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A multi-objective model for risk mitigating in supply chain design

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The goal of this study is to recognise various factors for responsive SCs that affect supply risk and model their impact on SC design and operation. We propose a conceptual model for SC responsiveness that encompasses practices such as flexibility, agility, internal integration, and visibility. This conceptual model is utilised to build up a multi-objective, multi-period SC design and operation model. A heuristic algorithm is developed to find the supplier, product, period, and production rate for the numerical problem. The improved genetic algorithm (GA) produces solutions with more accuracy in considerably less time than a traditional GA. Finally, an approach to prioritise the objective functions is developed that allows managers to focus on specific objective functions more than optimum values. This approach provides risk-averse, responsiveness-oriented, cost-effective managers the capability to set priorities based on their policies.

Keywords: supply chain; responsiveness; risk; genetic algorithm

1. Introduction

In today's dynamic business environment, SC responsiveness is the main factor in planning business accomplishments (Mohammaddust et al. 2017). SC responsiveness is described by the rate which an SC can adapt its output within the available levels of four external flexibility types: product, mix, volume, and delivery in answer to an outside motive, e.g. a customer order (Yi, Ngai, and Moon 2011). According to Holweg (2005), responsiveness is the strength to respond purposefully and within a suitable timescale to customer's demand or innovations in the marketplace, to bring about or sustain an ambitious advantage. A responsive SC reduces the lead time and enhances service reliability, fast responses, and adaptability. Many SCs are not ready to endure global competition because of responsiveness absence to satisfy market needs (Singh 2015; Ambulkar, Blackhurst, and Cantor 2016; Carbonara and Pellegrino 2018; Gouda and Saranga 2018; Yoon et al. 2018; Lücker, Seifert, and Biçer 2019). Developing plans for a responsive SC is a challenge because it needs an in-depth investigation of the communication among the principal agents responsible for responsiveness. We try to fulfil these gaps in the literature by presenting a more nuanced analysis of the antecedents of SC responsiveness. In doing so, we address SC responsiveness that is exposed to two types of risk: demand risk and supply risk. For instance, any disruption or fluctuation that affect supply and demand is called risk. The principal objectives of this research are to:

(1) recognise significant success determinants of responsiveness in SC,
(2) build the fundamental relationships among the antecedents of responsiveness,
(3) determine the impact of the conceptual model on SC design and operation modelling and solution.

The practical significance of this research paper is about a trade-off model in any SC where we have demand and/or supply risk. First, SC owners should determine how much SC investment on SC responsiveness including SC agility, flexibility, internal integration and visibility effective and enough is to mitigate existing demand and/or supply risk. Then, a trade-off model between cost, risk, and responsiveness provide us minimised cost which is adequate to mitigate the existing risk through SC responsiveness. Any possible combination of different items of SC responsiveness could be an alternative to mitigate risk, to understand which combinations should be selected in the optimisation solution.

This study is organised as follows. Section 2 presents a literature review of crucial responsiveness factors, associated definitions, and our conceptual model. Section 3 contains our mathematical model based on the results in Section 2. Section 4

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includes numerical results and the heuristic algorithm design. Section 5 shows the prioritisation method design for multi-objective problems with binary decision variables. Section 6 contains the results of the prioritisation algorithm. Finally, we conclude the paper in Section 7.

2. Literature review

In this section, we first discuss factors related to responsiveness. Among all factors affecting SC responsiveness, we narrow our focus to visibility, SC agility, internal integration, and external. The reason that we limit effective factors to these four is that these factors are tested statistically in the literature. Hypothesis tests in literature reveal that such factors improve SC responsiveness (Braunscheidel and Suresh 2009; Williams et al. 2013; Ojha et al. 2018; Ge et al. 2019; Vanalle, Lucato, and Ganga 2019). The other factors are listed in Table 1 to show how many factors exist to improve SC responsiveness.

Table 1. SC responsiveness drivers.

No.	Critical factors	References
1	Top management commitment is a part of responsiveness	Singh (2015), Kannabiran and Bhaumik (2005), Arshinder, Kanda, and Deshmukh (2007)
2	Strategy development is a part of flexibility	Singh (2015), Kannabiran and Bhaumik (2005), Melnyk et al. (2010), Sun, Hsu, and Hwang (2009), Mitra and Bhardwaj (2010), Qi, Zhao, and Sheu (2011), Khan, Christopher, and Creazza (2012), Doha, Das, and Pagell (2013), Talay, Calantone, and Voorhees (2014), Kumar, Singh, and Shankar (2014), Morita et al. (2015)
3	Resource development is a part of flexibility	Singh (2015), Shin, Collier, and Wilson (2000), Singh (2013)
4	Trust development between SC members is a part of responsiveness	Anderson and Narus (1990), Sahay (2003), Tejpal, Garg, and Sachdeva (2013)
5	Information sharing between SC members is a part of internal integration	De Treville, Shapiro, and Hameri (2004), Ramdas and Spekman (2000), Ozer (2003), Fawcett et al. (2009), Barratt and Oke (2007), Hendricks and Singhal (2012)
6	Risk and reward sharing by SC members is a part of part of responsiveness	Cachon and Lariviere (2005), Lee (2000), Zsidisin and Smith (2005), Jüttner (2005), NishatFaisal, Banwet, and Shankar (2006), Sodhi, Son, and Tang (2008), Sáenz and Revilla (2014), Narasimhan and Talluri (2009), Li et al. (2015), Bak (2018), Kumar and Park (2018)
7	Collaborative decision-making and planning by SC members is a part of internal integration	Zare Mehrjerdi (2009), Tsay (1999), Cachon and Fisher (2000), Disney and Towill (2003), Kim and Lee (2010)
8	Use of IT technology is a part of visibility	Fawcett et al. (2009), Lee and Ng (1997), Hult, Ketchen, and Arrfelt (2007), Kim, Cavusgil, and Calantone (2006)
9	Coordinated SC is a part of internal integration	Zare Mehrjerdi (2009), Kumar, Singh, and Shankar (2014), Singh (2013)
10	Accurate forecasting of data by SC Members is a part of internal integration	Michelino, Bianco, and Caputo (2008), Hendricks and Singhal (2005), Pawlak and Małyszek (2008)
11	Integrated inventory management by SC members is a part of internal integration	Sahay (2003), Hendricks and Singhal (2005), Pawlak and Małyszek (2008)
12	Lead time reduction is a part of agility	Disney and Towill (2003), Forza and Vinelli (2000), Gunasekaran, Patel, and Tirtiroglu (2001)
13	Agreed vision and goals of SC members are a part of visibility	Arshinder, Kanda, and Deshmukh (2007), Kumar, Singh, and Shankar (2014), Simatupang, Wright, and Sridharan (2002)
14	Long-term relationship between SC members is a part of responsiveness	Tejpal, Garg, and Sachdeva (2013), Olorunniwo and Hartfield (2001)
15	Availability of point of sales data is a part of visibility	Prajogo and Olhager (2012), Michelino, Bianco, and Caputo (2008), Pawlak and Małyszek (2008)
16	SC visibility	Williams et al. (2013), Hendricks and Singhal (2005), Matt, Rauch, and Dallasega (2015)
17	Internal integration	Williams et al. (2013), Schoenherr and Swink (2012)
18	External flexibility	Braunscheidel and Suresh (2009), Williams et al. (2013)
20	SC Agility	Brusset (2016), Gligor, Esmark, and Holcomb (2015)

2.1. Visibility and responsiveness

To reduce SC risk, supervisors showed that higher SC visibility by automatically and regularly receiving different kinds of supply and demand information (Williams et al. 2013; Ivanov, Das, and Choi 2018; Sawik 2018). Researchers have shown that such visibility allows excellent responsiveness (Lummus, Vokurka, and Duclos 2005; Singh 2015; Yin and Wang 2018; Ivanov, Dolgui, and Sokolov 2019). The need for visibility may have negative values, such as weak decision-making, the bullwhip consequence, unnecessary inventories, and exposing the profit margin of the whole SC (Prajogo and Olhager 2012; Ivanov and Dolgui 2018; Kumar Dadsena, Sarmah, and Naikan 2019). Greater visibility into supply and demand conditions permits quicker and greater decision-making for responsive production systems (De Treville, Shapiro, and Hameri 2004; Shekarian 2018; Parast, Sabahi, and Kamalahmadi 2019; Parast and Shekarian 2019). Commonly, SC visibility is represented as the capability of sharing on-time and reliable data on consumer demand, amount and spot of inventory, shipping cost, and other logistics elements through SC.

2.2. Internal integration and responsiveness

An organisation's internal integration provides corresponding information processing abilities needed to provide the responsiveness demanded from greater SC visibility (Williams et al. 2013). Schoenherr and Swink (Schoenherr and Swink 2012) explained that internal integration can reduce the relationship between external integration and company efficiency. Internal integration promotes practical goal adjustment, highlights inter-organisational inter-dependencies, and authorises the utilisation of each functional area's capacities through information sharing and useful collaboration (Schoenherr and Swink 2012). Therefore, internal integration empowers exceptional responsiveness (Sawhney 2006; Wong, Boon-Itt, and Wong 2011). Moreover, internal integration may be defined as an interconnection of processes and systems that help decision-making with a high quality of collaboration among functional areas.

2.3. Agility and SC responsiveness

Bernardes and Hanna (2009) defined agility as the ability of the system to rapidly reconfigure. Expeditious and higher efficient planning qualifies the company to improve its operations soon and completely in reply to the changing business conditions. Researchers have empirically associated internal integration with SC agility (Braunscheidel and Suresh 2009). Gunasekaran, Lai, and Cheng (2008) and Yusuf et al. (2004) suggested that agility is needed to heighten the ability of SC to react quickly to changes in customers' demand and therefore increase the responsiveness of SC. Reliable forecasting of data presents inventory reduction, agility in SC, and eventually a responsive SC. Agility in SC improves the responsiveness of SC (Li et al. 2008; Zare Mehrjerdi 2009). Williams et al. (2013) demonstrate that demand-information sharing and end-to-end visibility are critical enablers of SC agility (responsiveness). Agility enables an SC to adopt customers' requirements which will likely have a positive impact on customer retention and company performance (Shin et al. 2015). SC agility is defined as an ability of making rapidly possible changes or re-configurations often in an unpredictable environment.

2.4. External flexibility and SC responsiveness

The previous studies have classified various kinds of flexibility. Flexibility empowers organisations to follow supply and demand responsively. Many researchers have suggested hierarchical structures correlating flexibility characters to each other and overall responsiveness (Koste and Malhotra 1999; Holweg 2005; Reichhart and Holweg 2007; Stevenson and Spring 2007; Malhotra and Mackelprang 2012). The responsiveness in an SC is the velocity at which the system can change its output into the available range of four external flexibility types (product, mix, volume, and delivery) in response to an outer motive, e.g. a customer order (PietervanDonk and vanderVaart 2007). Modularity in a process and product design has been recommended as a way for companies to decrease their SC risk and to obtain a high level of adaptability (Kleindorfer and Saad 2005). Accordingly, responsiveness can be achieved through both flexibility and reconfigurability (Jimenez et al. 2015). Flexibility can be performed by executing an SC agile, i.e. adapting fast and efficiently to quickly evolving customer demands (Lin, Chiu, and Chu 2006). Therefore, external flexibility is defined as the abilities which reveal the ways that SC managers improve their production/delivery capacities and qualities in response to changes in customer markets and supply.

To provide a context for these four factors, Table 1 summarises the critical factors for SC responsiveness primarily identified by Singh (2015). Some of these factors are process-oriented, and some are result-oriented. Singh (2015) uses interpretive structural modelling (ISM) to create a complex system model of the relationships between factors. Our approach uses this concept with factors that have been statistically proven. A number of factors from Table 1 may be viewed as inputs into four factors forming the research focus.

Table 2. Direct and indirect determinants of responsiveness.

Source	Effective Factor	Hypothesis
Williams et al. (2013)	Internal integration	Internal integration is positively related to SC responsiveness
	Demand visibility	Internal integration positively moderates the relationship of demand visibility to SC responsiveness
	Supply visibility	Internal integration positively moderates the relationship of supply visibility to SC responsiveness
Braunscheidel and Suresh (2009)	Market orientation	Market orientation affects internal integration Market orientation affects external integration Market orientation affects external flexibility
	Learning orientation	Learning orientation affects internal integration
	Internal integration	Internal integration affects external integration Internal integration affects company's SC agility
	External integration	External integration affects company's SC agility
	External flexibility	External flexibility affects company's SC agility
	SC Agility	SC agility affects SC responsiveness
Gupta and Somers (1996), Womack and Jones (1996), Swafford, Ghosh, and Murthy (2006)	Mix and Volume of external flexibility	Mix and volume of external flexibility are intended to improve responsiveness in an organisation

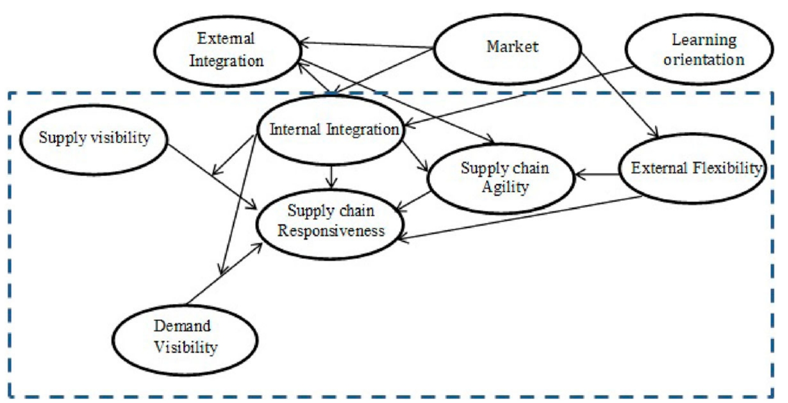

Figure 1. Graphical representation of relationships among the antecedents of responsiveness.

Table 2 lists the instances where the relationship among key variables related to SC responsiveness has been statistically supported. Figure 1 provides the graphical relationship between key factors and SC responsiveness based on our review of the literature (Gupta and Somers 1996; Womack and Jones 1996; Zhang, Vonderembse, and Lim 2003; Sawhney 2006; Braunscheidel and Suresh 2009; Williams et al. 2013). In other words, SC agility, internal integration, SC visibility and demand visibility increase SC responsiveness dramatically. It should be noted that these relationships were examined in isolation; thus, our contribution is to provide a more holistic and nuanced examination of the determinants of SC responsiveness inspired by the ISM output. We focus on those factors shown to have a direct impact on responsiveness as indicated by the dotted block in Figure 1.

We design a statistical test to investigate whether visibility is related positively to SC responsiveness since the relationship between SC visibility and responsiveness has not been verified in prior studies (Williams et al. 2013). To perform a regression analysis between visibility and responsiveness, we use numerical values on risk and visibility provided by Yu and Goh (2014). To calculate responsiveness values, we used a questionnaire (with almost 200 samples) with questions about customer satisfaction regarding the combination of internal integration, SC agility, SC visibility, and SC agility (Table 3).

H1: SC visibility is positively related to SC responsiveness.

Table 3. ANOVA table for regression analysis.

	Df	SS	MS	F	Significance p
Regression	1	4.61	4.61	27.267	0.001
Residual	7	1.18	0.169		
Total	8	5.79			

Table 4. Binary solution values (Y_{ijt}) for responsiveness.

	j_1		j_2	
	i_1	i_2	i_1	i_2
t_1	1	1	0	0
t_2	0	1	1	0
t_3	0	0	1	1
t_4	0	0	1	1

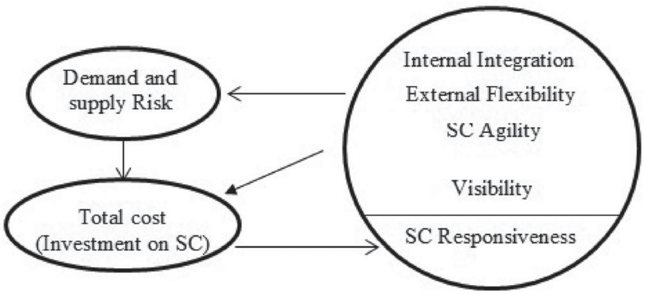

Figure 2. SC responsiveness under risk (Nooraie and Parast 2016).

Results in ANOVA Table 4 show that H1 is significant. According to Figure 1 and the hypothesis test, we design a conceptual model to show how responsiveness works in an SC under demand and supply risk. Figure 2 shows factors that have a direct impact on SC responsiveness in an SC under risk. Nooraie and Parast (Nooraie and Parast 2016) got the same results and showed that SC visibility has a positive impact on SC efficiency where it is interpreted as SC responsiveness. When demand and supply are under risk (i.e. demand and supply fluctuations), an SC should respond to changes in demand and supply. A cost is imposed by any investment in responsiveness builders (internal integration, agility, external flexibility, and visibility), so we have a trade-off between three main elements: responsiveness, risk, and cost. Moreover, improved responsiveness affects cost minimisation by benefits that come from customer satisfaction. In the next section, we discuss challenges to having three objective functions simultaneously in a mathematical model. To model SC responsiveness, we design it as a combination of internal integration, SC agility, flexibility, and visibility. In other words, any level of internal integration, SC agility, flexibility, and visibility provides a level of SC responsiveness.

2.5. Multi-objective mathematical model

Several existing test case prioritisation techniques leave out the execution cost of test cases and exploit a single objective function. Marchetto et al. (2016) presented a multi-objective test case prioritisation technique and determines the ordering of test cases that maximise the number of discovered faults that are both technical and business critical. In other words, new technique aims at both early discovering faults and reducing the execution cost of test cases. A critic on their paper, the method does not make percentage on each objective function based on any priority therefore we are looking a way to prioritise objective functions at the same time to say which objective function has the highest and which one has the lowest percentage.

3. Mathematical model

A mathematical model is proposed including SC responsiveness (SCRSP) based on its elements (internal integration, SC agility, visibility, and external flexibility) and SC risk as well as SC cost so that the suitable suppliers can be recognised.

The developed multiple-objective integer programming model holds three objectives: Responsiveness maximisation, Risk minimisation, and Cost minimisation. Responsiveness is a combination of essential factors including internal integration, external flexibility, agility, and visibility. The formulation of the model is explained as follows. The model is multi-product, multi-period and considers SC design (selection of participants) and operation (level of production for each participant). Nooraie and Parast (2016) showed that multi-objective time-dependent problem is NP hard, therefore, this model is NP hard too. In the model, each supplier includes an associated configuration of responsiveness and risk parameters. The list of notations in our model is as follow:

Indexes:

i: index of products

j: index of suppliers

t: index of time

Parameters:

B_{it}: budget available to enhance SCRSP for product i in period t

C_{jt}: production capacity of supplier j in period t

CR_{ijt}: cost of reducing risk for product i from supplier j in period t

CI_{ijt}: cost of enhancing internal integration to the current level for product i from supplier j in period t

CS_{ijt}: cost of enhancing SC agility to the current level for product i from supplier j in period t

CE_{ijt}: cost of enhancing external flexibility to current level for product i from supplier j in period t

CA_{ijt}: cost of enhancing the impact of internal integration on SC agility to the current level for product i from supplier j in period t

CF_{ijt}: cost of enhancing the impact of external flexibility on SC agility to the current level for product i from supplier j in period t

CV_{ijt}: cost of enhancing impact of visibility via internal integration moderator on SC responsiveness to current level for product i from supplier j in period t

D_{it}: demand of product i in period t

m_{ijt}: minimum order quantity for product i required by supplier j in period t

P_{ijt}: purchase price for product i supplied by supplier j in period t

IR_{ijt}: impact (financial loss) caused by risk for product i from supplier j in period t

R_{ijt}: risk for product i from supplier j in period t Rit: maximum allowable risk for product i in period t

IN_{ijt}: internal integration incurred if product i is supplied by supplier j in period t

SC_{ijt}: SC agility incurred if product i is supplied by supplier j in period t

EF_{ijt}: external flexibility incurred if product i is supplied by supplier j in period t

VS_{ijt}: visibility incurred via internal integration moderator if product i is supplied by supplier j in period t

EL_{ijt}: impact of external flexibility on SC agility incurred if product i is supplied by supplier j in period t

IS_{ijt}: impact of internal integration on SC agility incurred if product i is supplied by supplier j in period t

IN_{it}: minimum amount of internal integration needed for product i in period t

SC_{it}: minimum amount of SC agility needed for product i in period t

EF_{it}: minimum amount of external flexibility needed for product i in period t

EL_{it}: minimum amount of external flexibility impact on SC agility needed for product i in period t

IS_{it}: minimum amount of internal integration impact on SC agility needed for product i in period t

VS_{it}: minimum amount of visibility via internal integration moderator impact on SC responsiveness needed for product i in period t

Decision variables:

Y_{ijt}: A binary variable determined by whether product i is supplied by supplier j in period t

Q_{ijt}: Quantity of product i provided by supplier j in period t

The minimum amount of responsiveness is determined by agility, external flexibility, and internal integration levels. The mathematical model is as follow:

SCRSP Model:

$$\text{Max Responsiveness} = \sum_{i,j,t}(IN_{ijt}Y_{ijt} + SC_{ijt}Y_{ijt} + EF_{ijt}Y_{ijt} + IS_{ijt}Y_{ijt} + EL_{ijt}Y_{ijt} + VS_{ijt}Y_{ijt}) \quad (1)$$

$$\text{Min Risk} = \sum_{i,j,t} R_{ijt}Y_{ijt} \quad (2)$$

$$\text{Min Cost} = \sum_{i,j,t}(CI_{ijt}Y_{ijt} + CS_{ijt}Y_{ijt} + CE_{ijt}Y_{ijt} + CA_{ijt}Y_{ijt} + CF_{ijt}Y_{ijt} + CV_{ijt}Y_{ijt} + R_{ijt}CR_{ijt}Y_{ijt} + IR_{ijt}Y_{ijt} + P_{ijt}Q_{ijt}) \quad (3)$$

Subject to :

$$\sum_{j}(IN_{ijt}CI_{ijt} + SC_{ijt}CS_{ijt} + EF_{ijt}CE_{ijt} + IS_{ijt}CA_{ijt} + EL_{ijt}CF_{ijt}) + \sum_{i,j,t} VS_{ijt}CV_{ijt}Y_{ijt} \le B_{it} \quad \forall i,t \quad (4)$$

$$\sum_{j}(IN_{ijt} + SC_{ijt} + EF_{ijt} + IS_{ijt} + EL_{ijt}) + \sum_{i,j,t} VS_{ijt}Y_{ijt} \ge IN_{it} + SC_{it} + EF_{it} + IS_{it} + EL_{it} + VS_{it} \quad \forall i,t \quad (5)$$

$$\sum_{j} Q_{ijt} \ge D_{it} \quad \forall i,t \quad (6)$$

$$\sum_{i} Q_{ijt} \le \sum_{i} C_{jt}Y_{ijt} \quad \forall j,t \quad (7)$$

$$\sum_{j} R_{ijt}Y_{ijt} \le R_{it} \quad \forall i,t \quad (8)$$

$$Q_{ijt} \ge m_{ijt}Y_{ijt} \quad \forall i,j,t \quad (9)$$

$$Q_{ijt} \le NY_{ijt} \quad \forall i \quad (10)$$

$$Q_{ijt} \ge 0 \quad \forall i,j,t \quad (11)$$

$$Y_{ijt} \in \{0,1\} \quad \forall i,j,t \quad (12)$$

Constraint (4) limits the spending of SCRSP under a purposed budget for all suppliers. Constraint (5) considers the minimum value of responsiveness for each product. Constraint (6) estimates the demand volume for each product. Constraint set (7) serves as the capacity constraint for each supplier. Constraints in the set (8) limit the highest permissible risk for each product provided by suppliers. Constraint (9) defines the minimum order size of each product for all suppliers. Constraint set (10) checks a conflict of the decision variables; N is selected a comparatively large number (it is important to select a large number). Constraint set (11), while excessive, maintains the non-negativity of each value of each product. Constraint (12) is the definition of the decision variables. In the next section, we have a numerical example to explain how the model works (the first example of Appendix A).

Note that risk here is linear and additive as SC participants are added. We recognise some forms of risk reduction strategies involve increasing the number of participants. In this case, the number of participants will be kept small due to associated costs. Additionally, we represent the most flexible case where design (who participates) and operation (level of participation) may change in each new time period. This model could be decomposed into separate problems for each period to facilitate the solution. However, the multi-period problem as shown may be easily adapted to constrain the flexibility of design changes and associated costs with changes from period to period.

4. Heuristic solution

To solve the numerical example, we use a heuristic method based on an individual solution for each objective function (Tables 4, 5, and 6). General idea of this heuristic algorithm is based on following steps:

(1) Optimising total responsiveness only with constraints and keep solutions in terms of decision variables,
(2) Optimising total risk only with constraints and keep solutions in terms of decision variables,
(3) Optimising total cost only with constraints and keep solutions in terms of decision variables,
(4) Based on steps 1, 2, and 3 if the number of value 1 in decision variables is equal or more than 1, assign value 1 otherwise assign value 0,
(5) Keep the aggregation table in step 4 for GA seeding.

In other words, we assume that we have only one objective each time. For instance, Table 4 is the solution of responsiveness maximisation. Then, we have a solution in terms of binary variables. In the second problem, risk minimisation is also single objective solution solved in terms of binary variables (Table 5). The last model is cost minimisation as shown in Table 6. Each objective function is solved by related constraints, then the solutions on three objective functions are compared to each other based on binary variables, and the total occurrence of value 1 is reported for each Y_{ijt} (Table 7). The last column in Table 7, the total occurrence of value 1 for this Y_{ijt} is 2 or 3. This outcome is used to seed a GA that ensures

Table 5. Binary solution values (Y_{ijt}) for risk.

	j_1		j_2	
	i_1	i_2	i_1	i_2
t_1	1	0	0	1
t_2	1	1	0	0
t_3	1	1	0	0
t_4	0	1	1	0

Table 6. Binary solution values (Y_{ijt}) for cost.

	j_1		j_2	
	i_1	i_2	i_1	i_2
t_1	1	0	0	1
t_2	1	1	0	0
t_3	1	0	0	1
t_4	1	1	0	0

feasibility and searches for improved design and operation.

$$\text{Max Responsiveness} = \sum_{i,j,t}(IN_{ijt}Y_{ijt} + SC_{ijt}Y_{ijt} + EF_{ijt}Y_{ijt} + IS_{ijt}Y_{ijt} + EL_{ijt}Y_{ijt} + VS_{ijt}Y_{ijt}) \quad (1)$$

$$\text{Subject to : (4), (5), (8), (12)}$$

$$\text{Min Risk} = \sum_{i,j,t} R_{ijt}Y_{ijt} \quad (2)$$

$$\text{Subject to : (4), (5), (8), (12)}$$

$$\text{Min Cost} = \sum_{i,j,t}(CI_{ijt}Y_{ijt} + CS_{ijt}Y_{ijt} + CE_{ijt}Y_{ijt} + CA_{ijt}Y_{ijt} + CF_{ijt}Y_{ijt} + CV_{ijt}Y_{ijt} + R_{ijt}CR_{ijt}Y_{ijt} + IR_{ijt}Y_{ijt} + P_{ijt}Q_{ijt}) \quad (3)$$

$$\text{Subject to : (4), (5), (6), (7), (8), (9), (10), (11), (12)}$$

In Table 7, each objective function solution represented in terms of binary variables are provided in each column. As a trade-off among three objective functions, for each Y_{ijt}, if the number of value 1 in three cells is greater than or equal to 2, the value of that Y_{ijt} is 1, otherwise 0.

To assess the efficiency of the heuristic algorithm, we solved different numerical examples (Yu and Goh 2014; Nooraie and Parast 2016). Based on Appendix A's outputs, there are two runs for each i, j, t, which are related to the index of product, supplier, and time, respectively. The elapsed CPU time in terms of seconds shows improvement for the improved GA compared to GA. A fitness function is a particular type of objective function that is used to summarise, as a single figure of merit, how close a given design solution is to achieve the set aims. Moreover, the fitness function must not only correlate closely with the designer's goal, it must also be computed quickly. The speed of execution is very important, as a typical GA must be iterated many times in order to produce a usable result for a non-trivial problem.

Comparing two classes of fitness function which are connected to GA and the heuristic algorithm (improved GA) reveals that in the heuristic method, the fitness function is computed more quickly than in GA, note that this type of experiment provides good result on numerical efforts including 57 numerical cases with different amount of products, suppliers, and time periods. GA parameters are crossover probability, mutation probability, and population size. Thus, in terms of time spent to get an optimum solution, the heuristic algorithm is more efficient than GA. In Appendix A, improvement in the elapsed time and fitness function is reported by percentage. On average, the fitness function is improved by 31% and the elapsed time is improved by 7.68 seconds. The main reason for this improvement is the quality of the initial population. A multi-objective problem assumes the same weight among the objective functions. In such a case, the solution is a trade-off

Table 7. Numerical example solution and comparison.

Y_{ijt}	Responsiveness	Risk	Cost	High Frequency of Y_{ijt}
Y_{111}	1	1	1	1
Y_{112}	0	1	1	1
Y_{113}	0	1	1	1
Y_{114}	0	0	1	0
Y_{211}	1	0	0	0
Y_{212}	1	1	1	1
Y_{213}	0	1	0	0
Y_{214}	0	1	1	1
Y_{121}	0	0	0	0
Y_{122}	1	0	0	0
Y_{123}	1	0	0	0
Y_{124}	1	1	0	1
Y_{221}	0	1	1	1
Y_{222}	0	0	0	0
Y_{223}	1	0	1	1
Y_{224}	1	0	0	0
GA	132.66	26.65	90,648.67	
Heuristic Solution	127.47	27.85	96,331.73	

among objective functions. We design a solution process policy where a decision maker wants to prioritise the objective functions by different percentages to weight some objective functions more than others. The main reason for prioritisation is to prefer profit maximisation or cost minimisation as much as possible among the objective functions. In the next step, we design a heuristic algorithm to prioritise the objective functions.

5. Heuristic algorithm for prioritisation

In this section, we design steps to prioritise the objective functions in a multi-objective problem. This approach borrows from the earlier heuristic where the independent single objective solutions contribute to the heuristic solution. With this algorithm, the higher the weight, the more that objective function is considered in term of identifying SC participants. The following steps are to prioritise solutions based on weights:

- Step 1- Calculate the total number of all decision variables Y_{ijt}.
- Step 2- Assign the weight to each objective function in terms of percentage or decimal value (total weight is 100% or 1.00).
- Step 3- Calculate the product of the number of decision variables (from Step 1) by the weight of each objective function (total number of Y_{ijt} * weight for each objective function).
- Step 4- Round numbers from Step 3 to the nearest integer number.
- Step 5- If the largest priority in Step 2 belongs to a maximisation objective function, then sort $Y_{ijt} = 1$ based on the round numbers that resulted from Step 4, from max to min. Otherwise, sort min to max.
- Step 6- If the second objective function is maximisation, then assign value 1 to the best sort of max to min based on round number for the second objective function resulted by Step 4.
- Step 7- If the second objective function is minimisation, then assign value 1 to the best sort of min to max based on the formula explained in Step 5 for minimisation.
- Step 8- Similar to Step 5, find the best values Y_{ijt} for the third objective function based on minimisation or maximisation rules.
- Step 9- When all objective functions are determined based on decision variables $Y_{ijt} = 1$ then for the remaining unassigned Y_{ijt} assume value 0.
- Step 10- Finalise values 0 and 1 for Y_{ijt} based on binary values for each objective function. If for each Y_{ijt} there is equal or more than 1, then assume value 1 for that Y_{ijt} otherwise assign value 0 for the binary value.
- Step 11- Calculate each objective function based on finalised Y_{ijt} in Step 8.

$P_k =$ Percentage of k-th objective functions $k = 1 \cdots n$.

In the next section, various priorities on different sizes of numerical examples will provide more understanding on the prioritisation method.

Table 8. Improvements in objective functions based on prioritisation method.

	Weight											
Responsiveness	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.33	0.15	0.05	0.05	0.05
Risk	0.05	0.10	0.10	0.15	0.15	0.20	0.30	0.33	0.80	0.15	0.10	0.05
Cost	0.05	0.05	0.10	0.10	0.15	0.15	0.10	0.33	0.05	0.80	0.85	0.90
Responsiveness Improvement %	− 2	− 3	− 5	− 4	− 6	− 7	− 9	− 17	− 20	− 27	− 27	− 23
Risk Improvement %	2	2	3	3	4	5	7	8	18	4	2	1
Cost Improvement %	1	2	2	2	2	1	2	6	1	18	23	18
Average improvement %	0.33	0.33	–	0.33	–	− 0.33	–	− 1.00	− 0.33	− 1.67	− 0.67	− 1.33

6. Discussion

The main purpose of the numerical examples is to investigate the impact of different percentages of each objective function on the final solution. We also investigated how larger numerical examples affect time needed to solve a problem. Several numerical examples were designed based on different values of *i* (number of products), *j* (number of supplier), and *t* (number of time periods) presented in Appendix B. According to the results in Appendix B, the optimum solutions for numerical examples are provided where responsiveness, risk, and cost are calculated individually. Based on different priorities on the responsiveness, risk, and cost objective functions, it seems that improved GA solution normally emphasises responsiveness rather than risk and cost. Based on different percentages for objective functions, it is clear that the improved GA solution (where there is no priority) automatically has higher than 90% priority on responsiveness, while risk and cost individually have less than 5% priority each since each objective value (without priority) is close to where the percentage of responsiveness, risk and cost are 90%, 5%, and 5%, respectively.

The first finding from prioritisation reveals that a multi-objective solution does not consider equal weight for objective functions with the current priority method. The main reason for the inequity is related to the mathematical formulation, constraints, and numerical values. Apparently, assuming equal weight for objective functions, constraints, and feasibility conditions push the solution to the direction where objective functions have different weights. This fact can be shown when there is the same weight for each objective function (33%); then, objective values differ from values where equal weight is considered for objective functions. Gradually, we consider that the weight of responsiveness becomes smaller than 90%, while risk and cost respectively become larger than 5%, which shows a larger deviation from the improved GA solution. In a situation where risk minimisation has the highest priority among objective functions (for instance, 80%), it affects cost minimisation, where both risk and cost will have better solutions than GA solution. Therefore, the findings show that if two minimisation or maximisation functions exist among the objective functions, a higher or lower priority on each objective function would have an impact on the other objective function's optimal solution.

According to Table 8, it is possible to anticipate that when the weight of responsiveness is assumed more than 90%, there will be an expected improvement where the value of responsiveness will be larger than the near optimum value. From results, it is clear when the weights of the objective functions for responsiveness, risk, and cost are respectively 90%, 5%, and 5%. These objective values are close to near optimum values, which are given by the improved GA. From this analysis, we can say that the near optimum solution does not assume equal weights for objective functions. By decreasing the responsiveness priority, we would expect the value of responsiveness to become less than near optimum. Alternatively, by increasing the risk and cost priorities, the values of risk and cost become less than their near optimum values. Totally prioritisation method is an alternative method to prioritise objective functions in multi-objective problems where we have binary decision variables. The relationship between responsiveness, risk and cost in numerical examples (Appendix B) reveals that increasing improvement in responsiveness affects cost and risk decreases and vice versa. Therefore, there is always a trade-off among opposite objective functions, which change in terms of different percentage on each objective function.

Figure 3 shows a trade-off among three objective functions based on the percentage priority of each objective function. The horizontal axis starts with the near optimum solution where there is an equal priority for objective functions. Each of three objective functions group includes three percentages that are respectively assigned (from left to right) to responsiveness, risk, and cost. The vertical axis shows the numerical value of each objective function. Overall, in the prioritisation approach, the trade-off among objective functions depends on the percentage priority of each objective function. Any changes in priority of each objective function affect the trade-off among objective functions (Figure 4).

6.1. Theoretical contributions and managerial implications

In this paper, we developed a conceptual model for responsiveness where we showed that responsiveness is a combination of effective factors (agility, external flexibility, visibility, and internal integration). To the best of our knowledge,

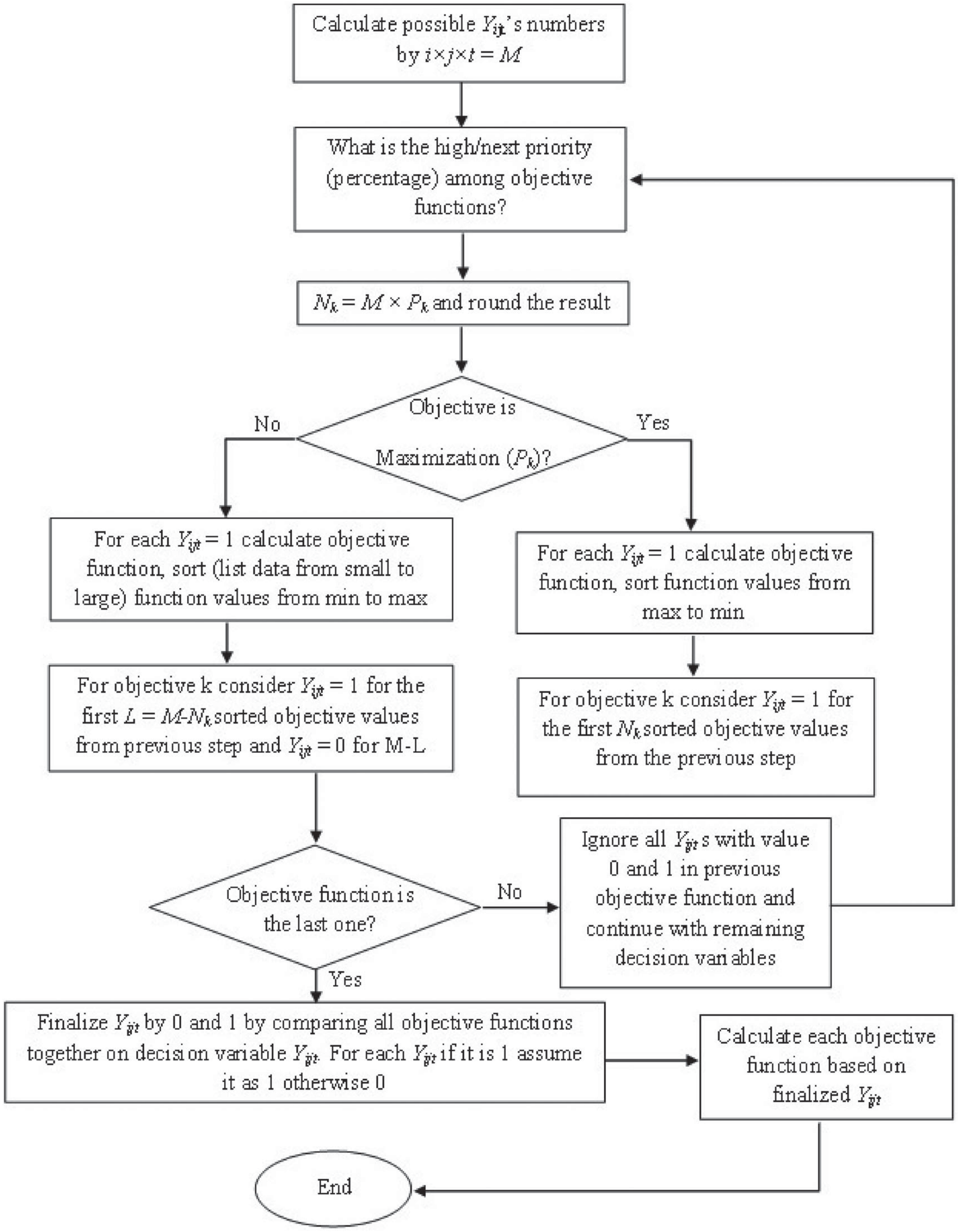

Figure 3. Heuristic algorithm for prioritisation.

this is the first study to address the antecedents and performance outcomes of responsiveness in an SC under risk of disruption.

Managerial implications of this research explain that in each SC where demand risk or supply risk exist, minimum cost to mitigate those risk should be determined based on the development of supply chin capabilities. In other words, for this case, in Industry a trade-off tells us how much cost as an investment of SC repressiveness enough is to mitigate existing demand risk. Also a prioritisation approach alternatively prioritise objective functions based on different percentages on objective

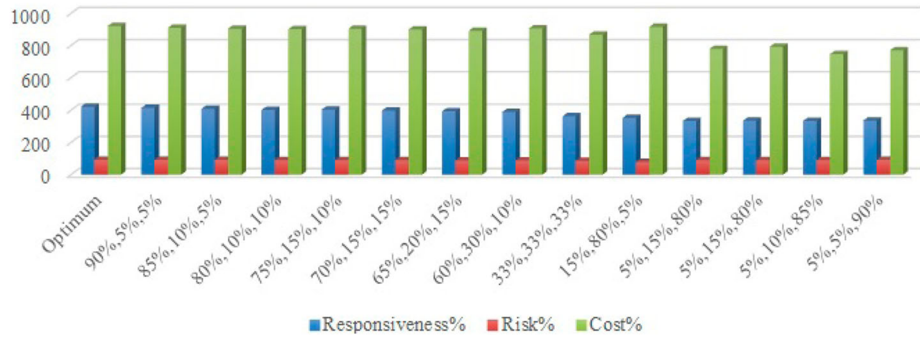

Figure 4. Trade-off among responsiveness, risk, and cost using the prioritisation approach.

Table 9. Some strategies to increase responsiveness.

Type of Risk imposed on SC	Investment in
Quality and quantity of products are under risk	Flexibility
Tracking customer needs through SC process is under risk	Visibility
Uncertainty about expected quality, quantity, delivery time, selling price, or service after sale provide risk in SC.	Agility
Risk of SC process is due to lack of an integrated system to connect internal processes to exchange data between supplying, warehousing, manufacturing, transportation, and distribution	Internal Integration

functions. This means that in a multi-objective function problem like goal programming, we can determine different goals for each objective functions but with a different approach.

Depending on the type of risk that is imposed on SC, a different amount of each factor can be used to increase responsiveness. Based on the conceptual model in Figure 1 and numerical results, we showed that increasing responsiveness affects risk and cost reduction. For instance, when the priority of responsiveness is 90% and risk and cost total 10%, the values of the objective functions for responsiveness (237.42), risk (48.45), and cost (458.54) are near optimum, which are responsiveness (232.67), risk (47.68), and cost (453.04). Any changes in priority percentage change the amount of each objective function. For instance, any percentage lower than 90% for responsiveness (i.e. 80%) provides lower responsiveness (226.02) than the optimum value, while a higher priority percentage for risk (10%) and cost (10%) result in lower risk (47.00) and cost (448.45). Therefore, for the current numerical examples (Appendix B), the base is respectively 90%, 5%, and 5% for responsiveness, risk, and cost.

We have critical definitions of practical factors that help us to determine some strategies to manage risk. Overall, SC visibility provides the capability to track parts, components, or products in transit from the manufacturer to their final destination. The goal of SC visibility is to strengthen SC by making data readily available to all stakeholders, including the customer (Hendricks and Singhal 2012). In considering external flexibility, we achieve abilities that show the ways that SC managers adjust their production/delivery quantities and qualities in response to shifts in customer demand and changes in supply (Williams et al. 2013). The literature suggests that agility is a concept to address competitiveness in a fast-paced and unpredictable industrial environment (Gligor, Esmark, and Holcomb 2015; Brusset 2016). Internal integration is an accomplished capability that follows from a set of interconnected systems and processes that help decision-making processes (Schoenherr and Swink 2012; Williams et al. 2013).

When the imposed risk affects the quantity of products, investment in flexibility is a good choice to increase the rate or production. When risk is related to tracking products for customer delivery, investment in visibility is very efficient. Last, when risk imposed on an SC provides uncertainty for any parameters in decision-making, such as future expectations about quality, quantity, delivery time, selling price, or service after sale, then investment in agility is more efficient. A combination of different risks (demand and supply) needs investment in all factors that affect responsiveness improvement. Table 9 provides strategies that could be used by managers to invest in effective factors at the time of imposed typical risk. The importance of effective factors is determined by the importance of the type of risk. If supply and demand risk affect customer orders in terms of delivery time, quantity, and quality, both flexibility and agility improvement are required. If an SC needs to reduce the costs of inventory, transportation, and distribution, improvement in visibility and internal integration are required. Therefore, a flexibility and agility improvement strategy is a customer-service-based strategy to keep customers satisfied. In other words, a flexibility and agility improvement strategy is a continuous improvement process for SC owners.

From a methodological standpoint, a multi-objective mixed-integer model with binary variables was developed based on three objective functions (risk, responsiveness, and SC cost) to investigate how these objective functions interact each other, to provide the optimum values on products, suppliers, time periods, and production rate, and to show how an increase in total SC cost (cost needed to improve internal integration, external flexibility, agility, and visibility) provides improvement in responsiveness to mitigate SC disruptions. A heuristic algorithm was designed to solve a triple-objective function model with different priorities for risk, responsiveness, and cost. Such an algorithm can be extended and used for any type of multi-objective mixed-integer linear or nonlinear model with binary variables; it is more efficient than GA when problem size is more complex, because the heuristic method simplifies a multi-objective problem by breaking the main problem into independent models, each with only one objective function.

In the numerical examples provided in Appendix A, the improved solution method that was introduced as the Improved GA provides better results in a comparison with GA. Therefore, we expect better results from efficient solution methods such as Improved GA if we have similar numerical values. We realise that the numerical dimensions depend on product order size, number of suppliers, and time periods; therefore, when the dimension of a numerical case increases in terms of product, supplier, and time period, the value of responsiveness, risk, and cost becomes larger (as shown in Appendix B) to determine how larger values for each parameter (parameters in the mathematical model) affect responsiveness, risk, and cost values. In such a model, it is important to have an accurate estimation (depending upon the number of samples, the expertise of respondent, industry type and question types) of the minimum responsiveness required to produce a product based on expected quality, delivery time, order size, service after sale, and selling price. Since we showed that the amount of responsiveness depends on effective factors (flexibility, agility, internal integration, and visibility), estimating the minimum amounts of such factors help to determine the minimum amount of responsiveness.

Our study also contributes to prioritising objective functions where a manager wants to increase or decrease objective functions as much as possible. This is applicable in cases where responsiveness is essential and needs to be addressed even at the expense of increasing cost. When 911, fire station, and hospital emergency rooms need to be responsive only, setting responsiveness with high priority is an alternative method to make differentiate among objective functions. Similarly, a risk minimisation policy can set risk minimisation to a higher priority in the prioritisation method. In such policies, we may need to deviate from the cost minimisation objective because of the nature of the business. This suggests that increasing responsiveness more than the optimum value may impose a cost on SC. Alternatively, the application of this solution method can be used by managers in any industry to prioritise their objectives based on their preferences. For instance, risk-averse managers can set risk minimisation to priority 90% or higher, while responsiveness-based companies can set responsiveness maximisation to a high priority. Similarly, companies with cost minimisation strategies can set a high priority on cost minimisation. The prioritisation method allows managers to focus on a specific objective/s in a multi-objective environment. Thus, by utilising a prioritisation process, a manager is able to maximise or minimise an objective more than the optimum solution in order to achieve the desired outcome.

7. Conclusion

Our conceptual model deals with internal integration, visibility, flexibility, and agility. The developed SC model considered supply and demand disruptions. The proposed model is focused on determining products, suppliers, and time periods as well as production volume for each product as a production plan for a triple-objective-functions model and to examine the trade-off among responsiveness, risk, and cost on mitigating SC disruption. Our model exposed to the disruption risk to understand the relationship among SC responsiveness, risk, and total cost, and to show how increasing responsiveness through investment on resiliency enhancers (flexibility, agility, internal integration, and visibility) can mitigate supply and demand disruptions. To solve the NP-hard model a GA based heuristic algorithm is designed and the analysis showed that the heuristic algorithm is more efficient than GA. We found that improvement in responsiveness enhancers decreases supply and demand disruption risks considerably. We also developed different strategies in terms of investment in responsiveness factors to manage potential SC risks.

In conclusion, our four main contributions are conceptual model derived by the research gap in the literature, mathematical trade-off model, Heuristic solution 1, and Heuristic solution 2 or prioritisation model. Using the novel prioritisation method for objective functions enables us to increase or decrease our objectives more than the optimum values, based on the manager's priority for any given objective values to satisfy organisational policies. It can be used instead of the goal programming method for multi-objective problems where we have binary variables and objective functions could be prioritised based on our novel algorithm and it focuses on the number of binary decision variables for the final solution. This method is not accurate enough in comparison to other methods, but it is very flexible for different percentages on the objective function. The main difference between this method and goal programming comes from a theory which prioritises objective functions based on the number of decision variables. For instance, when we state 80% of priority belongs to responsiveness it means that 80% of decision variables should be activated and responsiveness becomes large as much as possible. Certainly, this percentage (80%) pushes the other objective functions to get the lower percentages. The disadvantage of this technique states that a higher percentage of one objective function imposes values 0 and 1 on decision variables unintendedly that belong to the lower percentages.

The practicability of the proposed model was demonstrated through its application and efficiency in solving the multi-objective mixed-integer nonlinear and linear programme including binary variables. The results indicate that the proposed model can provide a promising strategy for efficient production planning in the context of SC with various types of risks.

Future research possibilities are as follows:

- Considering more factors from SC responsiveness literature such as market orientation, learning orientation, and external integration and their impact on responsiveness improvement, or determine how they are interrelated.
- Extending SC risk for service-oriented companies such as emergency procedures for patients.
- Considering a longer time horizon and examining how visibility, agility, external flexibility, and integral integration can be improved with more objective functions such as maximisation of visibility and internal integration.
- Considering more constraints such as production capacity, back order, and lost sales, environmental and regional risks, into SC disruption-risk model.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix. Section in appendix

Table A1. Appendix A.1

			GA		Adapted GA			
i	*j*	*t*	Fitness Function	Elapsed Time (Sec)	Fitness Function	Elapsed Time (Sec)	Improvement Fitness (%)	Improvement Elapsed Time (%)
2	2	4	85.32	0.05	57.65	0.05	32.43	8.26
2	2	5	95.68	0.03	82.48	0.03	13.79	2.91
2	2	6	28.64	0.09	21.37	0.08	25.37	9.91
2	2	7	167.32	0.04	107.95	0.04	35.48	6.54
2	3	4	84.37	0.10	46.36	0.09	45.05	11.50
2	3	5	150.88	0.16	124.69	0.15	17.36	2.91
2	3	6	238.88	0.40	156.13	0.36	34.64	9.09
2	3	7	256.69	1.02	180.77	0.96	29.58	5.66
2	4	4	231.92	0.85	199.93	0.76	13.79	10.71
2	4	5	190.02	0.30	146.17	0.28	23.08	5.66
2	4	6	210.61	0.68	138.56	0.66	34.21	2.91
2	4	7	236.84	0.75	158.95	0.73	32.89	2.91
2	5	4	229.80	0.16	144.53	0.14	37.11	10.71
2	5	5	280.15	0.34	209.07	0.30	25.37	11.50
2	5	6	273.37	0.58	208.68	0.52	23.66	9.91
2	5	7	185.67	0.16	132.62	0.15	28.57	9.91
3	2	4	173.49	1.58	152.18	1.48	12.28	6.54
3	2	5	199.59	0.24	139.57	0.23	30.07	2.91
3	3	4	91.64	2.41	70.49	2.21	23.08	8.26
3	3	5	329.73	29.61	208.69	27.17	36.71	8.26
3	3	6	278.55	54.53	226.46	51.44	18.70	5.66
3	3	7	444.47	57.94	271.02	51.27	39.02	11.50
3	4	4	272.33	19.45	191.78	18.52	29.58	4.76
3	4	5	248.85	34.10	144.68	30.72	41.86	9.91
3	4	6	226.67	48.86	161.91	44.02	28.57	9.91
3	4	7	193.46	56.35	149.97	52.18	22.48	7.41
3	5	4	311.85	108.16	216.56	98.32	30.56	9.09
3	5	5	328.76	107.14	263.01	95.66	20.00	10.71

Table A2. Appendix A.2

			GA		Adapted GA			
i	*j*	*t*	Fitness Function	Elapsed Time (Sec)	Fitness Function	Elapsed Time (Sec)	Improvement Fitness (%)	Improvement Elapsed Time (%)
3	5	6	344.57	72.54	228.19	66.55	33.77	8.26
3	5	7	289.78	26.21	202.64	24.96	30.07	4.76
4	3	4	426.74	48.65	243.85	43.43	42.86	10.71
4	3	5	151.62	54.20	112.31	47.96	25.93	11.50
4	3	6	542.52	77.36	310.01	72.30	42.86	6.54
4	3	7	619.24	110.47	353.85	101.35	42.86	8.26
4	4	4	618.56	88.06	423.67	81.54	31.51	7.41
4	4	5	589.54	131.86	508.22	118.80	13.79	9.91
4	4	6	848.99	169.39	463.93	158.31	45.36	6.54
4	4	7	761.96	59.66	420.97	54.24	44.75	9.09
4	5	4	795.11	131.71	506.44	124.26	36.31	5.66
4	5	5	702.76	205.03	456.34	199.06	35.06	2.91
4	5	6	1045.11	434.27	593.81	398.42	43.18	8.26
4	5	7	897.89	15.68	519.01	14.39	42.20	8.26
5	3	5	1195.35	78.05	686.98	75.05	42.53	3.85
5	3	6	1004.82	284.55	549.08	265.94	45.36	6.54
5	3	7	696.50	752.71	552.78	690.56	20.63	8.26
5	4	4	983.95	674.73	565.49	630.59	42.53	6.54
5	4	5	743.86	697.75	619.88	628.60	16.67	9.91
5	4	6	1053.03	343.95	706.73	312.68	32.89	9.09
5	4	7	775.23	752.47	640.69	677.90	17.36	9.91
5	5	4	1169.29	708.64	806.41	632.71	31.03	10.71
5	5	5	1557.56	433.66	895.15	421.03	42.53	2.91
5	5	6	1636.85	588.91	935.34	521.16	42.86	11.50
5	5	7	1261.83	484.57	963.23	448.68	23.66	7.41
6	5	10	1264.38	137.41	1062.50	129.63	15.97	5.66
8	9	11	23,174.21	372.05	12,803.43	332.19	44.75	10.71
9	10	13	20,037.62	564.35	16,159.37	547.91	19.35	2.91

Table A3. Appendix B.1

i	*j*	*t*	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)
Weight			No weight				0.90	0.05	0.05		0.85	0.10	0.05	
2	2	4	237.42	48.45	458.54	0.14	232.67	47.68	453.04	0.0067	229.82	47.68	450.29	0.0004
2	2	5	277.22	59.36	582.07	0.36	271.68	58.41	575.08	0.0004	268.35	58.41	571.59	0.0003
2	2	6	345.44	73.58	671.65	0.63	338.54	72.40	663.59	0.0008	334.39	72.40	659.56	0.0006
2	2	7	419.52	91.98	910.48	1.58	411.13	90.51	899.55	0.0006	406.10	90.51	894.09	0.0005
2	3	4	366.18	83.71	937.36	0.45	358.86	82.37	926.12	0.0004	354.47	82.37	920.49	0.0005
2	3	5	444.63	95.40	929.52	1.43	435.74	93.88	918.36	0.0005	430.40	93.88	912.79	0.0005
2	3	6	552.06	121.51	1234.06	4.02	541.02	119.57	1219.25	0.0008	534.40	119.57	1211.85	0.0006
2	4	4	491.06	104.41	1015.95	1.96	481.24	102.74	1003.76	0.0007	475.34	102.74	997.66	0.0005
2	4	5	621.98	135.97	1365.82	8.88	609.54	133.80	1349.43	0.0007	602.08	133.80	1341.23	0.0011
2	4	6	29.13	7.07	33.34	33.24	28.55	6.96	32.94	0.0008	28.20	6.96	32.74	0.0009
2	5	4	609.52	131.82	1296.08	4.87	597.32	129.72	1280.53	0.0008	590.01	129.72	1272.75	0.0006
2	5	5	751.55	176.69	1857.89	8.91	736.52	173.86	1835.59	0.0009	727.50	173.86	1824.45	0.0008
3	2	4	343.73	75.34	681.46	0.65	336.85	74.13	673.29	0.0004	332.73	74.13	669.20	0.0004
3	2	5	422.27	92.72	921.09	5.16	413.82	91.23	910.04	0.00	408.75	91.23	904.51	0.00

Table A4. Appendix B.2

i	j	t	Max. Responsiveness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsiveness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsiveness	Min. Risk	Min. Cost	Elapsed Time (Sec.)
Weight			0.80	0.10	0.10		0.75	0.15	0.10		0.70	0.15	0.15	
2	2	4	226.02	47.00	448.45	0.0003	227.45	47.00	450.29	0.0003	223.65	46.61	447.53	0.0003
2	2	5	263.92	57.58	569.26	0.0003	265.58	57.58	571.59	0.0004	261.14	57.11	568.10	0.0003
2	2	6	328.86	71.37	656.88	0.0004	330.94	71.37	659.56	0.0008	325.41	70.78	655.53	0.0006
2	2	7	399.38	89.22	890.45	0.0005	401.90	89.22	894.09	0.0005	395.19	88.48	888.63	0.0009
2	3	4	348.61	81.20	916.74	0.0004	350.80	81.20	920.49	0.0004	344.95	80.53	914.87	0.0004
2	3	5	423.29	92.54	909.07	0.0005	425.95	92.54	912.79	0.0005	418.84	91.78	907.21	0.0005
2	3	6	525.56	117.86	1206.91	0.0006	528.88	117.86	1211.85	0.0006	520.04	116.89	1204.44	0.0006
2	4	4	467.49	101.28	993.60	0.0005	470.43	101.28	997.66	0.0005	462.58	100.45	991.57	0.0005
2	4	5	592.13	131.89	1335.77	0.0008	595.86	131.89	1341.23	0.0007	585.91	130.81	1333.04	0.0007
2	4	6	27.73	6.86	32.61	0.0008	27.91	6.86	32.74	0.0008	27.44	6.80	32.54	0.0007
2	5	4	580.26	127.87	1267.57	0.0006	583.92	127.87	1272.75	0.0006	574.16	126.82	1264.98	0.0006
2	5	5	715.47	171.39	1817.01	0.0008	719.98	171.39	1824.45	0.0008	707.96	169.97	1813.30	0.0008
3	2	4	327.23	73.08	666.47	0.0004	329.29	73.08	669.20	0.0004	323.79	72.47	665.11	0.0004
3	2	5	402.00	89.93	900.83	0.00	404.53	89.93	904.51	0.00	397.77	89.19	898.99	0.00

Table A5. Appendix B.3

i	*j*	*t*	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)
Weight			0.65	0.20	0.15		0.60	0.30	0.10		0.33	0.33	0.33	
2	2	4	221.27	45.93	443.87	0.0003	218.42	45.45	451.20	0.0004	203.70	44.96	431.94	0.0003
2	2	5	258.37	56.28	563.44	0.0005	255.04	55.68	572.76	0.0003	237.86	55.09	548.31	0.0006
2	2	6	321.95	69.75	650.16	0.0005	317.81	69.02	660.91	0.0004	296.39	68.28	632.70	0.0004
2	2	7	390.99	87.19	881.34	0.0009	385.96	86.27	895.91	0.0009	359.95	85.35	857.67	0.0009
2	3	4	341.28	79.36	907.37	0.0004	336.89	78.52	922.37	0.0004	314.19	77.68	883.00	0.0004
2	3	5	414.39	90.44	899.77	0.0007	409.06	89.49	914.65	0.0005	381.49	88.54	875.61	0.0005
2	3	6	514.52	115.19	1194.57	0.0010	507.90	113.98	1214.32	0.0007	473.67	112.76	1162.48	0.0006
2	4	4	457.67	98.98	983.44	0.0006	451.77	97.94	999.70	0.0005	421.33	96.90	957.03	0.0005
2	4	5	579.69	128.90	1322.11	0.0006	572.23	127.54	1343.96	0.0006	533.66	126.18	1286.60	0.0006
2	4	6	27.15	6.70	32.27	0.0008	26.80	6.63	32.81	0.0009	24.99	6.56	31.41	0.0008
2	5	4	568.07	124.97	1254.61	0.0007	560.75	123.65	1275.35	0.0006	522.96	122.33	1220.91	0.0006
2	5	5	700.44	167.50	1798.44	0.0008	691.42	165.73	1828.16	0.0008	644.83	163.97	1750.13	0.0008
3	2	4	320.36	71.42	659.66	0.0004	316.23	70.66	670.56	0.0005	294.92	69.91	641.94	0.0004
3	2	5	393.55	87.89	891.62	0.00	388.48	86.97	906.36	0.00	362.30	86.04	867.67	0.00

Table A6. Appendix B.4

i	*j*	*t*	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsive-ness	Min. Risk	Min. Cost	Elapsed Time (Sec.)
Weight			0.15	0.80	0.05		0.05	0.15	0.80		0.05	0.15	0.80	
2	2	4	198.01	40.99	455.79	0.0003	187.56	46.61	387.92	0.0003	188.04	46.51	394.34	0.0003
2	2	5	231.20	50.22	578.58	0.0003	219.01	57.11	492.43	0.0003	219.56	56.99	500.58	0.0003
2	2	6	288.10	62.25	667.62	0.0006	272.90	70.78	568.22	0.0007	273.59	70.64	577.62	0.0004
2	2	7	349.88	77.81	905.01	0.0005	331.42	88.48	770.26	0.0005	332.26	88.30	783.01	0.0005
2	3	4	305.40	70.82	931.74	0.0005	289.29	80.53	793.01	0.0004	290.02	80.36	806.13	0.0004
2	3	5	370.82	80.71	923.94	0.0005	351.26	91.78	786.37	0.0005	352.15	91.59	799.39	0.0006
2	3	6	460.42	102.80	1226.66	0.0006	436.13	116.89	1044.01	0.0007	437.23	116.65	1061.29	0.0006
2	4	4	409.54	88.33	1009.85	0.0005	387.94	100.45	859.49	0.0005	388.92	100.24	873.72	0.0005
2	4	5	518.73	115.03	1357.62	0.0006	491.37	130.81	1155.48	0.0007	492.61	130.53	1174.60	0.0007
2	4	6	24.30	5.98	33.14	0.0007	23.01	6.80	28.21	0.0013	23.07	6.79	28.67	0.0017
2	5	4	508.34	111.52	1288.31	0.0006	481.52	126.82	1096.49	0.0007	482.74	126.55	1114.63	0.0007
2	5	5	626.79	149.48	1846.74	0.0008	593.72	169.97	1571.77	0.0008	595.22	169.62	1597.78	0.0008
3	2	4	286.67	63.73	677.37	0.0004	271.55	72.47	576.52	0.0004	272.23	72.32	586.06	0.0004
3	2	5	352.17	78.44	915.57	0.00	333.59	89.19	779.25	0.00	334.43	89.01	792.14	0.00

Table A7. Appendix B.5

i	*j*	*t*	Max. Responsiveness	Min. Risk	Min. Cost	Elapsed Time (Sec.)	Max. Responsiveness	Min. Risk	Min. Cost	Elapsed Time (Sec.)
Weight			0.05	0.10	0.85		0.05	0.05	0.90	
2	2	4	187.56	47.39	371.42	0.0003	188.98	47.87	383.34	0.0003
2	2	5	219.01	58.06	471.48	0.0003	220.67	58.65	486.61	0.0003
2	2	6	272.90	71.96	544.04	0.0004	274.97	72.70	561.50	0.0004
2	2	7	331.42	89.95	737.49	0.0005	333.94	90.87	761.16	0.0005
2	3	4	289.29	81.87	759.27	0.0004	291.48	82.71	783.64	0.0004
2	3	5	351.26	93.31	752.91	0.0005	353.92	94.26	777.08	0.0005
2	3	6	436.13	118.84	999.59	0.0006	439.44	120.05	1031.67	0.0006
2	4	4	387.94	102.12	822.92	0.0006	390.88	103.16	849.33	0.0005
2	4	5	491.37	132.98	1106.31	0.0007	495.10	134.34	1141.82	0.0006
2	4	6	23.01	6.91	27.00	0.0015	23.19	6.98	27.87	0.0011
2	5	4	481.52	128.92	1049.83	0.0006	485.17	130.24	1083.53	0.0006
2	5	5	593.72	172.80	1504.89	0.0008	598.23	174.57	1553.19	0.0008
3	2	4	271.55	73.68	551.99	0.0004	273.61	74.43	569.70	0.0004
3	2	5	333.59	90.68	746.09	0.00	336.12	91.60	770.03	0.00