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Supply Chain Greening versus Resilience

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ABSTRACT:

The relationship between supply chain resilience and environmental sustainability (greening) has been a topic of peripheral discussion in the research literature. The aim in this paper is to investigate, from a supply chain modeling perspective, the extent to which supply chain greening and resilience strategies are supportive of each other. A strategic supply chain design model is introduced that utilizes an environmental performance scoring approach and a new robustness measure, called "elastic p-robustness", to (1) explore the relationship between greening and buttressing (building resilience), and (2) identify potential tradeoffs to develop "resiliently green" and "greenly resilient" supply chains. Utilizing real data from a multinational apparel company, our analyses and investigations arrive at important practical implications and managerial insights and set the stage for additional research in this area.

KEY WORDS: ***Supply Chain Management; Green; Environmental Sustainability; Resilience; Buttressing; Network Design; Elastic p-Robust Approach.***

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1. Introduction

Organizations are under varied and increasing pressure from a broad spectrum of stakeholders to incorporate environmental sustainability measures into their supply chain (SC) management practices. This is evidenced by the new environmental regulatory mandates and tighter sustainability reporting regulations (Fahimnia et al., 2014a; Zakeri et al., 2014). One of the most salient and cogent "business case" arguments for the adoption of green SCs is the issue of maintaining business continuity. The incorporation of environmental goals into the traditional cost-oriented SC management practices reduces long-term business risks, is strategically prudent, and reduces the SC disruptions facing organizations from a global perspective (Reinhardt, 1998; Sarkis, 2009).

Business continuity is also a key feature of SC resilience. A resilient SC can be defined as one whose operations remain unaffected or minimally affected when a facility or multiple facilities are disrupted by a natural or manmade disaster. Other terms that could be conceivably included within a resilience spectrum include SC reliability (Peng et al., 2011; Snyder and Daskin, 2005) and SC robustness (Esmaeilikia et al., 2014; Zokaee et al., 2014). The increasing frequency and intensity of natural disasters, such as floods, earthquakes and hurricanes, as well as a continuous stream of anthropogenic catastrophes, such as strikes and terrorist attacks, necessitate the design of more resilient SCs that are more responsive in the face of such unavoidable risks (Jabbarzadeh et al., 2014).

Given these arguments, a critical question is whether or not SC greening and SC resilience are supportive of each other. There are arguments for and against building a complementary versus tradeoff relationship. For example having sustainable seafood, essentially limits overfishing and maintains a stable, resilient SC. In other situations, requiring suppliers to be green and putting additional greening costs on them may result in having fewer suppliers which can influence the overall SC resilience in tackling disruptions. The literature and importance of both SC greening and resilience have each expanded greatly in recent years (Fahimnia et al., 2014b; Pereira et al., 2014). However, the investigation of these two topics together has yet to be explored in a focused and nuanced way. Therefore, the research question is now defined as "under what circumstances is it possible for a SC to simultaneously sustain economic growth, minimize environmental impacts, and yet be resilient to disruptions?" We aim to investigate this from a SC modeling perspective. Although empirical analyses and qualitative case studies can be used to evaluate these situations, organizations may not have easily and clearly defined joint greening and resiliency practices in SCs to arrive a clear outcomes. Thus, a modeling approach to help simulate and experiment with a relatively novel, but important set of practices, is an important method for gaining insights using case data.

We limit the scope of our study to strategic SC design decision making. SC network design decisions include determining the type and mix of products to produce, the suppliers to source from, the location of manufacturing and storage facilities, the production and material handling technology to acquire/develop, the transportation modes and routes, and the markets to serve. These strategic decisions typically require large capital investments, carry long-term impacts on the SC, and are expensive to reverse, if not irreversible (Farahani et al., 2014). The use of strategic SC network design is a good vehicle for this investigation due to the significant role of SC design decisions in setting boundaries for tactical and operational decision makings, and because research in this area has expanded from a strictly financial focus to include SC greening and resilience goals.

We define "greening" as those strategies that are used to develop and manage a more environmentally sustainable SC. We also use the term "buttressing" for strategies that are adopted to build resilience into the SC. A "resiliently green SC" is defined as a green SC with some degree of resilience and a "greenly resilient SC" as a resilient SC with some degree of greening.[*] With these definitions, the clear focus and objectives of this research are twofold: (1) investigating the relationship between greening and buttressing at the SC design level, and (2) exploring the potential tradeoffs that may exist for developing resiliently green and greenly resilient SCs.

The remainder of the paper is organized as follows. Section 2 reviews the modeling efforts in two areas of green SC design and resilient SC design. Section 3 provides an overview of robustness measures and introduces a new measure, called "elastic *p*-robustness", to more effectively quantify SC resilience in a range of disruption scenarios. The mathematical model of a realistic SC network design problem is presented in Section 4. The case problem is illustrated in Section 5 followed by developing the decision scenarios that will be used for a thorough discussion of the SC greening-resilience relationship in Section 5. Section 6 is the concluding section which provides a summary of contributions and key findings, study limitations, and directions for future research in this area.

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[*] As example for a resiliently green SC is an organization that implements a take-back program focused on minimizing hazardous wastes in their SC and extended producer responsibility through remanufacturing. The primary motivation of this initiative would be for greening purposes. But, at the same time, the organization could think of improved SC resilience by making sure the remanufactured and recycled materials would be available for continued operations and hence is treated as a reliable source of material supply. Alternatively, a greenly resilient SC can be an organization that wishes to build excess capacities through extra trucks, inventory or warehouses, to help build SC resilience. While the predominant goal is to buttress the SC and build additional resilience, they may also wish to do this in a way to save energy and waste, and reduce their environmental footprint. The latter is a resilient SC with some degree of greening.

2. Literature Review

The modeling effort in this paper is positioned within the area of SC network design with explicit consideration of (1) design of green SCs, and (2) design of resilient SCs. In this section, brief overviews of the existing literature in these two areas are presented. Our study aims to investigate the nexus of these two topics.

2.1 Modeling efforts for designing green SCs

Green and environmentally sustainable SC management has garnered increased attention due to various market, regulatory, and economic concerns. It has been defined in many ways, but essentially it seeks to incorporate explicit consideration of ecological dimensions in the design, planning, and management of SCs (Varsei et al., 2014). Research on green SC management has tended to focus on empirical and conceptual studies, whilst the quantitative modeling efforts have received significantly less attention (Fahimnia et al., 2014b; Seuring, 2013). Part of the reason may be that SC modeling, in general, is a non-trivial exercise (Fahimnia et al., 2012) and it becomes even more complex for greening of SCs due to the additional variables and constraints (Fahimnia et al., 2014c). Decision tools and analytical optimization models can help organizations address SC greening concerns.

Although many ecological concerns can be analytically modeled, most of this literature focuses on minimization of cost and greenhouse gas emissions as the financial and environmental objectives (Benjaafar et al., 2013; Brandenburg et al., 2014; Elhedhli and Merrick, 2012; Tang and Zhou, 2012). There are few studies that do not fall in this category. For example, Nagurney and Nagurney (2010) use a variety of emissions, even solid wastes, to design a green SC network. Some other studies, such as Pinto-Varela et al. (2011) and Yeh and Chuang (2011), utilize a set of green scoring or ecological indicators that are broader in perspective than carbon emissions alone. Fahimnia et al. (2014c) investigate tradeoffs between cost and carbon emissions, energy consumption and waste generation to explore the relationship between SC greenness and leanness.

The need for the development of green SC design and planning models continues to grow to help organizations better integrate economic/business and environmental goals at the strategic, tactical and operational planning levels (Fahimnia et al., 2014b). Multi-criteria decision making and mathematical programming represent the most common modeling approaches to investigate the greening of SCs (Brandenburg et al., 2014). Within these analytical formal modeling approaches, specific models and measures include (1) optimization models and solution methods for SC network design seeking to balance SC cost and CO2 emissions (Chaabane et al., 2011; Elhedhli and Merrick, 2012; Wang et al., 2011), (2) integration of life cycle assessment (LCA) principles for environmental impacts assessment during strategic SC design (Bojarski et al., 2009; Chaabane et al., 2012; Hugo and Pistikopoulos, 2005),

(3) development and application of appropriate performance measures and eco-indicators for SC design optimization (Pinto-Varela et al., 2011); and (4) introducing environmental policy instruments such as carbon tax and trading mechanisms in strategic design (Chaabane et al., 2012; Diabat et al., 2013) and tactical planning of SCs (Fahimnia et al., 2013a; Fahimnia et al., 2013b; Zakeri et al., 2014).

In order to develop and apply various analytical models, appropriate performance measures will need to be identified. The number and variety of performance metrics and measures that can be utilized from an environmental and natural resource perspective can be quite extensive (Bai and Sarkis, 2014; Hervani et al., 2005; Olugu and Wong, 2011). In fact, a recent review found about 2,555 unique SC performance metrics, although not all were based solely on environmental dimensions (Ahi and Searcy, 2015). The most popular green measures used in the previous literature included general air emissions and pollutants, greenhouse gas emissions, energy use, and energy consumption. Tools and methods to identify the key performance measures for green SC is an emergent area of research (Bai and Sarkis, 2014; Grimm et al., 2014). Although we do not attend to this issue in the paper, identification and filtering of performance measures is needed when seeking to apply the optimization tools.

Other than the type and purpose of the model, the variations in the performance measures may be due to the type of industry or industrial sector or position in the SC; e.g. upstream, downstream, reverse SC (Bai and Sarkis, 2014; Olugu and Wong, 2011). Such specific information is usually available to organizations across industries and the SC. For example, the general-purpose environmental impact assessment methods such as Eco-indicator 99 (Goedkoop et al., 2009), IMPACT 2002+ (Jolliet et al., 2003), and CML2001 (Guinèe et al., 2001) have been broadly adopted and customized by organizations in different industries. These environmental performance measures utilized in these impact assessment tools may include energy sources, water usage, GHG emissions, hazardous/chemical material usage, land use, acquired environmental certificates, and environmental technology and innovation investments. However, such holistic list of measures may need to be refined to fit the purpose for specific case analysis. An example of this will such effort will be illustrated in this paper (see section 5). Although many types of metrics and models have been developed and applied, none of the green SC modeling approaches in the literature has explicitly studied the joint SC greening and resilience performance.

2.2 Modeling efforts for designing resilient SCs

Resilient SC network design is a relatively new research trend in response to the increasing frequency of SC disruptions (Snyder et al., 2012). Different approaches and solution techniques have been developed and applied to address system resilience issues. Snyder and Daskin (2005) used an expected value approach for the incorporation of disruption risks into a classical facility location problem. Aryanezhad et al. (2010) and Chen et al. (2011) extend the base model of Snyder and Daskin (2005) to include inventory decisions assuming equal and independent disruption probabilities in facilities. Unequal facility disruption probabilities have been studied by a number of researchers (Berman et al., 2007; Cui et al., 2010; Li and Savachkin, 2013; Li et al., 2013; Li and Ouyang, 2010; Lim et al., 2010; O'Hanley et al., 2013). SC design models for situations with dependent facility disruption probabilities have also been investigated (Jabbarzadeh et al., 2012; Shen et al., 2011). These studies are based on expected value approaches and ignore the risk preferences of a decision maker. Although scenario-based SC design models that incorporate the total profit variance to address the risk-aversion attitude of a decision maker has been recently introduced (Baghalian et al., 2013).

A primary drawback of these approaches is that they assume that the probability of disruption is known. However, since historical data on rare events such as earthquakes, floods, strikes, and terrorist attacks are limited or nonexistent, the likelihood of a disruption occurrence is hard to quantify (Simchi-Levi et al., 2014). Some recent studies have focused on risk aversion decision making where a conservative decision maker aims to optimize the worst-case situations. Medal et al. (2014) investigate a facility location problem seeking to minimize the maximum distance of a demand point assigned to a facility when a disruption occurs. Hernandez et al. (2014) use a multi-objective optimization approach to seek a tradeoff between the total weighted travelling distance before and after disruptions. Losada et al. (2012) present a bi-level model for protecting a SC against worst-case losses focusing on the role of facility recovery time on system performance and the possibility of multiple disruptions occurring across the SC.

A downside of these latter class of models is their overly conservative assumptions as they focus on minimizing the worst-case losses. To address this issue, Peng et al. (2011) use a *p*-robustness measure in a scenario-based SC network design model. The model minimizes the SC cost in a situation when no disruption occurs (called a nominal scenario), whilst ensuring that the solutions under a set of disruption scenarios have a constrained relative regret. The approach was shown to produce less conservative solutions than those obtained by the traditional robustness criteria.

The brief reviews presented in Sections 2.1 and 2.2 show that the modeling efforts on design of "green SCs" and "resilient SCs" have been completed in isolation. In reality, however, there may be green interventions with undesirable consequences on the SC resilience making the network more vulnerable to disruptions. An example could be some of the lean practices that result in reduced safety inventory levels, making a SC inherently greener, whilst less responsive to variations in product demand. Our aim in this paper is to explore the relationship between greening and buttressing strategies and whether tradeoffs exist for the development of resiliently green and greenly resilient SCs. An environmental performance scoring approach and a new robustness measure, named elastic *p*-robustness, are used to investigate the greening-resilience relationship for a multinational company from the apparel industry.

3. Elastic p-Robustness Measure

At the core of the green and resilient SC deign modeling effort in this paper is to identify the appropriate robustness measure to adopt. Several robustness measures and algorithms have been developed and applied (see the reviews of Kouvelis and Yu (1997) and Snyder (2006)). Most of these methods use a cost measure to assess the SC resilience in different disruption situations. Minimax cost (minimizing the maximum cost across scenarios) and Minimax regret (minimizing the maximum regret across scenarios) have been the two most common robustness measures in the context of SC design and planning (Snyder and Daskin, 2006).

Let us start with introducing some notations and fundamental relationships. Let S be a set of scenarios, indexed by s. Each scenario represents a possible disruption situation. Scenario 1 (s=1) is called a *nominal scenario* (the baseline) when no disruption occurs and hence a system operates in a perfect situation with no disruption possibility. Let P_s be a deterministic minimization problem for each scenario $s \in S$ and w_s^* be the optimal solution for P_s. Then, the objective functions for the minimax cost and minimax regret measures can be formulated as follows.

$$\text{(Minimax cost)} \qquad \text{minimize} \max_{s \in S} \; w_s(X) \tag{1}$$

$$\text{(Minimax regret)} \qquad \text{minimize} \max_{s \in S} \; \frac{w_s(X) - w_s^*}{w_s^*} \tag{2}$$

Where X is a feasible solution to P_s for all $s \in S$ and $w_s(X)$ represents the objective value of P_s under solution X. From Equation (2), the "regret" of a solution in a given scenario is obtained from the difference between the cost of the solution in that scenario and the cost of the optimal solution at the nominal scenario.

Another popular robustness measure is the so-called p-robustness measure, introduced by Kouvelis et al. (1992) for a facility layout problem. This measure minimizes the total cost under the nominal scenario, while ensuring that the deviation of the solution from optimality under each scenario does not exceed an acceptable positive value, p, indicating the deviation from the desirable robustness degree. The p-robustness measure can be formulated as follows.

$$(p\text{-robustness}) \qquad \text{minimize} \; W_1(\mathrm{X}) \tag{3}$$

Subject to:

$$\frac{w_s(X) - w_s^*}{w_s^*} \le p \qquad \forall s \in S \tag{4}$$

Where *s*=1 denotes the nominal scenario, W_1 (X) represents the total cost under the nominal scenario and *p* is a positive constant indicating the acceptable deviation of solutions from optimality. The left hand side of Equation (4) is the relative regret if scenario *s* occurs. Constraint (4) aims to set an upper-bound for the maximum allowable relative regret of each scenario. Equation (4) can be rewritten as follows.

$$w_s(X) \leq (1+p)w^*_s \qquad \forall s \in S \tag{5}$$

It has been shown that a *p*-robustness measure can produce less conservative solutions compared to those produced by minimax cost and minimax regret (see for example Gutierrez and Kouvelis (1995), Gutiérrez et al. (1996) , Snyder and Daskin (2006) and Peng et al. (2011)). One concern with the *p*-robustness approach is that constraint (5) can highly restrict the feasible region of solutions, making it difficult or even impossible to find a feasible solution to a problem at smaller *p* values. In other cases, this issue may have influences on the quality of solutions. For example, a small violation of constraint (5) in only one scenario is sufficient to discard a solution, whereas the solution may have proven effective under many other scenarios. To address this concern, we introduce an extension of *p*-robustness measure, named "*elastic p-robustness*" as follows.

$$\text{(elastic } p\text{-robustness)} \qquad \text{minimize } w_1(X) + \sum_{s \in S-\{1\}} \alpha_s \delta_s \tag{6}$$

Subject to:

$$w_s(X) - \delta_s \leq \left(1+\frac{1}{p}\right)w_s^* \qquad \forall s \in S-\{1\} \tag{7}$$

$$\delta_s \geq 0 \qquad \forall s \in S \tag{8}$$

In the proposed elastic *p*-robustness approach, δ_s is a decision variable indicating how much the objective value under scenario $s \in S$ needs to be decreased to have a relative regret not more than $\frac{1}{p}$. Since deviation is allowed, α_s is defined as a positive constant to penalize the violation of the relative regret $\frac{1}{p}$ under scenario $s \in S$. Obviously, low values for α_s will allow large violations, whereas a higher value will make violations more expensive in terms of objective function values, and hence only allow smaller violations. One way to choose a value for α_s is to set $\alpha_s = \frac{w^*_1}{w^*_s}$. In which case, $\alpha_s \delta_s$ will be equal to $\frac{w^*_1}{w^*_s}\delta_s$, where $\frac{\delta_s}{w^*_s}$ denotes deviation from the relative regret $\frac{1}{p}$ under scenario $s \in S$.

Multiplying $\frac{\delta_s}{w^*_s}$ by w^*_1 ensures that $\alpha_s\delta_s$ will have a unit similar to $w_1(X)$, the objective value under the nominal scenario (i.e. when *s*=1).

Unlike constraint (5), constraint (7) allows for violation of the relative regret *p* if the objective value can be improved and hence does not impose an extreme limitation on the feasible region of solutions. Using this approach, finding a feasible solution to the problem is possible at any *p* value. In addition, high-quality solutions are not discarded due to only small violations against the allowable relative regret $\frac{1}{p}$. Obviously, *p*-robustness and elastic *p*-robustness measures yield analogous solutions when adequately large values are assigned to penalty weights α_s. In a situation when scenarios are of different importance to a decision maker, the deviation from desirable robustness degree, *p*, becomes scenario-dependent and is denoted as p_s.

4. Problem Definition and Model Formulation

The mathematical and modeling underpinnings for solving the joint resilience and greening issues facing SCs were provided in the previous section. In this section we present a specific SC design model that introduces greening and resilience modeling and parameters. In the problem definition and eventual formulation an actual case example is used.

To set the stage for this investigation, we study a SC comprised of geographically dispersed manufacturing plants, distribution centers (DCs) and market zones. Fixed and variable production costs as well as the environmental performance scores (EPSs) are determined for each manufacturing plant based on the production technology adopted, green initiatives undertaken, and sustainability performance of the raw material suppliers. Determining EPSs requires a set of assessment criteria against which manufacturing plants and their suppliers can be assessed. The assessment criteria can be obtained from the established environmental impact assessment methods such as Eco-indicator 99 (Goedkoop et al., 2009), IMPACT 2002+ (Jolliet et al., 2003), and CML2001 (Guinèe et al., 2001). Such criteria may include the available energy sources, water usage, GHG emissions, hazardous/chemical material usage, land use, acquired environmental certificates, and environmental technology and innovation investments. These assessment criteria may need to be further refined to those items more directly related to strategic SC design decisions and to match the characteristics of the specific case situation (see for example the case problem presented in Section 5). In distribution, multiple transport modes are available for the shipment of items between SC nodes. Unit shipment costs and EPSs are determined based on the transport mode chosen. Similar to manufacturing plants, DCs may have different holding costs and EPSs depending on the location, size, material handling system and technology adopted, and environmental initiatives undertaken.

Aggregate EPSs (combined EPS values in manufacturing/sourcing, transport and storage) can be used to determine the greening degree of the SC. For a SC to be considered as "Green", the aggregate EPSs must be higher than a specific threshold score (i.e. to ensure that EPSs are kept within an acceptable range). That is, a green SC must be able to display a minimum acceptable environmental performance across the SC. The threshold EPSs are usually industry-specific and are defined by related industry experts. The application of threshold scores and how they can be used in determining the greening degree of a SC is exemplified in the case study presented in Section 5.

Manufacturing plants and DCs are subject to major disruptions. A set of scenarios are developed for the case study to represent situations where one or more facilities are affected by disruption(s). The proposed model aims to determine the network design decisions that minimize overall SC cost whilst ensuring that (1) the environmental performance of the network is kept within an acceptable range and (2) the network remains resilient under all or most of the facility disruption scenarios. To ensure that the SC is resilient to a predefined degree, we consider a constraint similar to elastic p-robust constraint (7) aiming to prevent relative regrets of more than $\frac{1}{p}$ across all disruption scenarios. Parameter p is referred to as "Resilience degree", hereafter. Obviously, larger p values result in lower values for relative regret and hence a more resilient SC design.

The network design decisions are made in two stages. Stage 1 decisions are independent of disruption scenarios and include determining locations and capacities of manufacturing plants, production technology adopted at each manufacturing plant, and locations and capacities of DCs. Stage 2 decisions are scenario-dependent and are therefore taken for specific disruption scenarios. Stage 2 decisions include determining transport modes and quantities for the shipment of products from manufacturing plants to DCs and from DCs to market zones as well as the quantity of lost sales.

A set of indices, parameters and decision variables are used for mathematical modeling of this problem.

Indices:

I	Set of candidate locations for manufacturing plants, indexed by i
J	Set of candidate locations for DCs, indexed by j
K	Set of market zones, indexed by k
L	Set of capacity levels of a manufacturing plant, indexed by l
T	Set of product types/families, indexed by t
M	Set of transport modes for the shipment of products from manufacturing plants to DCs, indexed by m
N	Set of production technologies, indexed by n

O	Set of capacity levels of a DC, indexed by o
R	Set of transport modes for the shipment of products from DCs to market zones, indexed by r
S	Set of disruption scenarios, indexed by s

Parameters:

a_i^s	Equal to 1 if manufacturing plant i is disrupted in scenario s; 0, otherwise.
b_j^s	Equal to 1 if DC j is disrupted in scenario s; 0, otherwise.
d_{kt}^s	Forecasted demand for product t in market zone k in scenario s (units)
f_{iln}	Fixed cost of establishing a manufacturing plant with capacity level l and production technology n at location i ($)
f'_{jo}	Fixed cost of establishing a DC with capacity level o at location j ($)
g_{int}	Variable cost of manufacturing a unit of product t in manufacturing plant i with production technology n ($/unit)
h_{nt}	Processing time to produce a unit of product t using production technology n (hour)
c_{iln}	Production capacity of a manufacturing plant with capacity level l and production technology n at location i (hour)
v_{ijmt}	Unit cost of transportation for the shipment of product t from manufacturing plant i to DC j through transport mode m
v'_{jkrt}	Unit cost of transportation for the shipment of product t from DC j to market zone k through transport mode m
u_{kt}	Unit cost of lost sales for product t at market zone k ($/unit)
h'_t	Volume of a unit of product t (m^3)
c'_{jo}	Storage capacity of a DC with capacity level o at location j (m^3)
e_{int}	EPS for producing product t with technology n in manufacturing plant i (score)
e'_{ijmt}	EPS for the shipment of product t from manufacturing plant i to DC j through transport mode m (score)
e''_{jt}	EPS of holding of product t in DC j (score)
e'''_{jkrt}	EPS for the shipment of product t from DC j to market zone k through transport mode m (score)

w_s^*	Optimal value for the objective function under scenario *s* ($)
p	Resilience degree
α_s	Penalty weight for violation of the desirable resilience level *p* under scenario *s*
ε	Threshold EPS in production: the lowest allowable EPS in manufacturing
ε'	Threshold EPS in inbound transportation: the lowest allowable EPS for shipment of products from plants to DCs (score)
ε'''	Threshold EPS in outbound transportation: the lowest allowable EPS for shipment of products from DCs to market zones (score)
ε''	Threshold EPS in storage: the lowest allowable EPS for holding products in DCs (score)

Decision variables:

X_{iln}	A binary variable, equal to 1 if a manufacturing plant with capacity level *l* and production technology *n* is established at location *i*; 0, otherwise.
X'_{jo}	A binary variable, equal to 1 if a DC with capacity level *o* is established at location *j*; 0, otherwise.
Q_{int}^s	Quantity of product *t* produced with production technology *n* in manufacturing plant *i* under scenario *s*
U_{kt}^s	Quantity of lost sales for product *t* at market zone *k* under scenario *s*
Y_{ijmt}^s	Quantity of product *t* shipped from manufacturing plant *i* to DC *j* through transport mode *m* under scenario *s*
Z_{jkrt}^s	Quantity of product *t* shipped from DC *j* to market zone *k* through transport mode *r* under scenario *s*
δ_s	Violation of the total cost corresponding to the relative regret $\frac{1}{p}$ under scenario *s*

Using the above parameters and decision variables, we can now formulate the cost parameters that will eventually form the objective function. The total SC cost under each scenario include

$$\text{Cost of establishing manufacturing plants} = \text{MC}_s = \sum_{i \in I} \sum_{l \in L} \sum_{n \in N} f_{iln} X_{iln} \tag{9}$$

$$\text{Cost of establishing DCs} = \text{DC}_s = \sum_{j \in J} \sum_{o \in O} f'_{jo} X'_{jo} \tag{10}$$

$$\text{Shipment costs} = \text{SC}_s = \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \sum_{t \in T} v_{ijmt} Y_{ijmt}^s + \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} v'_{jkmt} Z_{jkrt}^s \tag{11}$$

$$\text{Production costs} = \mathrm{PC}_s = \sum_{i\in I}\sum_{n\in N}\sum_{t\in T} g_{int} Q^s_{int} \tag{12}$$

$$\text{Cost of lost sales} = \mathrm{LC}_s = \sum_{k\in K}\sum_{t\in T} u_{kt} U^s_{kt} \tag{13}$$

Equation (9) expresses the fixed cost of establishing manufacturing plants with different production technologies and capacity levels. Equation (10) presents the fixed cost of locating DCs with different capacity levels. Equation (11) indicates the transportation costs for the shipment of products form manufacturing plants to DCs and from DCs to markets. Equation (12) shows manufacturing costs using different production technologies. Equation (13) represents the total cost of lost sales.

To formulate the robust model, we utilize the Elastic *p*-robustness approach presented in Section 3. Considering Equation (6) and the above cost components, the objective function is formulated as follows:

$$\text{Objective function:} \qquad \text{minimize } \left(MC_1 + DC_1 + SC_1 + PC_1 + LC_1\right) + \left(\sum_{s\in S-\{1\}} \alpha_s \delta_s\right) \tag{14}$$

The first term of the objective function (14) expresses the total SC cost under the nominal scenario. Scenario 1 (s=1) is the nominal scenario when no facility disruption occurs in the SC. The second term of the objective function (14) is the summation of penalties corresponding to percentage deviation from optimality under all scenarios, excluding the nominal scenario.

The proposed model is subject to the following constraints:

$$\sum_{l\in L}\sum_{n\in N} X_{iln} \le 1 \qquad \forall i\in I \tag{15}$$

$$\sum_{o\in O} X'_{jo} \le 1 \qquad \forall j\in J \tag{16}$$

$$\sum_{n\in N} Q^s_{int} = \sum_{j\in J}\sum_{m\in M} Y^s_{ijmt} \qquad \forall i\in I, \forall t\in T, \forall s\in S \tag{17}$$

$$\sum_{i\in I}\sum_{m\in M} Y^s_{ijmt} = \sum_{k\in K}\sum_{r\in R} Z^s_{jkrt} \qquad \forall j\in J, \forall t\in T, \forall s\in S \tag{18}$$

$$\sum_{j\in J}\sum_{r\in R} Z^s_{jkrt} = d^s_{kt} - U^s_{kt} \qquad \forall k\in K, \forall t\in T, \forall s\in S \tag{19}$$

$$\sum_{t\in T} h_{nt} Q^s_{int} \le a^s_i \sum_{l\in L} c_{iln} X_{iln} \qquad \forall i\in I, \forall n\in N, \forall s\in S \tag{20}$$

$$\sum_{i\in I}\sum_{m\in M}\sum_{t\in T} h'_t Y^s_{ijmt} \le b^s_j \sum_{o\in O} c'_{jo} X'_{jo} \qquad \forall j\in J, \forall s\in S \tag{21}$$

$$\frac{\sum_{i\in I}\sum_{n\in N}\sum_{t\in T} e_{int} Q_{int}^{s}}{\sum_{i\in I}\sum_{n\in N}\sum_{t\in T} Q_{int}^{s}} \geq \varepsilon \qquad \forall s \in S \tag{22}$$

$$\frac{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} e'_{ijmt} Y_{ijmt}^{s}}{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} Y_{ijmt}^{s}} \geq \varepsilon' \qquad \forall s \in S \tag{23}$$

$$\frac{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} e''_{jt} Y_{ijmst}^{s}}{\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} Y_{ijmst}^{s}} \geq \varepsilon'' \qquad \forall s \in S \tag{24}$$

$$\frac{\sum_{j\in J}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} e'''_{jkrt} Z_{jkrt}^{s}}{\sum_{j\in J}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} Z_{jkrt}^{s}} \geq \varepsilon''' \qquad \forall s \in S \tag{25}$$

$$\left(MC_s + DC_s + SC_s + PC_s + LC_s\right) - \delta_s \leq \left(1 + \frac{1}{p}\right) w_s^{*} \qquad \forall s \in S \tag{26}$$

$$X_{iln} \in \{0,1\} \qquad \forall i \in I, \forall l \in L, \forall n \in N \tag{27}$$

$$X'_{jo} \in \{0,1\} \qquad \forall j \in J, \forall o \in O \tag{28}$$

$$Q_{int}^{s} \geq 0 \qquad \forall i \in I, \forall n \in N, \forall s \in S, \forall t \in T \tag{29}$$

$$U_{kt}^{s} \geq 0 \qquad \forall k \in K, \forall s \in S, \forall t \in T \tag{30}$$

$$Y_{ijmt}^{s} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall m \in M, \forall s \in S, \forall t \in T \tag{31}$$

$$Z_{jkrt}^{s} \geq 0 \qquad \forall j \in J, \forall k \in K, \forall r \in R, \forall s \in S, \forall t \in T \tag{32}$$

$$\delta_s \geq 0 \qquad \forall s \in S \tag{33}$$

Constraints (15) and (16) ensure that only one facility can be established in candidate locations for manufacturing plants and DCs, respectively. Constraints (17), (18) and (19) represent the flow balance constraints in manufacturing plants, DCs and market locations, respectively. Constraint (17) ensures that the quantity of products shipped from a manufacturing plant is equal to the quantity of products produced in that plant. The balance constrains in DCs and market locations are represented in constraints (18) and (19). Constraints (20) and (21) enforce the capacity limitation of manufacturing plants and DCs for different disruption scenarios. Constraints (22)-(25) express the environmental performance constraints in manufacturing plants, inbound transportation, storage, and outbound transportation, respectively. More explicitly, constraint (22) ensures that the average EPS for producing products is not less than the threshold EPS in manufacturing, where $\sum_{i\in I}\sum_{n\in N}\sum_{t\in T}Q_{int}^{s}$ denotes the total products produced, and the left hand side equation calculates the average aggregate EPS in manufacturing. Likewise, constraints (23)-(25) enforce that the average aggregate EPSs for inbound transportation, storage, and outbound transportation are kept above the corresponding threshold scores. It is worth reinforcing that setting larger threshold EPSs results in tighter environmental constraints and hence design of a greener SC.

Constraint (26) presents the elastic *p*-robust constraint defined in Equation (7). A higher value for the resilience degree (*p*) makes the right hand side of the constraint (26) smaller. In this case, the total SC cost under each scenario (i.e. the sum of $MC_s+DC_s+SC_s+PC_s+LC_s$) tends to become smaller to avoid higher values for δ_s which imposes larger penalties in the objective function. Therefore, higher values for the resilience degree results in a lower total cost under each scenario and hence a more resilient SC in disruptions. Constraints (27)-(33) define the domains of the decisions variables.

Even though constraints (22)-(25) are nonlinear, they can be easily transformed into their equivalent linear forms, as shown in Equations (34)-(37).

$$\sum_{i\in I}\sum_{n\in N}\sum_{t\in T}e_{int}Q_{int}^{s}\geq\varepsilon\sum_{i\in I}\sum_{n\in N}\sum_{t\in T}Q_{int}^{s}\qquad\forall s\in S\qquad(34)$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}e'_{ijmt}Y_{ijmt}^{s}\geq\varepsilon'\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}Y_{ijmt}^{s}\qquad\forall s\in S\qquad(35)$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}e''_{jt}Y_{ijmst}^{s}\geq\varepsilon''\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}Y_{ijmst}^{s}\qquad\forall s\in S\qquad(36)$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T}e'''_{jkrt}Z_{jkrt}^{s}\geq\varepsilon'''\sum_{j\in J}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T}Z_{jkrt}^{s}\qquad\forall s\in S\qquad(37)$$

5. Case Problem and Decision Scenarios

Over the past decade, the apparel industry has witnessed an increasing use of synthetic material versus natural cotton in clothing (Gam et al., 2009; Prentice, 2014). Synthetic clothing is made of synthetic fiber which is produced by forcing liquids through tiny holes in a metal plate, called a spinneret, and allowing them to harden. The use of different liquids and spinnerets produce various types of fibers such as polyester, nylon, acrylic and rayon. Synthetic fiber production is highly energy intensive and the process greenness is mainly dependent on the energy sources available, followed by chemical and water use. Synthetic yarn is then transformed into fabric through knitting, dyeing, and finishing. Dying uses substantial amounts of water; although, greening initiatives can be undertaken to reduce water usage.

ACO is a multinational corporation involved in the production and distribution of sportswear clothing. ACO is headquartered in Australia for its Australasia production and distribution. On one hand, ACO has been forced to enhance its environmental sustainability performance due to the tighter-than-ever environmental regulatory mandates and the associated stakeholder pressures. On the other hand, the global dispersion of ACO facilities has increased the likelihood of the firm being affected by various kind of regional and global disruptions. The question therefore is how to reconfigure the existing SC to be both green and resilient and yet economically viable. However, the relationship between environmental sustainability interventions and SC resilience has never been explored by ACO managers. In line with the primary goals of this paper, the SC design model and methodology presented in this paper was utilized to complete a thorough analysis for ACO to (1) investigate the relationship between greening and resilience when determining the SC structure, and (2) explore the potential tradeoffs for developing resiliently green and greenly resilient SCs.

Synthetic fabric is the core raw material used in all product types in ACO. Fabrics are sourced from a number of local suppliers for the manufacturing of four product families including tops, pants, shorts, and jackets (T=4). Candidate locations for establishing manufacturing plants (I=4) are China (Quanzhou), Vietnam (Ho Chi Minh), Cambodia (Phnom Penh), and Bangladesh (Dhaka). Production processes in manufacturing plants include design, cutting, sewing, assembly, and packaging. A manufacturing plant can be built in three sizes: large, medium, and small (L=3). The availability of different production technologies may vary from one location to another. In general, production technologies/machineries are graded between 1 and 5, with 5 being the greenest and usually the most expensive to adopt (N=5). The type of production technology, the size of the plant, the labor and management wages, and the associated overhead costs determine the unit production cost at each plant.

Products are shipped from plants to wholesalers (market zones) in five Australian states including New South Wales (NSW), Victoria (VIC), Queensland (QLD), South Australia (SA) and Western Australia (WA) through three candidate DCs in WA (Perth), SA (Adelaide) and NSW (Sydney), respectively (K=5 and J=3). Large, medium, and small DCs can be leased at each location (O=3). The DC leases are signed for strategic periods, typically longer than two years, allowing the long-term installation of shelves and material handling systems. Sea transport is the only option for the shipment of products from Asian plants to Australian DCs (M=1). The inbound transportation for the shipment of items from DCs to wholesalers can be via sea, rail or road transport modes (R=3). The cost of lost sales varies from one product type to another and from one market to another. The schematic view of a potential SC network for ACO is shown in Figure 1.

The EPS of a manufacturing plant is determined based on the environmental performance of the plant (e.g. production technology adopted and energy sources available) and the performance of its synthetic fabric suppliers (e.g. energy sources used, water and chemical usage and GHG emissions performance). The environmental assessment criteria developed and adopted by IMPACT 2002+ (Jolliet et al., 2003) were used as the starting point. The criteria were further refined to those concerning SC network design in synthetic product manufacturing. This was completed by a panel of industry experts comprised of three individuals from two Asian and one Australian environmental consultancy firms with specialized knowledge and experience in the apparel industry. Once the criteria were established, site visits and direct audits were completed by the panel and all related observations were documented. EPSs were finally assigned to all plants on a scale of 1-10, with 10 being the greenest.

Due to the energy and water intensive nature of synthetic fabric production, the impact of supplier environmental performance has tended to have a dominant influence on EPSs (weighted 85% of the overall score) compared to that of a manufacturing plant (weighted 15%). For example, Chinese and Vietnamese plants seem to be ranked the most environmentally sustainable, predominantly due to better environmental performance of the local suppliers of synthetic fabrics. However, fixed and variable production costs in these locations are typically higher than those of Bangladesh and Cambodia. Identical EPSs are used in DCs as there are negligible variations across the nation in sustainability performance of DCs. In transport, EPSs are determined based on the transport mode chosen, with sea transport being the greenest and rail playing an intermediate role between sea and road transports.

Figure 1. The multinational SC structure of ACO, sportswear clothing

The model presented in Section 4 was coded in GAMS 24.1. To set the stage for a thorough greening-resilience analysis in Section 6, we develop 21 disruption scenarios representing possible facility disruption situations at ACO (*S*=21). ACO has four manufacturing plants each of which can be either disrupted or non-disrupted. Thus, we have a total of 2×2×2×2 = 16 possible plant disruption scenarios. Amongst these, one scenario represents a situation when all four plants are non-disrupted. We exclude this scenario and will later take it into consideration as part of a base scenario. In the other 15 scenarios, at least one manufacturing plant is disrupted. We also exclude the scenario where all manufacturing plants are disrupted simultaneously as no insight can be gained when demand is entirely unfulfilled. Thus, 14 possible plant disruption scenarios are defined. Likewise, for the three DCs with two possible situations for each (i.e. disrupted or non-disrupted), a total of 2×2×2 = 8 scenarios can be developed for DC disruptions. Excluding the scenarios when all DCs are disrupted or non-disrupted, will leave us with six DC disruption scenarios. The summation of 14 plan disruption scenarios and six DC disruption scenarios gives us a total of 20 scenarios. There is also a base scenario when none of the plants and DCs are disrupted. We name this latter scenario the "nominal scenario". It should be noted that we disregard the less likely situations when plants and DCs are simultaneously disrupted. However, a more conservative decision maker can also develop additional scenarios to represent these situations. Table 1 summarizes the characteristics of 21 scenarios as outlined above. The first scenario (*s1*) is the nominal scenario and represents a business-as-usual situation (i.e. when no facility is disrupted) followed by 14 plant disruption scenarios (*s2*-*s15*) and six DC disruption scenarios (*s16*-*s21*).

Table 1. Facility disruption scenarios

Facility disruption scenario	Affected facilities
Nominal scenario	
Scenario 1 (*s1*)	-------------
Plant disruption scenarios	
Scenario 2 (*s2*)	Dhaka (*i4*)
Scenario 3 (*s3*)	Phnom Penh (*i3*)
Scenario 4 (*s4*)	Phnom Penh (*i3*), Dhaka (*i4*)
Scenario 5 (*s5*)	Ho Chi Minh (*i2*)
Scenario 6 (*s6*)	Ho Chi Minh (*i2*), Dhaka (*i4*)
Scenario 7 (*s7*)	Ho Chi Minh (*i2*), Phnom Penh (*i3*)
Scenario 8 (*s8*)	Ho Chi Minh (*i2*), Phnom Penh (*i3*), Dhaka (*i4*)
Scenario 9 (*s9*)	Quanzhou (*i1*)
Scenario 10 (*s10*)	Quanzhou (*i1*), Dhaka (*i4*)
Scenario 11 (*s11*)	Quanzhou (*i1*), Phnom Penh (*i3*)
Scenario 12 (*s12*)	Quanzhou (*i1*), Phnom Penh (*i3*), Dhaka (*i4*)
Scenario 13 (*s13*)	Quanzhou (*i1*), Ho Chi Minh (*i2*)
Scenario 14 (*s14*)	Quanzhou (*i1*), Ho Chi Minh (*i2*), Dhaka (*i4*)
Scenario 15 (*s15*)	Quanzhou (*i1*), Ho Chi Minh (*i2*), Phnom Penh (*i3*)
DC disruption scenarios	
Scenario 16 (*s16*)	Sydney (*j3*)
Scenario 17 (*s17*)	Adelaide (*j2*)
Scenario 18 (*s18*)	Adelaide (*j2*), Sydney (*j3*)
Scenario 19 (*s19*)	Perth 9 (*j1*)
Scenario 20 (*s20*)	Perth 9 (*j1*), Sydney (*j3*)
Scenario 21 (*s21*)	Perth 9 (*j1*), Adelaide (*j2*)

6. Discussions: The Greening-Resilience Relationship

This section provides a thorough analysis of the relationship between SC greening and resilience for ACO based on the scenarios developed in Section 5. Four possible SC network configurations/structures are defined. The performance of each configuration is examined under 21 scenarios developed in Section 5. Table 2 shows the characteristics of the four hypothetical SC configurations. Using the same objective function, the four configurations are resulted from different values assigned to the parameters ε and p. We use the terms "brown" versus "green" and "frail" versus "resilient" to express the greening and resilience degrees of a SC configuration. An EPS of 7 was defined by the panel of experts (see panel details in Section 5) as threshold EPS in apparel industry. This implies that a minimum ε value of 7 is required for a SC to be considered as "Green". Our initial experiments revealed that the SC resilience for the proposed case problem, using a cost measure, will not improve for p values greater than 5.5 (see the sensitivity analyses in Sections 6.4 and 6.5). A resilience degree of $p = 5.5$ is therefore considered indication of a "Resilient" SC.

Table 2. The four SC network configurations for greening-resilience analysis

SC Configuration	Characteristics
Configuration 1: A brown frail SC design	Greening and resilience factors are disregarded and SC design decisions are determined by solving the model for very small values for ε and p.
Configuration 2: A brown resilient SC design	Greening factors are disregarded and a resilient SC is designed by solving the model for a very small value for ε and $p = 5.5$.
Configuration 3: A green frail SC design	Resilience factors are disregarded and a green SC is designed by solving the model for a very small value for p and $\varepsilon = 7$ (i.e. a minimum EPS of 7 in all facilities)
Configuration 4: A green & resilient SC design	Considering both greening and resilience factors by solving the model for $\varepsilon = 7$ and $p = 5.5$.

6.1 A cost comparison

We first compare the cost performance of the four SC configurations (Table 2) under disruption scenarios defined in Table 1. Initial numerical results are shown in Table 3. Applying enhanced *p*-robustness measure instead of original *p*-robustness, the constraint (5) is violated under scenarios s5, s8, s9, and s13-s15 in configuration 2. Likewise, we have small deviations from $p = 5.5$ under scenarios s2-s7, s10-s14, s16-s17 and s19 in configuration 4. On the other hand, no violation from constraint (5) is observed in configurations 1 and 3 due to the high value of *p* in these configurations.

Comparing the SC costs at the nominal scenario (scenario 1, a business-as-usual situation) in configurations 2 and 3, we find that a SC is the least costly design with no greening and resilience considerations. Thus, both greening and resilience require additional cost. Greening is more costly than building resilience into the SC ($962,603 versus $937,323). A green and resilient SC (configuration 4) seems to be the most expensive to establish. From these results, focusing on SC cost minimization in normal operational circumstances would result in the selection of configuration 1 with no resilience and greening considerations.

Now, let's examine the SC cost performance when disruptions occur. Table 3 shows that configuration 2, a resilient SC, is the least costly under all plant/DC disruption scenarios when compared to configuration 3 (a strictly green situation) and configuration 4 (a green, resilient situation). Configuration 2 also outperforms configuration 1 in 15 out of 20 plant/DC disruption scenarios. This observation is not surprising as a resilient SC is expected to be more flexible and efficient in the face of disruptions. What is interesting is the behavior of a strictly green SC under disruption risks. Not only is the SC cost for configuration 3 the highest under most scenarios, but it also shows the greatest cost variation between the nominal scenario and other scenarios (compare with the less significant SC cost variations across scenarios under configurations 2 and 4). These observations imply that a strictly green SC has the greatest overall uncertainty from potential facility disruptions.

Table 3. Total SC cost of each configuration under various disruption scenarios

Scenario	Configuration 1 (brown frail SC)	Configuration 2 (brown resilient SC)	Configuration 3 (green frail SC)	Configuration 4 (green resilient SC)
1	776,142	937,323	962,603	1,153,336
2	1,275,750	991,223	1,225,752	1,203,716
3	1,249,458	964,323	1,365,927	1,162,973
4	2,139,036	1,091,161	1,791,296	1,216,648
5	776,142	937,323	962,603	1,154,236
6	1,275,750	1,035,036	1,225,752	1,208,916
7	1,249,458	1,012,481	1,365,927	1,283,376
8	2,139,036	1,697,917	1,791,296	1,648,514
9	776,142	937,323	2,170,036	1,153,336
10	1,275,750	991,223	2,170,036	1,203,716
11	1,249,458	964,323	2,170,036	1,275,298
12	2,139,036	1,494,495	2,170,036	1,610,233
13	776,142	937,323	2,170,036	1,266,029
14	1,275,750	1,437,250	2,170,036	1,601,845
15	1,249,458	1,410,958	2,170,036	2,354,536
16	1,139,302	943,254	1,285,734	1,159,160
17	1,139,186	943,028	1,282,646	1,158,303
18	1,640,786	1,499,322	1,744,218	1,647,537
19	1,017,450	943,078	1,173,354	1,159,292
20	1,509,697	1,495,935	1,624,306	1,646,999
21	1,511,908	1,499,482	1,625,252	1,650,148

For a more nuanced cost comparison, Table 4 and Figure 2 provide additional results. Table 4 shows the percentage SC cost difference between different configurations under each disruption scenario. For each configuration, Figure 2 graphically shows the average cost incurred under all disruption scenarios. It should be noted that the experiments were completed for individual scenarios and we only use an average indicator here due to space limitation and that the average values were felt to be a good indicator of the population. A comparison between configurations 2 and 1 (the second column in Table 4) shows that building resilience can incur a 20.7% cost increase when there is no disruption. However, this additional cost incurred on buttressing the SC can save as much as 49% (in scenario 9) depending on the location and severity of a disruption. The buttressing investment is an insurance premium that protects the SC against disruption risks by designing a more flexible SC network. Figure 2 shows that the average SC cost is at the lowest in configuration 2 (about 8.2% lower than configuration 1, the closest alternative). An insight from this observation is that a resilient SC is, in general, the cheapest alternative from a strategic design viewpoint. However, since we use an average cost metric, this finding may not hold under all scenarios; for example, a resilient and green SC outperforms a resilient SC under scenario 8. A more accurate cost analysis requires access to the probability of occurrence for individual disruption scenarios, although historical data on such events are usually limited or nonexistent.

Comparison between configurations 3 and 1 can provide insights on greening the SC with no disruption risk consideration. Table 4 and Figure 2 clearly indicate that greening is expensive. When attempting to green a SC, the average SC cost increases by over 35%, yet the cost increase can be as high as 180% under scenario 9 when the manufacturing facility in Quanzhou is disrupted (see Table 4). In these situations, greening seems to reduce the network resilience or more expensive to maintain the same resilience degree (note the increased and highest SC cost under most disruption scenarios). Simultaneous incorporation of greening and resilience factors, configuration 4, is also relatively costly when compared to configuration 1. The average SC cost in this case increases by 11.9% (see configurations 4 vs. 1). Especially under the nominal scenario, it incurs a 49% cost increase for a base SC to be converted to both green and resilient. Nevertheless, joint consideration of SC greening and resilience improves SC resilience when compared to frail and brown networks.

From the comparison of configurations 4 and 2, the average SC cost increases by about 21% for greening a resilient SC. An interesting insight can be gained from this observation and comparing it with cost differences between configurations 3 and 1. Greening a resilient SC is considerably less costly than greening a frail SC (a 21% increase in the former versus a 35% increase in the latter). Thus, in this case situation a resilient SC would have greater incentive to go green than a frail SC. Also, comparing the results in columns “configuration 4 vs. configuration 3” and “configuration 2 vs. configuration 1”, we observe that planning for disruptions saves more strategic costs when resilience is built into a green SC than a brown SC (a 12.6% increase in the former versus an increase of 8.2% in the latter). Thus, there is more marginal incentive to buttress a green SC than buttressing a brown SC. Obviously, the actual cost figures and impacts on the SC performance for this organization are only known upon the realization of a disruption scenario.

Table 4. SC cost difference between paired configurations at each disruption scenario (%)

Scenarios	Config 2 vs. Config 1	Config 3 vs. Config 1	Config 4 vs. Config 1	Config 3 vs. Config 2	Config 4 vs. Config 2	Config 4 vs. Config 3
1	20.7	24.0	48.6	2.7	23.1	19.8
2	-22.3	-3.9	-5.7	23.7	21.4	-1.8
3	-22.8	9.3	-6.9	41.7	20.6	-14.9
4	-49.0	-16.3	-43.1	64.2	11.5	-32.1
5	20.8	24.0	48.7	2.7	23.1	19.9
6	-18.9	-3.9	-5.2	18.4	16.8	-1.4
7	-19.0	9.3	2.7	34.9	26.8	-6.0
8	-20.6	-16.3	-22.9	5.5	-2.9	-8.0
9	20.8	179.6	48.6	131.5	23.1	-46.9
10	-22.3	70.1	-5.7	118.9	21.4	-44.5
11	-22.8	73.7	2.1	125.0	32.3	-41.2
12	-30.1	1.5	-24.7	45.2	7.7	-25.8
13	20.8	179.6	63.1	131.5	35.1	-41.7
14	12.7	70.1	25.6	51.0	11.5	-26.2
15	12.9	73.7	88.4	53.8	66.9	8.5
16	-17.2	12.9	1.7	36.3	22.9	-9.8
17	-17.2	12.6	1.7	36.0	22.8	-9.7
18	-8.6	6.3	0.4	16.3	9.9	-5.5
19	-7.3	15.3	13.9	24.4	22.9	-1.2
20	-0.9	7.6	9.1	8.6	10.1	1.4
21	-0.8	7.5	9.1	8.4	10.1	1.5
Average	-8.2	35.1	11.9	46.7	20.8	-12.6

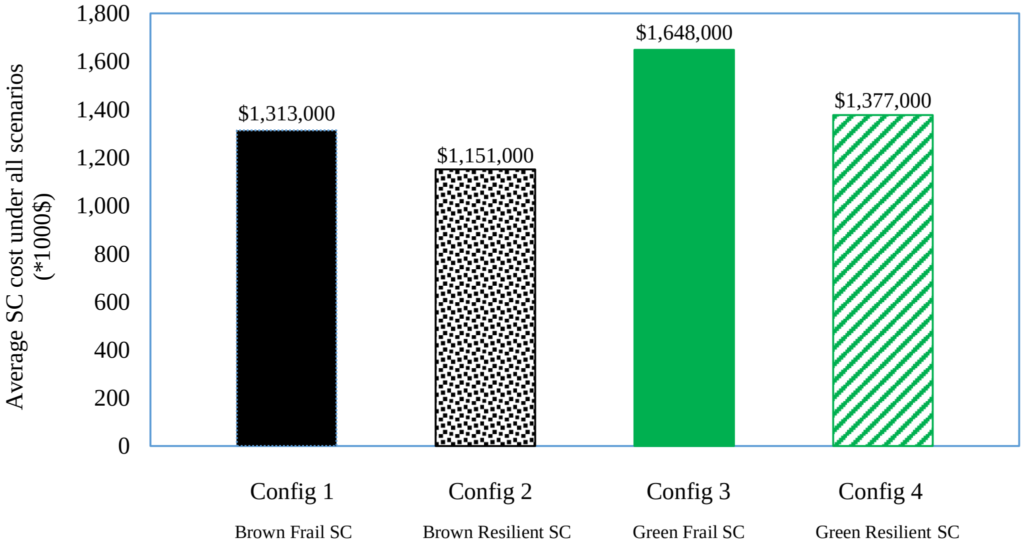


Figure 2. Average SC cost under all disruption scenarios

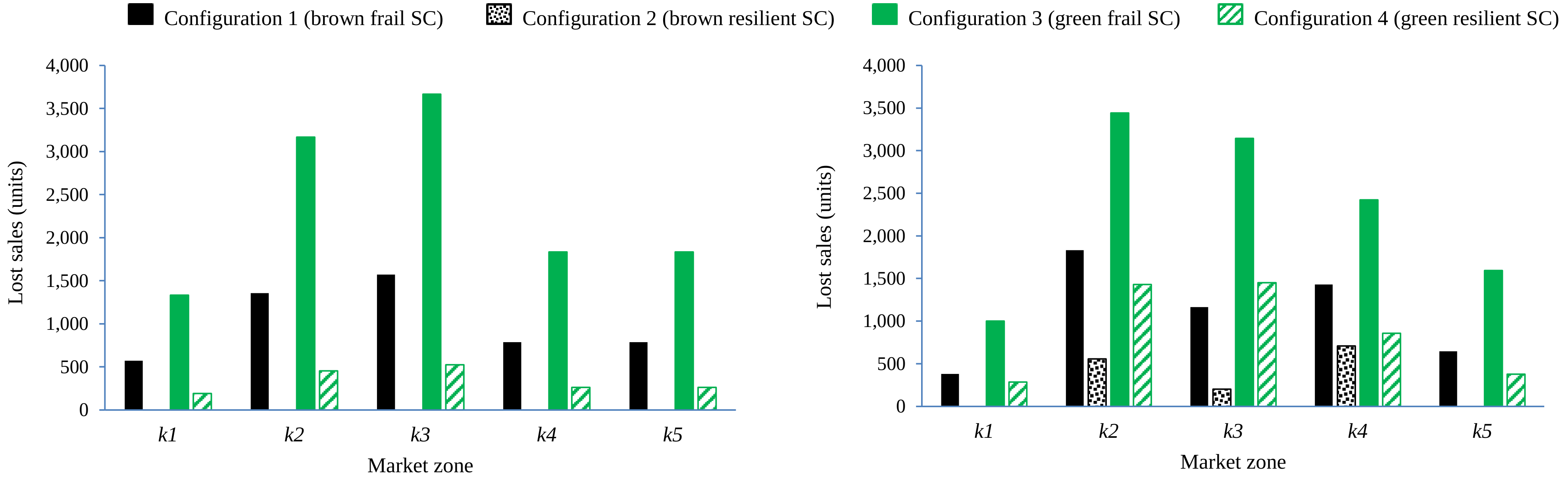
6.2 A service level comparison

We now complete a service level comparison between different SC configurations using average product lost sales as a service level measure. Lost sales are calculated based on a per-item penalty cost when demand for a product cannot be fulfilled due to the supply capacity shortage caused by a disruption. Obviously, a penalty cost may reflect the compensations paid to unhappy customers as well as the quantifiable costs of a potential long-term reputational damage. This section aims to examine to what extent the choice of a green and/or resilient configuration can influence the level of product lost sales.

For each product type, Figure 3 illustrates the average lost sales at each market location under each SC configuration. The first observation is that buttressing the SC results in significant improvement in service level (see configuration 2 against 1, and configuration 4 against 3). For the tops clothing product family (*t1*), for example, a 100% service level improvement is gained in all market zones by buttressing a brown SC (note the zero lost sales of configuration 2 in Figure 3a).

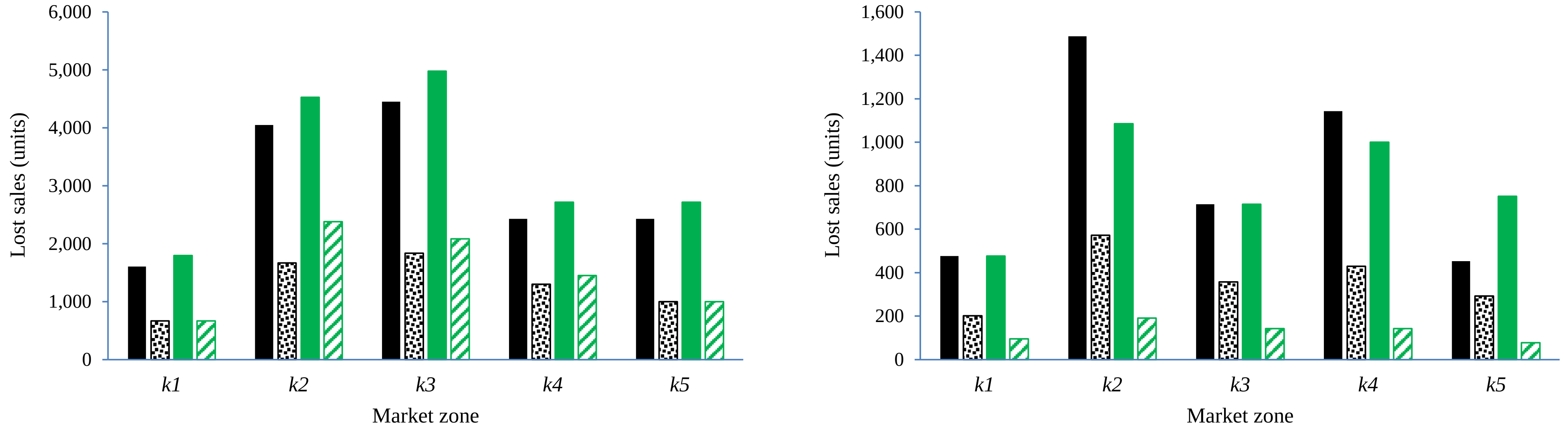
The green SC design displays the worst service level amongst all configurations. Thus, not only is strictly green SC most costly, but it also has the lowest service level. These results seem counter-intuitive. On one hand, a primary incentive to go green is to establish and sustain a good corporate image. On the other hand, a strictly green SC results in an increased lost sales which may result in long-term reputational damage under a disruption scenario. Marrying SC greening and resilience seems to be one solution to this contradiction, even though in the short term it may result in a relatively costly alternative.

We also observe that in most cases buttressing a green SC appears to result in greater service level improvement than buttressing a brown SC. Therefore, planning for resilience may be more worthwhile for a green SC in terms of lost sales improvement. This observation coincides with the cost performance results presented in Section 6.1. Not only does a green and resilient SC (configuration 4) result in higher service than frail SCs (configurations 1 and 3), but there are also situations where configuration 4 outperforms configuration 2 in service level (see Figure 3d, for example). More detailed results (not reported in the figure) show that configuration 4 only loses sales under severe scenario 15 when multiple SC facilities are disrupted. A green and resilient SC may therefore be regarded as a better or “as good” performer when compared to a purely resilient SC.



3a. Tops (*t1*)

3b. Pants (*t2*)



3c. Shorts (*t3*)

3d. Jackets (*t4*)

Figure 3. Average lost sales for each product type in five market zones

6.3 A SC configuration comparison

In this section, the size and type of facilities within each configuration and relative influences are evaluated. The characteristics of the four SC configurations including the size and technology type of the manufacturing plants and the size of the DCs are shown in Table 5. The values in Table 5 were obtained by solving the model separately for each configuration. For instance, solving the model for the first configuration involves opening large plants with production technology level 1 (*N1*) in Cambodia (*i3*) and Bangladesh (*i4*). Also, for the first configuration a small DC is located in Western Australia (j1) and two large DCs are opened in South Australia (*j2*) and New South Wales (*j3*).

An immediate observation is that the manufacturing plant in Vietnam (*i2*) is only opened in configurations 2 and 4 which represent the more resilient SCs. This observation indicates that one strategy in buttressing the SC against potential facility disruptions is to open more facilities in different geographical locations. The second observation relates to the capacity/size of the manufacturing facilities. Larger plants are established in configurations 2 and 4 to help the SC shift its production operations between facilities when facing disruption in one location. Therefore, establishing numerous and larger facilities in dispersed locations is used as a strategy for better production capacity adjustment during disruption situations. This structural analysis also explains the additional costs incurred to design and manage a more resilient SC; the costs to immunize the SC against disruptions.

The above discussion on the size of manufacturing facilities also holds for the size of storage facilities. Larger DCs are used in configurations 2 and 4, although, unlike production facilities, the three DCs are operational in all configurations, presumably, due to the geographical dispersion of market zones across the nation. Also, it is worth mentioning that in no configuration is the DC in west coast (*j1*) larger than DCs in the south and east coasts (*j2* and *j3*), evidently due to the larger population density and market demand in the other two areas.

configurations 3 and 4 use greener production technologies which constitute part of the costs incurred for greening the SC in these two configurations. The results show that greening the SC results in opening smaller facilities with greener technologies. However, production technology is not the only greening measure as EPSs are assigned based on the production technology adopted, energy sources available, and the environmental performance of the suppliers of each plant. Determining the actual cost of greening may require a more detailed set of data and analyses of the cost components, which is beyond the scope of this study.

Table 5. Characteristics of production and storage facilities for each configuration

	Manufacturing plants								DCs		
	i1		*i2*		*i3*		*i4*		*j1*	*j2*	*j3*
Configuration 1: A brown frail SC					L*	N1**	L	N1	S	M	M
Configuration 2: A brown resilient SC	M	N1	L	N1	L	N1	L	N1	L	L	L
Configuration 3: A green frail SC	S	N5			M	N1	S	N2	S	M	M
Configuration 4: A green & resilient SC	L	N2	L	N4	L	N5	S	N3	L	L	L

* Facility sizes L: Large, M: Medium, S: Small

** Production technology adopted N1-N5 (N5 being the greenest)

6.4 Sensitivity analysis: a resiliently green SC

A more detailed resilience analysis for a green SC is now completed by examining the impact of varying resilience degree (p) on the cost performance of a green SC. The aim here is to explore the cost tradeoffs for the development of *a resiliently green SC* (a green SC with some degree of resilience). This analysis helps a decision maker identify potential tradeoffs between the total cost and the resilience of the SC (and thereby to choose an appropriate value for the resilience degree (p) of the SC) and to scrutinize how much it costs to buttress a green SC.

Figure 4 illustrates the cost performance of a green SC over a range of resilience degrees, while the values of the other parameters are equal to those in configuration 3. At each resilience degree, the total SC cost of the nominal scenario (solid line) and the average SC cost in disruption scenarios (dashed line) are shown. Note that we refer to the nominal scenario as business-as-usual. The figure visually illustrates the tradeoff between the SC cost in a business-as-usual situation and the average SC cost under a set of disruption scenarios. The latter can be named *the price of buttressing*. No changes in the SC cost can be observed for p values smaller than 0.8 and larger than 5.5.

The cost curves display erratic behavior as the resilience degree increases. An immediate and interesting insight from Figure 4 is that a significant reduction in SC cost in disruption situations can be gained (see the dashed line steepness at its left end) at initial rises in nominal costs of a green SC (the solid line steepness). Even though our earlier numerical results revealed that buttressing a green SC is expensive (if seeking to develop a green and fully resilient SC), this cost tradeoff analysis shows that developing a resiliently green SC can be less costly at smaller resilience degrees. Developing a green SC with a resilience degree of up to p=2 may impose an approximately 9% SC cost increase under the nominal scenario. Obviously, there will also be accompanying service level improvement benefits (smaller lost sales) corresponding to the level of improved resilience. This finding is important since it introduces joint financial and reputational incentives for a green SC to become "resiliently green", but this decision requires a careful tradeoff analysis.

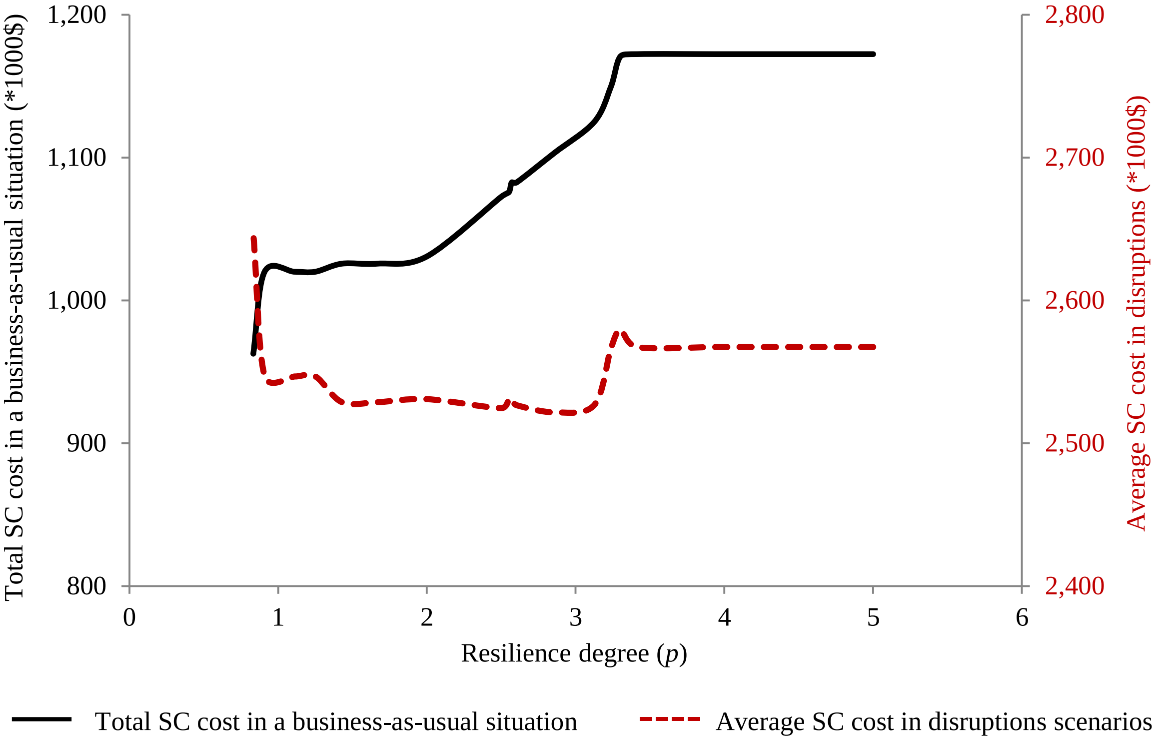


Figure 4. The impact of varying resilience degree on a green SC

6.5 Sensitivity analysis: a greenly resilient SC

A greening analysis on a resilient SC (configuration 2) is also completed to determine what tradeoffs exist for developing a *greenly resilient SC*. The aim is to explore tradeoffs between the greening degree and the cost of a resilient SC. The greening degree of the SC is imposed by the value of the threshold EPSs (ε). We investigate the influence of varying ε on the SC cost performance, while the values of the other parameters are set equal to what we had in configuration 4. Such analysis can help a decision maker determine the costs associated with enhancing the greenness of a resilience SC and eventually finding a more suitable value for the parameter ε .

Figure 5 shows changes in costs of a resilient SC, including changes in total cost in a business-as-usual situation and average cost under disruption scenarios, as the greening degree (expressed by the threshold EPS) increases towards threshold EPS 10, the greenest performance. For this analysis, manufacturing EPSs are used as the only greening measure. The rationale for this focus is that the production of synthetic material is the predominant environmental sustainability concern in the apparel industry, and in particular sportswear manufacturing (most production processes are water- and energy-intensive).

However, aggregated weighted EPSs can be used for sustainability analyses of all SC participants, if necessary.

Figure 5 shows that the average SC cost for managing potential facility disruptions has a continuously increasing pattern as the network becomes greener, evidenced by the trend of the dashed line. This result reinforces previous observations in this paper that SC greening makes the network more vulnerable to disruptions. In most cases, more costs are also incurred under the nominal scenario for greening the SC. For ACO, there is a slight decrease in SC cost when EPS rises from a 7.5 to 8 rating. In a business-as-usual situation, developing a green SC with a threshold EPS of 8 is almost as costly as a SC with a threshold EPS of 6. Although, the former incurs more costs if disruptions occur. This is a good example for situations when a tradeoff analysis can help determine the appropriate SC greening degree, and hence threshold EPSs. It is also an illustration of a broader analysis over various greening ranges when facing a nonlinear cost structure. ACO would interpret this result by choosing an EPS of 8 over 7.5 because the reduced SC costs under the nominal scenario outweighs the average cost increase in disruption situations.

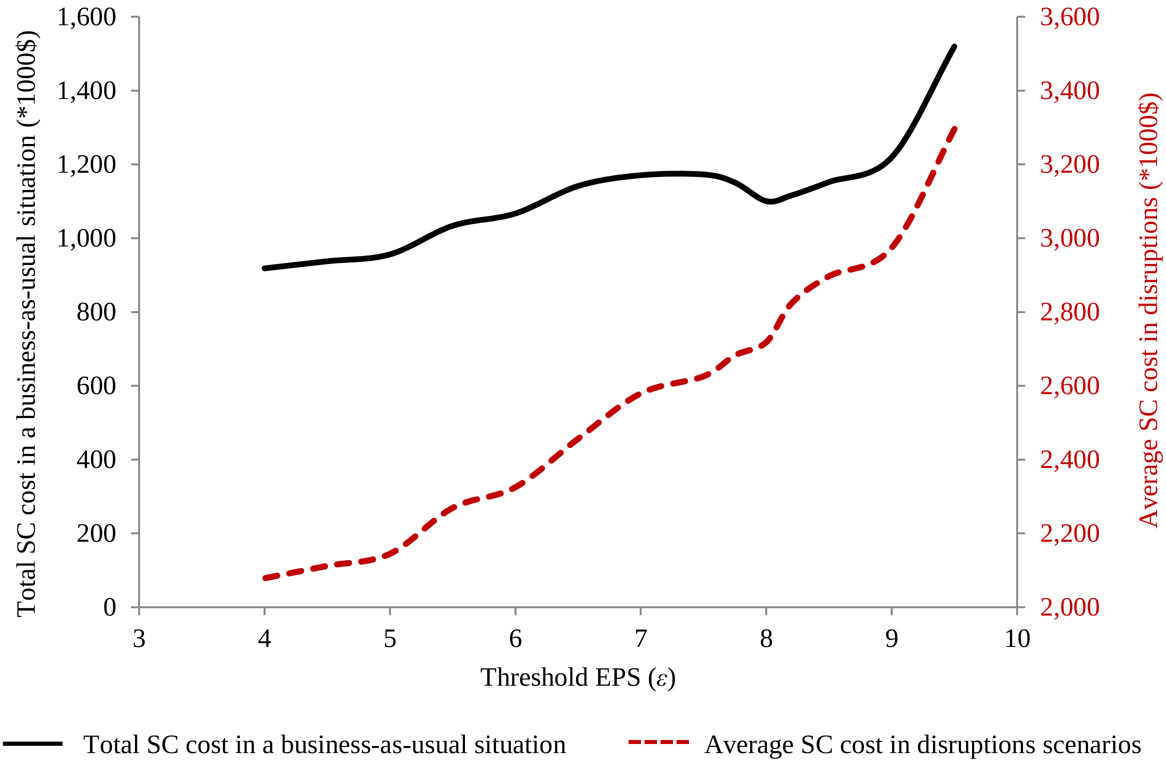


Figure 5. The impact of varying greening degree (expressed by threshold EPS) on SC resilience

7. Conclusions

SC modeling literature focusing on the design of *eco-efficient* and *resilient* SCs has expanded rapidly in recent years. These two emerging topics have been investigated in isolation. Analytical modeling efforts can provide organizations with exploratory insights into the potential impacts of greening interventions on SC resilience, or vice versa. This is the area we aimed to contribute to in this paper. In particular, we focused our study and investigation on (1) exploring the relationship between SC greening and resilience at the SC design level, and (2) seeking greening-resilience tradeoffs for design of resiliently green SCs and greenly resilient SCs.

An environmental performance scoring approach and a new robustness measure, named elastic *p*-robustness, were used to complete a thorough greening-resilience analysis for a case company from the apparel industry. The key managerial insights obtained include (1) both greening and resilience comes with a cost and hence a SC is the least expensive to design with no greening and disruption risk considerations; (2) a strictly green SC is the most affected, in terms of SC costs and service level, by disruptions of any kind; (3) a resilient SC is the most efficient, a financial measure, and effective, a service level measure, alternative in the long term because the additional costs incurred to buttress a SC can save significant dollars in disruptions; (4) greening a resilient SC is considerably less costly than greening a frail SC; and (5) from a strategic viewpoint, buttressing a green SC is more worthwhile (in terms of SC costs and service level) than buttressing a brown SC.

For the case company and its parametric data, a tradeoff analysis helped identify the appropriate degrees of greening and resilience to plan for. The greening-resilience tradeoff analysis for the proposed case company showed that building a small degree of resilience into a green SC can save substantial costs and improve service level in disruption situations. This situation represents a strong financial and reputational incentive for a green SC to become “resiliently green”. Whilst such results may not hold for cases with different parametric properties and characteristics, the methodology and tool presented in this paper can be effective for general SC greening-resilience tradeoff analysis.

Although the methodology and models presented here can provide significant insights, there are limitations that can be used to help expand research at the nexus of SC greening and resilience. For example, different types of disruptions may impact various regions in differing ways. The SC greening-resilience argument can be studied in situations where facilities are affected differently when disruptions occur. Given that this study is an early attempt to explore the greening-resilience relationship, it did not intend to cover all disruption aspects, such as disruption frequency, probability, severity, etc. Introduction of these various characteristics can provide valuable insights.

This study focused only on the analysis at the strategic design level. Another direction for future research can be to complete similar analyses and tradeoff investigations at the tactical and operational planning levels. Looking at these lower levels of analysis will help explore how such tradeoff decisions can be affected by short-term and frequent supply, demand and lead-time variations/interruptions. Furthermore, the issue of reputational costs and benefits from greening and its explicit integration into these models need to be further investigated. And finally, the potential cost of greening-based disruptions, such as toxic spells, can be incorporated as the level of analysis shifts towards broader industry and/or government policy concerns.

These are some foreseen future research directions identified from the limitations of the model and case example. We believe that there are significantly more issues that can be investigated from these very important and fertile directions for future research. The implications of these joint investigations for both greening and resilience can be either broadened or more focused.

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