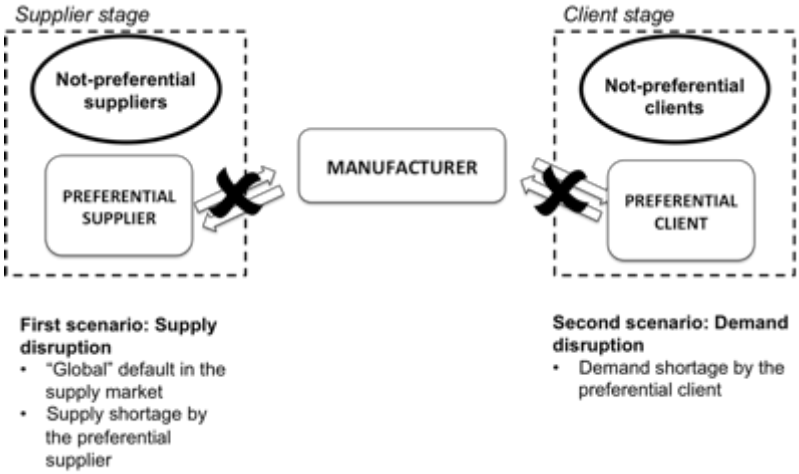


Figure 2. Decision-making process for exercising options in supply risk scenario

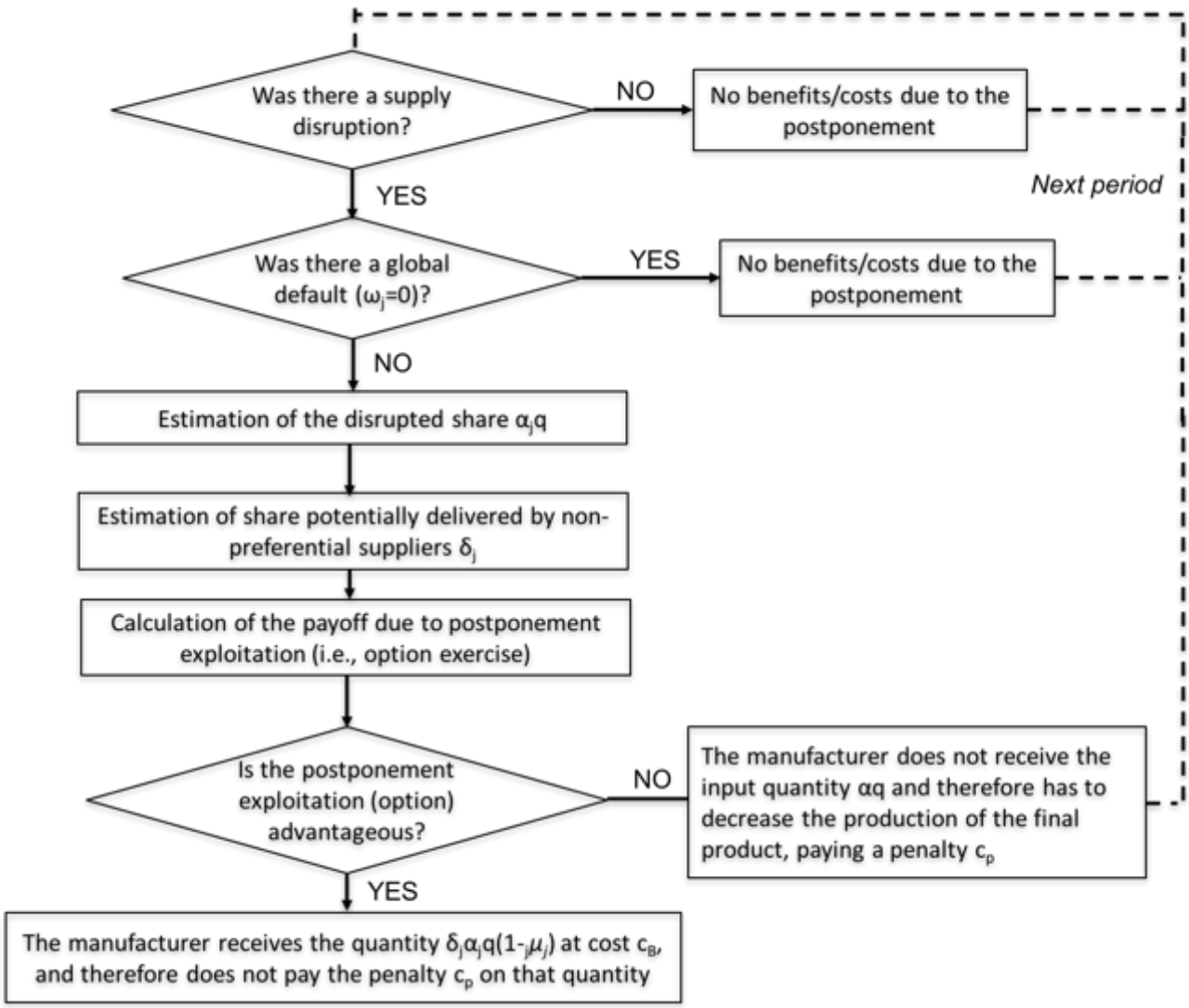


Figure 3. Decision-making process for exercising options in demand risk scenario.

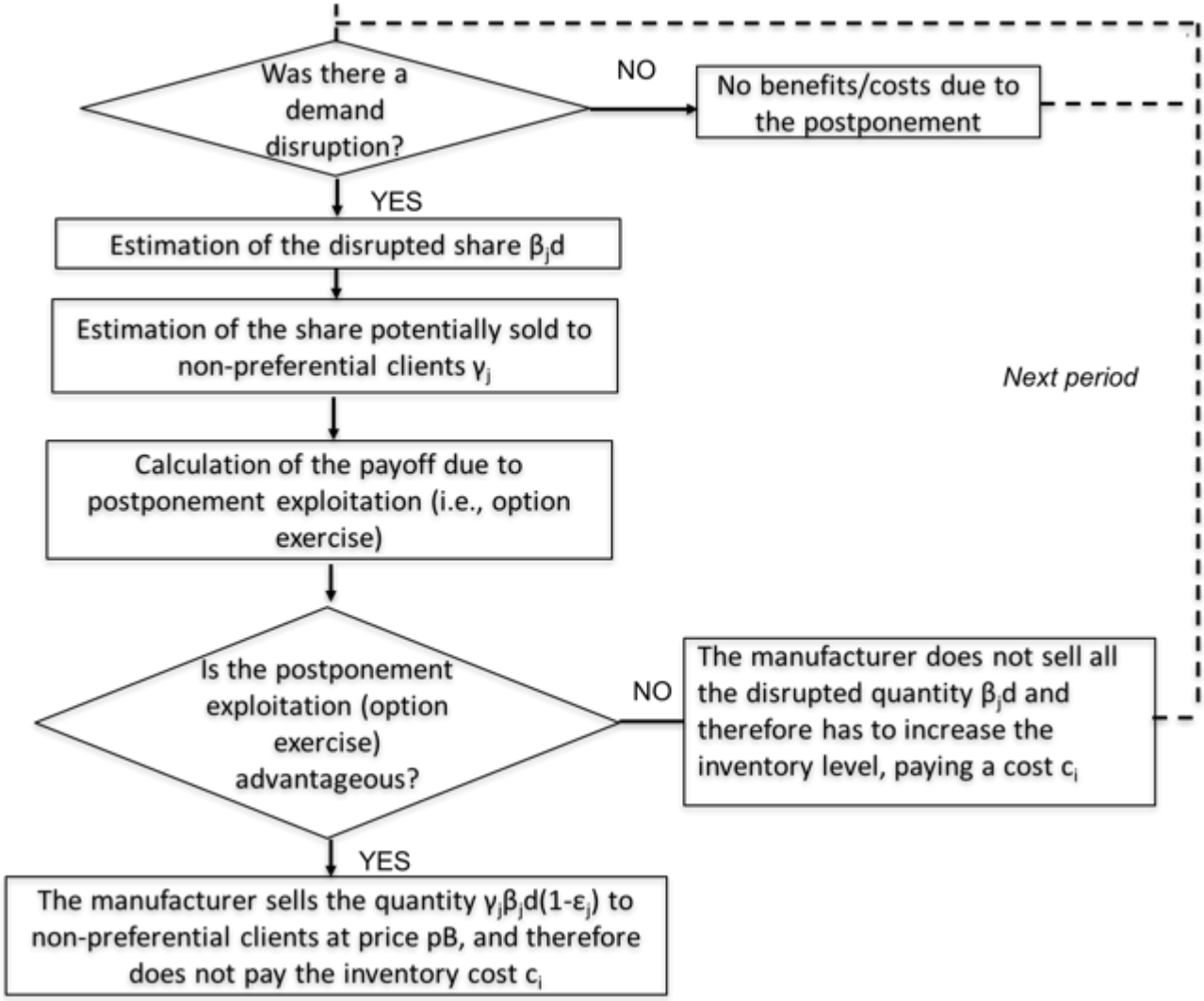
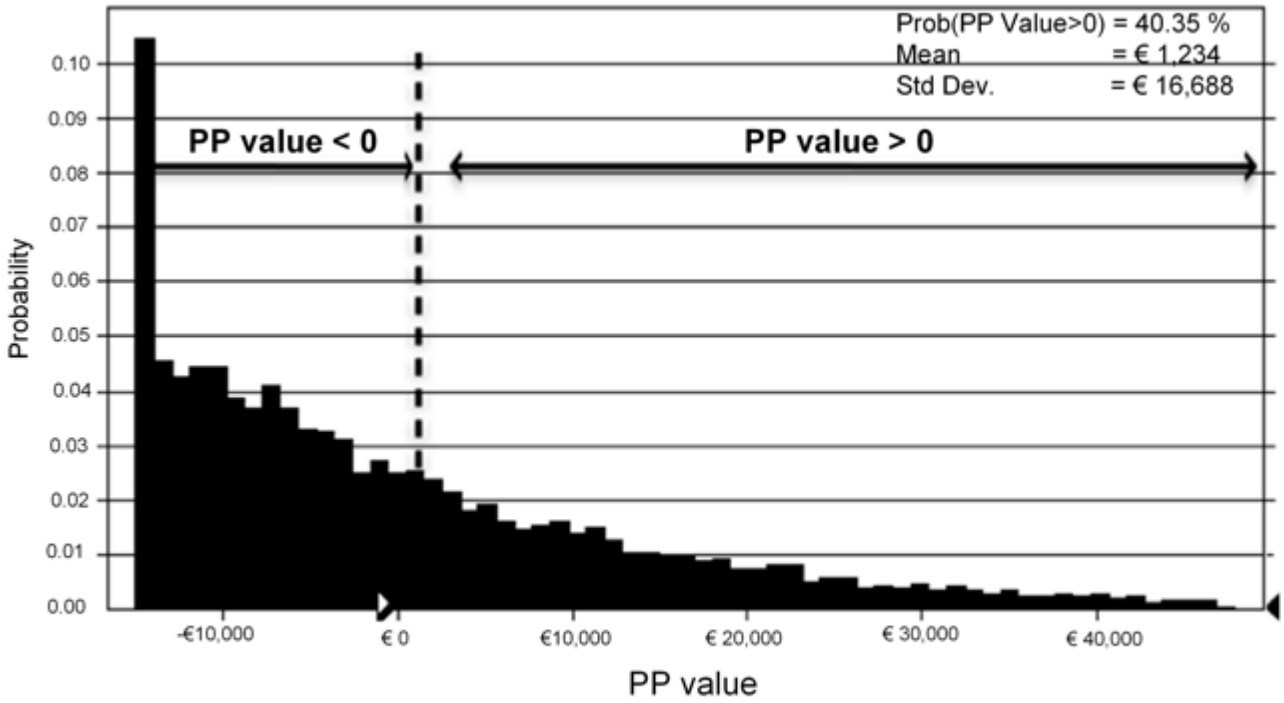
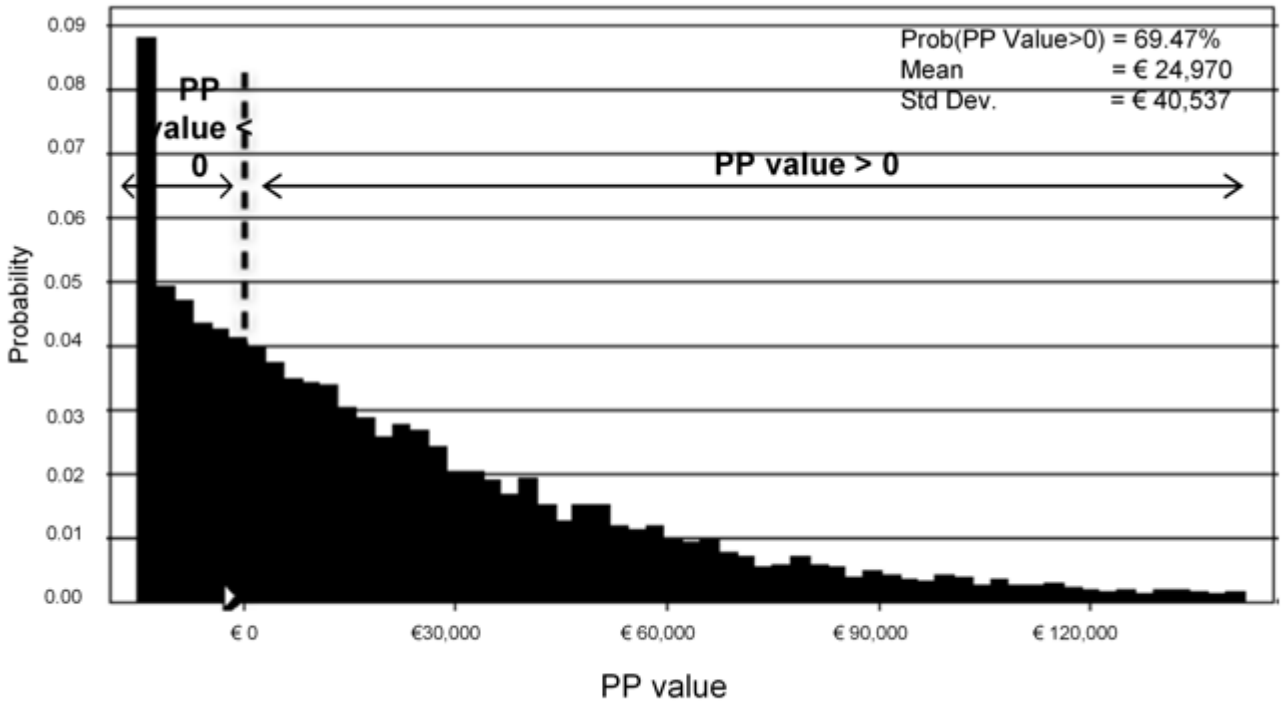


Figure 4. Probabilistic net benefits of postponement in mitigating supply (a) and demand (b) disruptions.



(a)



(b)

Figure 5. Trends of the postponement value respect to the DP position.

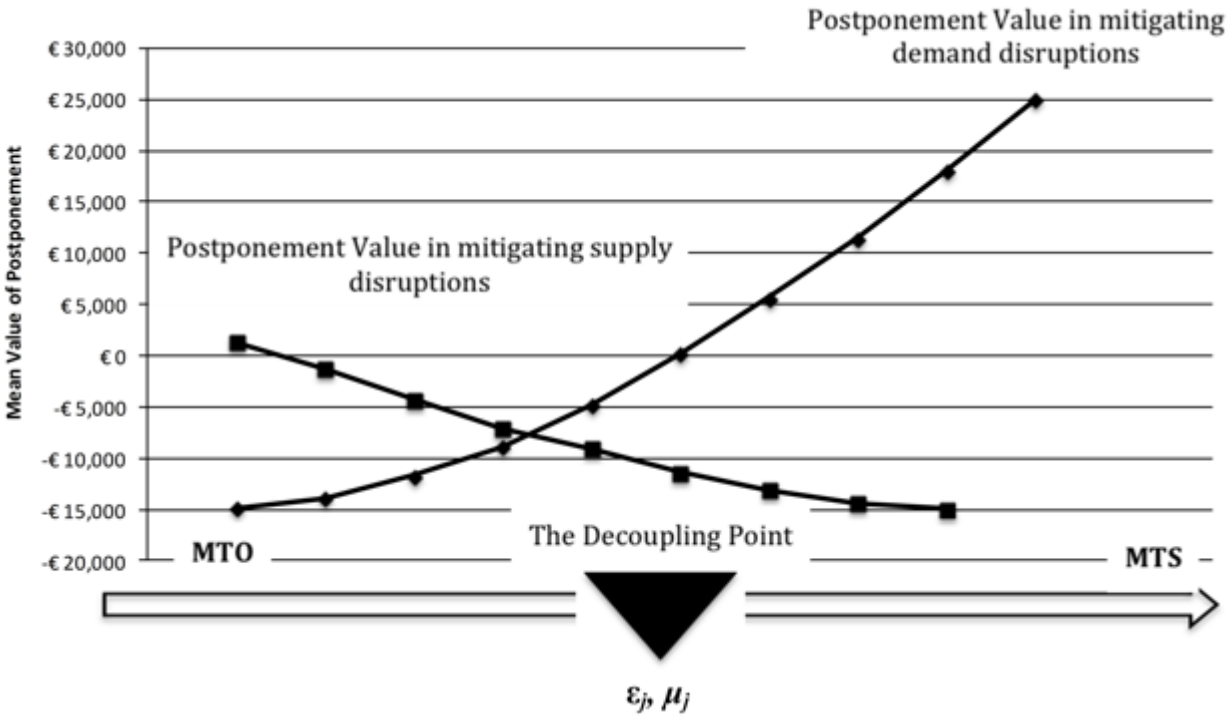
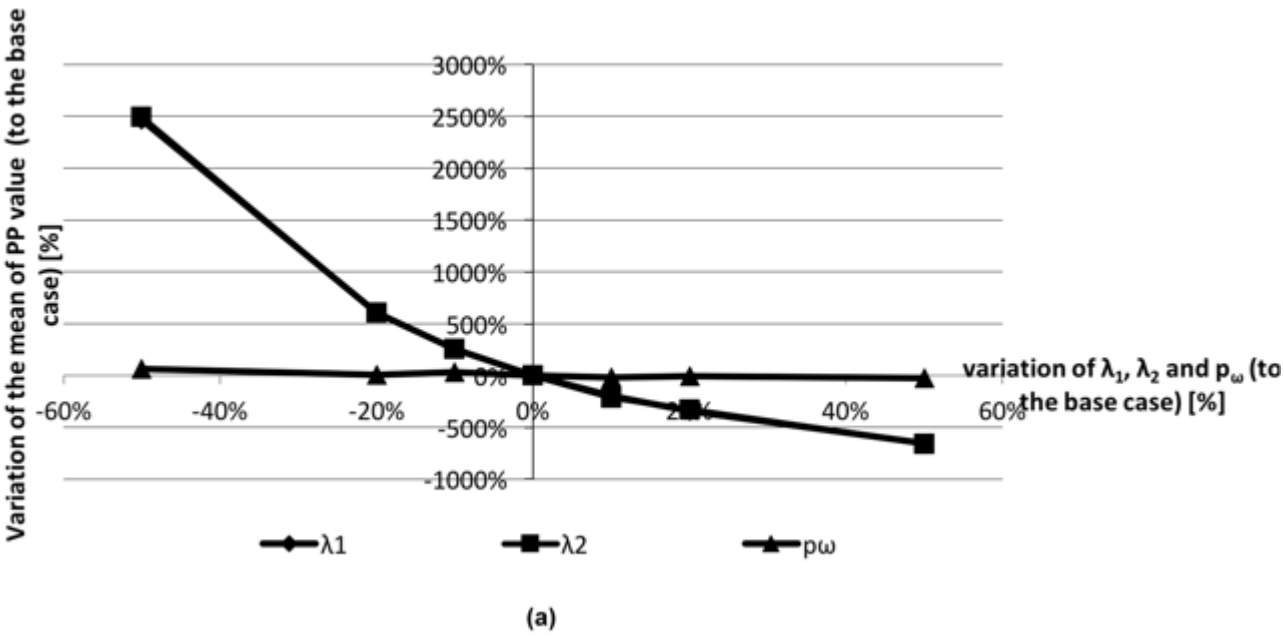
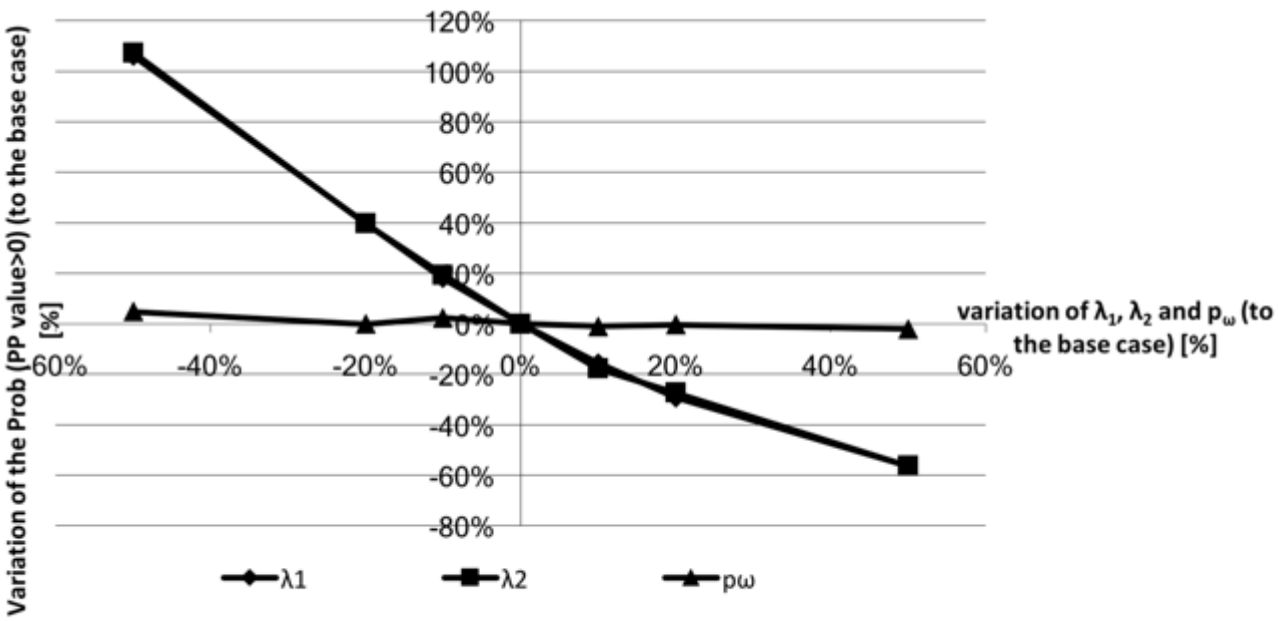


Figure 6. Results of the sensitivity analysis performed on the variables λ_1, λ_2 and p_ω (mean value (a) and Prob(PP Value>0) (b)).





(b)

Figure 7. Results of the sensitivity analysis on the sector riskiness (measured by p_ω).

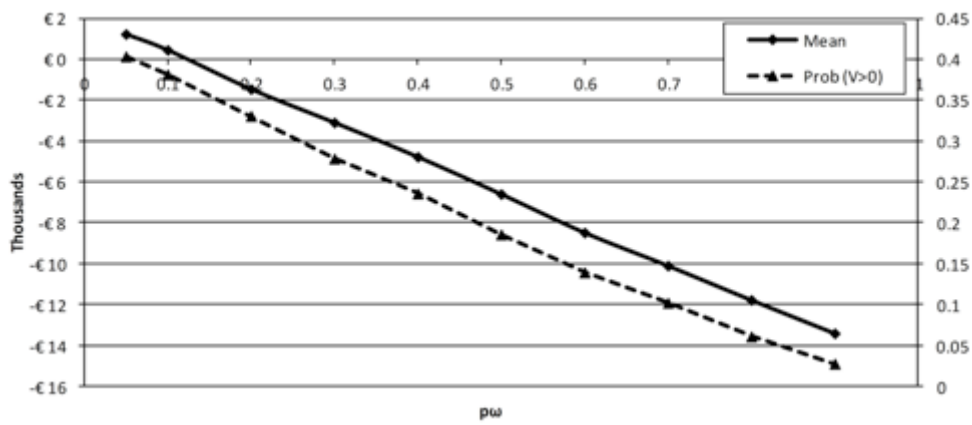
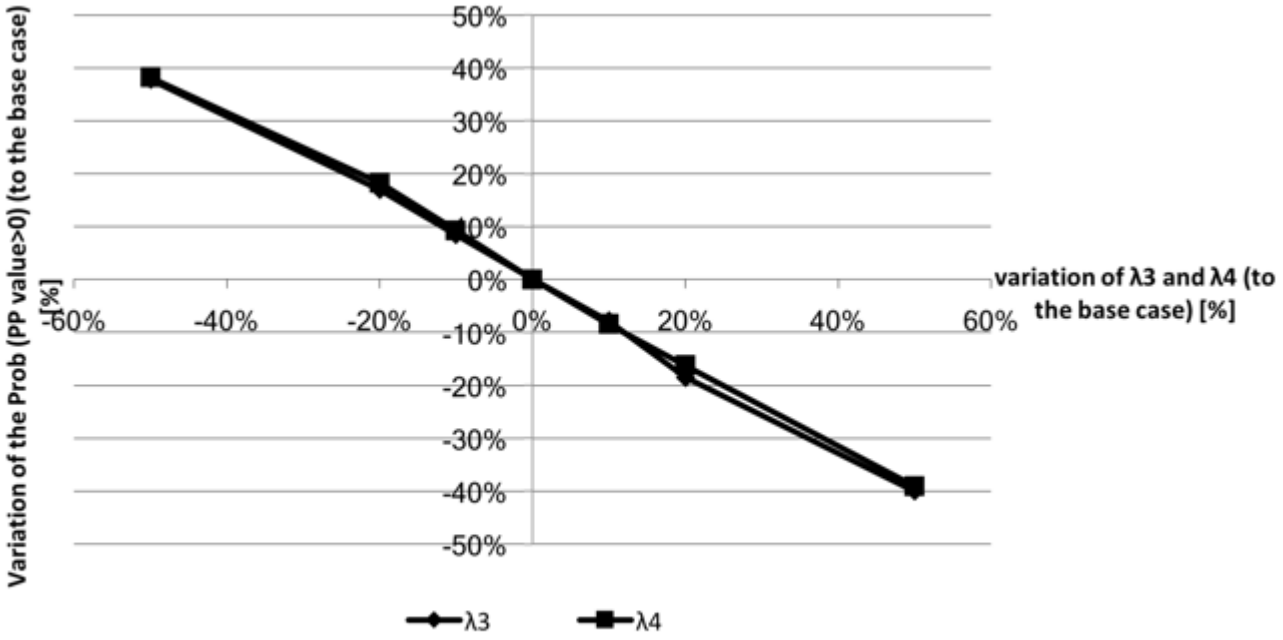
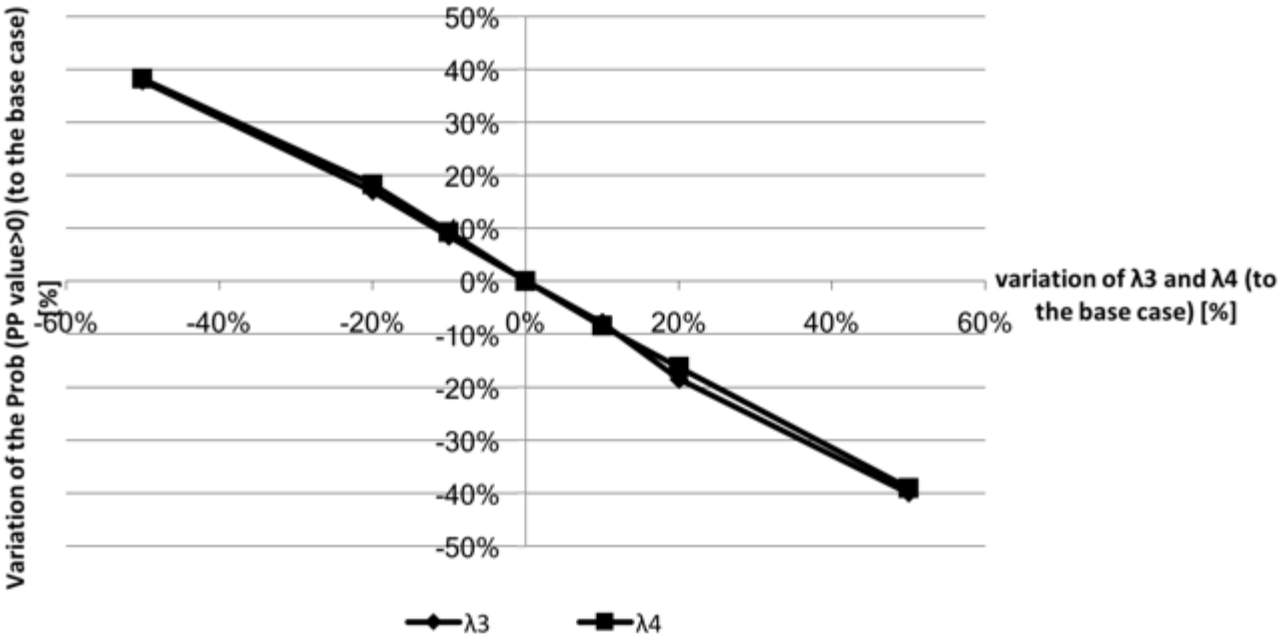


Figure 8. Results of the sensitivity analysis performed on the variables λ_3 and λ_4 (mean value (a) and Prob(PP Value>0) (b)).


Variation of the Prob (PP value>0) (to the base case) [%]
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-40%
-20%
0%
20%
40%
60%
variation of λ3 and λ4 (to the base case) [%]
λ3
λ4

(a)


Variation of the Prob (PP value>0) (to the base case) [%]
50%
40%
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-50%
-60%
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-20%
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20%
40%
60%
variation of λ3 and λ4 (to the base case) [%]
λ3
λ4

(b)

Table 1. Basic setting for numerical experiments: deterministic values and input random variables.

Deterministic variables	**Value**	**Definition**
T	12 months	total length of the relationship
N	1 months	re-order period
n = T/N	12	number of re-order periods
c_A	6 € per unit	unit cost of purchasing from the preferential supplier
c_m	1.5 € per unit	unit variable manufacturing cost
$c_t = c_A + c_m$	7.5 € per unit	total unit variable cost
Q = D	150,000 unit	total quantity of purchase
$Q_j = Q/n$	12,500 unit	quantity of purchasing in each period
d	12,500 unit	amount of the final product sold in each period
p_f	14 € per unit	unit price of the final product
c_p	5 € per unit	cost penalty per unit due to the unsatisfied demand
c_i	5 € per unit	inventory cost per unit
i	0.15	annual discount rate
ε_j	0	demand reduction due to the DP position
μ_j	0.1	supply reduction due to the DP position
$i_p = (1+i)^{N/12}-1$	0.02	periodic discount rate
K	5,000 €	switching *costs associated with* changing production mode (in case of exploiting postponement)
C_S	15,000 €	sunk (fixed) cost due to the implementation of the postponement strategy

Input random variables	**Probability distribution function**	**Parameters**
Share of the supply shortage α_j Є [0,1]	Exponential distribution	$\lambda_1 = 5.5$
Global default ω_j	ON/OFF	ON $p_\omega = 0.05$ OFF $(1- p_\omega) = 0.95$
Number of orders with global default m	Geometric distribution	k = 0.9
Share of the total quantity supplied by the not-preferential supplier δ_j Є [0,1]	Exponential distribution	$\lambda_2 = 5.5$
Unit cost of purchasing from the not preferential suppliers $c_B(j)$	mean reverting stochastic process	s* = 9.95 σ = 0.15
Final product price charged to the preferential buyer $p_A(j)$	mean reverting stochastic process	s* = 13.16 σ = 0.14
Price applied to the differentiated and customized final product sold to the not-preferential buyer $p_B(j)$	mean reverting stochastic process	s* = 15.14 σ = 0.14
Share of the demand shortage β_j Є [0,1]	Exponential distribution	$\lambda_3 = 5.5$
Share of the total quantity sold to the not-preferential buyers γ_j Є[0,1]	Exponential distribution	$\lambda_4 = 5.5$
Correlation between α_j and δ_j		r = -0.2
Correlation between β_j and γ_j		$r_1 = -0.2$

Table 2. Results of sensitivity analysis on εj and on μj

	Value of Postponement in case of demand disruptions			**Value of Postponement in case of supply disruptions**	
ε_j	**Mean**	**Prob (PP Value>0)**	μ_j	**Mean**	**Prob (PP Value>0)**
0	**€ 24,970**	**69.47%**			
0.1	€ 17,997	62.09%	**0.1**	**€ 1,361**	**40.75%**
0.2	€ 11,460	54.99%	0.2	-€ 1,214	34.22%
0.3	€ 5,620	45.52%	0.3	-€ 4,244	25.11%
0.4	€ 239	34.87%	0.4	-€ 7,099	16.97%
0.5	-€ 4,823	23.12%	0.5	-€ 9,049	11.14%
0.6	-€ 8,863	12.79%	0.6	-€ 11,412	5.15%
0.7	-€ 11,722	5.80%	0.7	-€ 13,090	1.80%
0.8	-€ 13,894	1.12%	0.8	-€ 14,353	0.29%
0.9	-€ 14,870	0.01%	0.9	-€ 14,930	0.00%

Table 3. Results of sensitivity analysis on r and r_1

r / r_1		**Value of Postponement in case of supply disruptions**	**Value of Postponement in case of demand disruptions**
	Probability (PP Value >0)	40.35%	69.47%
-0.2	Mean	€ 1,234	€ 24,970
	Std Dev.	€ 16,688	€ 40,537
	Probability (PP Value >0)	0.37%	18.18%
-0.8	Mean	-€ 13,149	-€ 6,452
	Std Dev.	€ 2,772	€ 12,546