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Evaluation of robustness of supply chain information-sharing strategies using a hybrid Taguchi and multiple criteria decision-making method

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ABSTRACT

The advances in information technology have prompted the development of many supply chain information-sharing strategies, including electronic point of sales (EPOS), vendor-managed inventory (VMI), e-shopping, emergency transshipments, and so on. However, variations in the business environment can produce uncertainty and increase decision-making complexity for enterprises selecting from various supply chain information-sharing strategies. An effective and efficient supply chain strategy should be capable of reducing costs and raising customer-service levels, and should be capable of enhancing the robustness of the supply chain. In this study, the robustness of different supply chain strategies under various uncertain environments is studied using the simulated beer game. Techniques included Taguchi methodology and multiple criteria decision-making methods (MCDMs), including simple multiple attribute rating technology (SMART), technique for order performance by similarity to ideal solution (TOPSIS), and grey relational analysis (GRA). The signal-to-noise (S/N) ratio for each criterion is calculated to indicate the robustness of performance. This S/N ratio is used to determine an overall evaluation among various supply chain information-sharing strategies. The simulation results show that e-shopping has the most robust performance in uncertain environments.

1. Introduction

The continuing advance in information technology (IT), which has revolutionised so many contemporary business processes, has also contributed to more efficient supply chain management (SCM). Increased efficiency in information sharing among various organisations in supply networks has improved operational performance, enhanced customer service, reduced costs, improved quality, and enhanced competitiveness. As Simchi-Levi et al. (2003) have emphasised, improved information sharing can reduce variation within a supply chain, provide forecasts that are more accurate for suppliers, facilitate quicker responses, and improve supply adaptability. In a similar vein, Fiala (2005) noted that, the application of IT facilitates cooperation among the members of a supply chain. Moreover, information sharing reduces the Bullwhip Effect and enhances shared benefits (compared with that achieved by isolated entities).

Given the obvious benefits of information sharing for effective SCM, a variety of information-sharing strategies have been devised—including electronic point of sale (EPOS) technology, vendor-managed inventory (VMI), e-shopping, and emergency transshipment. The performances of these information-sharing strategies are affected by uncertainty in the economic business environment—although the extent to which each is affected varies from strategy to strategy. This variability increases the complexity of selecting an appropriate information-sharing strategy for any given supply chain.

Stevenson (2002) has shown that the selection of an appropriate information-sharing strategy has long-term implications for a supply network. An appropriate supply chain strategy should be capable of reducing costs and improving customer service, and of enhancing efficiency under conditions of uncertainty (so-called 'robustness'). The selection of a robust information-sharing strategy is therefore an important issue for contemporary SCM.

Every supply chain has to cope with uncertainty. Changing demand is an obvious cause of uncertainty, but it is not the only factor worthy of investigation. Other factors that can cause uncertainty in SCM include delivery lead-time, production output, and transportation time.

Although it is generally accepted that significant benefits can potentially be obtained by applying information sharing along a supply chain, no study has been undertaken to explore the robustness of existing supply chain information-sharing

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strategies. The present study uses supply chain information-sharing strategies from extant literatures. The uncertainty factors within a supply chain are used as external factors of the Taguchi method to realize the noise for a specific information-sharing strategy under alternative scenarios. Subsequently, beer game simulation models of alternative supply chain information-sharing strategies are constructed using simulation software. The signal-to noise (S/N) ratio defined in the Taguchi method is adopted to evaluate the robustness of a specific information-sharing strategy.

The present study evaluates both the inventory cost and the customer service level as performance measures; and thus becomes a multiple criteria decision-making (MCDM) problem. Three MCDM methods—simple multiple attribute rating technology (SMART), technique for order performance by similarity to ideal solution (TOPSIS) and grey relational analysis (GRA) are adopted for the final decision on the robustness of a particular information-sharing strategy.

The remainder of this paper is organized as follows. Section 2 reviews the pertinent literature. Section 3 provides details of the proposed methodology. The empirical data are discussed in Section 4. Conclusions and future research opportunities are addressed in the final section.

2. Literature review

Peppers and Rogers (1997) have advocated the use of information and communication technology (ICT) in the form of one-to-one e-business within a supply chain. Yet there is a little empirical evidence that such an approach will improve the overall performance of the supply chain in delivering customers' needs (Disney et al., 2004).

The following commonly used generic supply chain scenarios are shown in Fig. 1.

The *traditional supply chain* has four echelons (factory, distributor, warehouse, and retailer) linked in series. The *reduced supply chain* removes the retailer from the traditional supply chain. The *e-shopping supply chain* has direct information and materials flow between the manufacturer and the final-customer. The *EPOS supply chain* shares demand information with each echelon of the supply chain. The *vendor managed inventory* (*VMI*) *supply chain* has a protocol positioned between two elements in the supply chain that gives the necessary inventory and sales information. The vendor assumes the responsibility of tracking and replenishing a customer's inventory. The other strategies include, *manufacturer-managed inventory strategy*, where the stock levels in all echelons are controlled by the factory; *emergency transshipments strategy*, where an express transportation route that bypasses an echelon in the supply chain is permitted; *eliminate*, where the distributor is removed from the supply chain; *EPOS-integrated emergency transshipments strategy*; EPOS with distributor removed; and EPOS-integrated emergency transshipments with distributor removed.

According to Disney et al. (2004), the traditional supply chain was found to have the greatest Bullwhip Effect. They identified this based on the inventory cost sequencing of different supply chain information-sharing strategies using the beer game. Among the other four e-business supply chain information-sharing strategies, the VMI strategy had the poorest inventory holding costs and Bullwhip Effect—mainly because the players in the beer game had problems in implementing the concept.

To mitigate this problem, simulation can be used to ascertain whether this has any effect on the experimental results. Simultaneously, a better understanding of the various strategies is likely to be achieved if a greater number of supply chain

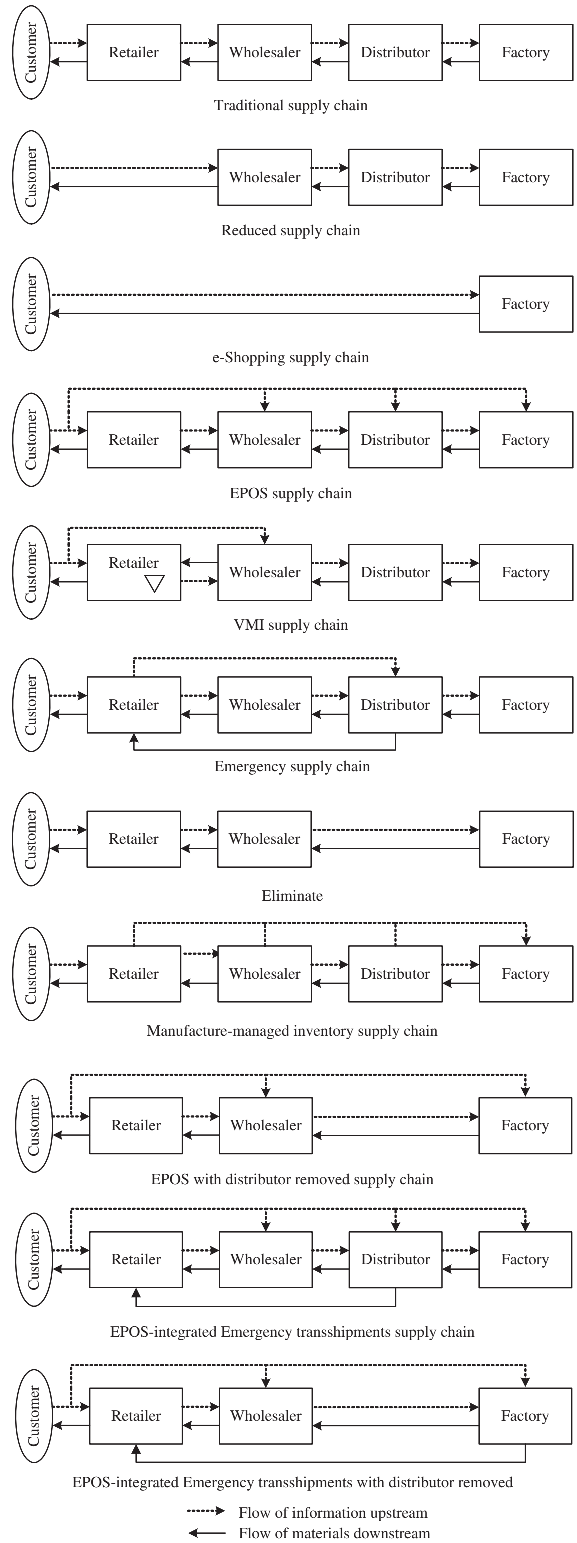

Fig. 1. Eleven supply chain scenarios.

performance indices are utilised. In this regard, Hong-Minh et al. (2000) have studied the impact of various supply chain information-sharing strategies under conditions of uncertainty, especially in relation to the effect on customer service of lateral emergency transshipments among supply chain partners.

The studies of Disney et al. (2004) and Hong-Minh et al. (2000) focused on the impact of a limited number of dynamic uncertainty factors on a variety of supply chain information-sharing strategies. However, these factors do not represent the full spectrum of environmental uncertainties. In this regard, Tang (2006) has classified supply chain uncertainties in terms of *operational risks*—including uncertain demands, uncertain supply yields, uncertain supply lead-times, and uncertain supply costs.

Taguchi methods, which are also referred to as quality engineering methods, are statistical techniques developed by Genichi Taguchi to improve the quality of manufactured goods. Robustness is the quality of being able to withstand changes in procedure or circumstance. A system, organism, or design may be said to be robust if it is capable of coping well with variations in its operating environment with minimal damage, alteration or loss of functionality (Taguchi, 1987). Taguchi (1992) successfully used the calculated S/N ratios as an index of robustness to deal with industrial quality issues. The S/N ratio considers both the mean and variance of quality, i.e., the S/N ratio is obtained by integrating the optimal quality and the minimization of variance to be a single objective function. A higher S/N ratio indicates the better robustness of the system. Readers are referred to Taguchi (1987) and Phadke (1989) for a detailed discussion.

Many multiple criteria decision-making (MCDM) methods have been developed for dealing with multi-criteria problems. Yang and Chou (2005) have utilised these techniques using a combination of L_{18} orthogonal array (with five control factors on three levels) and the technique for order performance by similarity to ideal solution (TOPSIS) to identify the optimal output and production cycle time of the ink-marking process in an integrated-circuit (IC) packaging company. Yang et al. (2007) also utilised TOPSIS to solve a dynamic operator allocation problem.

The Taguchi methods can be used to handle a single-response optimization problem. It is possible to obtain the overall performance index (OPI) of multiple responses by combining TOPSIS with Taguchi methods (Tong et al., 2004). TOPSIS simultaneously considers the distances to the ideal solution and the negative ideal solution regarding each alternative and selects the relatively closest one to the ideal solution as the best alternative. The optimal combination of factor levels can be used to identify the highest OPI, which can subsequently reduce quality variation as well as letting the mean value approach the objective value.

Kuo et al. (2008) proposed a grey-based Taguchi method to solve the multi-response simulation problem. The grey-based Taguchi method is based on the optimizing procedure of the Taguchi method, and adopts grey relational analysis (GRA) to transfer multi-response problems into single-response problems.

3. Methodology

The analytical process for the present study was divided into four phases. The first was to select the appropriate supply chain information-sharing strategy and to collect applicable information before constructing the simulation model. The second was to confirm the uncertain factors and factor level that might affect the supply chain. If, for example, the performance influenced by uncertain factors presents an obvious tendency, the variation of demand and lead time have negative influence on the service-level and inventory cost. In this instance, the noise factors can be compounded into two opposite scenarios. One stands for the most stable condition and the other represents the largest variation condition; otherwise, a further judgment of noise factors is required by experimentation. After confirmation of the supply chain information-sharing strategy and scenarios, the preliminary experimental programme was then generated. The experiment began whenever the construction of a simulation model was finished. The third phase was to build a beer game simulation model. The fourth phase was to execute the experiment for collecting the required data under various performance criteria. Then, S/N ratios were calculated as an index of robustness of a supply chain information-sharing strategy. Finally, multiple criteria decision-making (MCDM) methods were used to evaluate the overall performance of each programme under different criteria.

3.1. Construction of simulation model

The beer game was adopted in this study for empirical illustrations. The simulation models were constructed using simulation tools, after selecting the supply chain information-sharing strategy. The simulation software used in the study was Arena®10.0 (Kelton et al., 2007), developed by the Rockwell company. The decision to establish if the system had reached a steady state was based on daily recorded inventory level. These data were used to graph the variations of inventory. This was used to measure the required time for system warm-up—due to the empty state of the system at commencement.

The simulation results presented random properties because random variables existed in the simulation setting. To increase confidence of the simulation results, an appropriate number of simulation replications were required. Kelton et al. (2007) proposed that the simulation replication should be pre-set. When the half-width of confidence interval is smaller than a user-specified value (for example, within 10% of mean), the number of replication is acceptable.

3.2. Taguchi method

In this present study, the robust design of Taguchi method is applied to evaluate the robustness of a variety of supply chain information-sharing strategies. Two major tools are utilised in the Taguchi methodology: (i) orthogonal array; and (ii) signal-to-noise ratio (S/N ratio).

The first technique (orthogonal array) addresses the problem of dealing with the steadily increasing number of factors that must be considered, and the consequent complexity of any experiment designed to investigate all factors. By using the orthogonal array, a more reliable estimation of the effect of factors can be obtained with fewer experiments. Compound noise factors method, is a technique in which multiple noise factors are varied simultaneously as if they were a single noise factor. In most documented applications, an outer array of noise factors is replaced by the compound noise factor being varied between two levels. Taguchi (1987) and Phadke (1989) suggested forming compound noise factors based on the directionality of the noise factor effects thereby creating two conditions that represent, in some sense, opposite extremes.

The second technique (S/N ratio) attempts to optimise the robustness of a product or manufacturing process. It can show quality variations and has both simplicity and additive characteristics. The S/N ratio is closely related to 'quality loss function' and can be used to measure the stability of quality. A higher S/N ratio indicates a reduction in quality loss (Phadke, 1989). The S/N ratio characteristics are divided into four categories when the characteristic is continuous, specifically:

$$\text{'The-nominal-the-best' characteristics}: SN_{NTB} = 10\log_{10}\left(\frac{\overline{y}^2}{s^2}\right);$$

'The−smaller−the−better' characteristics :

$$SN_{STB} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right);$$

'The−larger−the−better' characteristics :

$$SN_{LTB} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right);\ \text{and}$$

'Signed target type' (STT) characteristics : $SN_{STT} = -10\log_{10}(s^2)$

in which $\bar{y}$ is the average of observed data; s^2 is the variance of y; n is the number of observations; and y represents the observed data.

For each type of characteristic, the higher the S/N ratio the better result.

3.3. Multiple criteria decision-making methods

Multiple criteria decision-making (MCDM) methods provide an efficient means of assisting decision-makers to choose the best programme under different criteria. Some tools and standard operational processes are used to assist the decision-maker to achieve the goal of a systematised solution.

The SMART is popular because its analysis incorporates a wide variety of quantitative and qualitative criteria. SMART uses the simple additive weight (SAW) method to obtain total values for individual alternatives, helping to rank them according to order of preference (Edwards, 1977; Edwards and Barron, 1994). SMART has been successfully applied in many MCDM problems.

The 'technique for order performance by similarity to ideal solution' (TOPSIS) was proposed by Hwang and Yoon (1981). The basic concept of TOPSIS is that the relative distances between each programme and both positive and negative ideal solutions are taken into consideration with a view to selecting a programme that is close to the positive ideal solution but far away from the negative solution. The so-called 'positive ideal solution' is the performance value that has best performance value among all alternatives, and the so-called 'negative solution' is that with the worst performance value.

Grey system theory, as propounded by Deng (1982), is a multidisciplinary theory dealing with grey systems that are characterised by both partially known and partially unknown information. Grey forecasting models have gained in popularity in time-series forecasting due to their simplicity and ability to characterise an unknown system by using as few as four data points (Tseng et al., 2001; Hsu, 2003; Lin and Yang, 2003).

Three multiple criteria decision-making (MCDM) methods, SMART, TOPSIS and GRA, are applied in this study to identify the better programme under differing criteria. More details regarding TOPSIS and GRA can be found in Kuo et al. (2008), with Yang and Chou (2005) giving a more concise expose.

4. Illustrative example

4.1. The beer game

The 'beer distribution game' (commonly known as the beer game) was adopted in this study to simulate the robustness of supply chain information-sharing strategies. The beer game was developed at the Sloan School of Management in the early 1960s (Jarmain, 1963), and is now recognised as a classic supply chain problem; that is widely used in graduate business programs to teach the concepts of supply chain management (Mosekilde et al., 1991).

The beer game involves four echelons—factory, distributor, wholesaler, and retailer. Orders from the customer go to the retailer, then to the wholesaler, then to the distributor, and finally reach the factory. In the meantime, deliveries are shipped from the factory down through the supply chain until they reach the customer. The beer game is widely used to acquaint students with the causal relationships that exist between their decision-making and the behaviour of supply chains emulated by simulation models of ordering policies. The results of the game are typically counterintuitive, because large oscillations appear in the order-rate in response to a step-increase in customer demand (Sterman, 1988).

4.2. Order strategy

In the simulation process, the order strategies adopted in production and distribution were adapted from the 'automatic pipeline inventory and order-based production control system' (APIOPBCS), used to investigate emergency delivery strategy and related supply chain information-sharing strategies by Hong-Minh et al. (2000). Naim and Towill (1995) found that the structure of APIOPBCS gives an adequate representation of human behaviour in the beer game.

There are three control parameters: *Ta* (smoothing parameter), *Ti* (parameter used to adjust inventory), and *Tw* (parameter used to adjust WIP). When Ti=Tw=8 and Ta=0, this represents a make-to-order system, whereas if Ti=1 and Tw=8, this represents a make-to-stock system. John et al. (1994) indicate that a good compromise solution between the response of inventory recovery and the stability of order quantity can be obtained by combining the make-to-order and make-to-stock systems.

4.3. Simulation model

Based on a survey of the literature, the following commonly used strategies were selected for study in this simulation: (i) traditional supply chain; (ii) reduced supply chain; (iii) e-shopping; (iv) electronic point of sales (EPOS); (v) vendor-managed inventory (VMI); (vi) manufacture-managed inventory strategy; (vii) emergency transshipments strategy; (viii) eliminate; (ix) EPOS-integrated emergency transshipments strategy; (x) EPOS with distributor removed; and (xi) EPOS-integrated emergency transshipments with distributor removed.

4.3.1. Information required for constructing simulation model

Before constructing the simulation model, certain assumptions of the problem were defined as the simulation period for the study was set at 30 days a month for 2 years (720 days in total). The same decision criteria, weighting, parameters, and desired inventory settings were used for each echelon, and the same weighting was set for each performance index (Hong-Minh et al., 2000).

There are seven environmental uncertainty factors in the present study. They are: (i) lead-time of order; (ii) lead-time of delivery; (iii) lead-time of production; (iv) capacity; (v) product quality; (vi) customer demand; and (vii) interval between arrivals of customers. Two selected performance indices are the total inventory cost of each echelon and customer-service level.

4.3.2. Settings of parameter and target inventory level

This decision model APIOPBCS included several parameters (*Ta*, *Ti*, *Tw*) for target inventory-level setting. Various parameter settings have been proposed by previous researchers (see Table 1). The settings used in the present study were based on those of

John et al. (1994) (that is, $Ta=8$, $Ti=4$, $Tw=8$). The effects of other settings on simulation results are discussed in Section 4.5.

The setting of the target inventory level was based on the traditional supply chain strategy. The customer service level (CSL) was based on an inventory level of 80% CSL.

4.3.3. Number of replications

In accordance with the method proposed by Kelton et al. (2007), simulation was first conducted with 10 replications. This number of replications is acceptable if the confidence interval 'half width' is $<10\%$. The traditional supply chain strategy requires 18 replications with a 95% level of confidence because its half-width is $>10\%$. Simulations of 20 replications were therefore conducted for the follow-up simulation of the traditional supply chain strategy.

The average customer-service level of the manufacturer-managed inventory strategy presented a large variation. The required number of replications was 596. Both inventory cost and customer-service levels were significantly worse. Manufacturer-managed inventory strategy thus had an inferior solution, and was excluded from this study.

From the experimental results, it was found that the performances for both inventory cost and customer-service level are significantly dire. The reason is that the manufacture-managed inventory strategy allows the factory to have a view on the total stock in the supply chain. Only the factory makes decisions on what to order to ensure the pipeline from raw material to the end customer remains full. This can be explained by the inadequacy of the pull policy used along the chain. The factory should be able to push the products down the supply chain. Because the results show that manufacture-managed inventory strategy is incomplete, (the factory should have the capability to push the products to lower echelons) (Hong-Minh et al., 2000), this strategy will not be taken into account in this study.

4.4. Experimental scenarios

The uncertainty factors involved in this study included: (i) order lead-time; (ii) delivery lead-time; (iii) production lead-time; (iv) capacity; (v) product quality; (vi) customer demand; and (vii) interval between arrivals of customers. To avoid the extensive experiment that would be required using these seven uncertainty factors, the compounding noise factors of the Taguchi method were utilised to construct two extreme conditions (that is, combinations of a 'good' tendency and a 'bad' tendency under certain compounding levels of noise factors).

First, the scenarios of minimum variation (N_1) and maximum variation (N_4) were constructed. The setting of the coefficient of variation, $C.V=0$, was set for the scenario of minimum variation (N_1), and $C.V=0.3$ was set for the scenario of maximum variation (N_4). Secondly, to obtain a more precise estimation of the simulations for all supply chain information-sharing strategies under changing environments, the above two scenarios were mixed to construct two medium-variation uncertainty conditions (N_2 and N_3).

The lead-time is assumed to follow a normal distribution in the simulation. According to the beer game settings, the average lead-time is 14 days. The constant value, $C.V=0$, was set as the uncertainty factor level setting of the minimum variation scenario N_1. The constant value, 14, was used to define order lead-time, delivery lead-time, production lead-time, and the customers' inter-arrival time for N_1. The value, $C.V=0.3$, was set as the uncertainty factor level setting of the maximum variation scenario N_4. Therefore, the lead-time of N_4 is set to be $N(14, 4.2)$. The productivity is assumed to follow uniform distribution. Therefore, there is no upper limit on the capacity setting for N_1. The production capacity with limitation condition is set to be $UNIF(15,48)$ for N_4. The product quality is usually presented as percentage. The product quality is set to be 100% and 90% for N_1 and N_4, respectively. The customer demand is assumed to follow normal distribution. The average customer demand is set to be a constant value, 8, for N_1. The customer demand for N_4 is set to be $N(8, 2.4)$. The customers' inter-arrival time is assumed to follow exponential distribution. According to the beer game settings, the customers' inter-arrival time is set to be 7 days and $EXPO(7)$ for N_1 and N_4, respectively.

For the medium variation, N_2, only the lead-time presented a random variation of normal distribution. The remainder of the factors were set in accordance with the most stable condition. For the other medium-variation scenario, N_3, the lead-time was constant. The remainder of the factors were set under the most unstable condition. Table 2 presents the four experimental scenarios established in this study.

4.5. Experimental analysis

4.5.1. Calculation of S/N ratio

The experiment was conducted for all supply chain information-sharing strategies under four scenarios. The result showed an average value for each scenario. Inventory cost is allocated to the 'smaller-the-better' (STB) scenario, and the calculated S/N ratio of total inventory cost is presented in Table 3.

Customer-service is attributed to the 'larger-the-better' (LTB) scenario, and the calculated S/N ratio of customer service is presented in Table 4.

Table 1
Various parameter settings.

Number	Parameter settings
1	$Ta=8$, $Ti=4$, $Tw=8$ (John et al., 1994)
2	$Ta=8$, $Ti=4$, $Tw=15$ (Disney et al., 1997)
3	$Ta=8$, $Ti=4$, $Tw=4$ (Naim and Towill, 1995)
4	$Ta=4$, $Ti=7$, $Tw=28$ (Disney, 2001)

Table 2
The four experimental scenarios.

	N_1	N_2	N_3	N_4
Lead time of order	14 days	N(14,4.2)	14 days	N(14,4.2)
Lead time of delivery	14 days	N(14,4.2)	14 days	N(14,4.2)
Lead time of production	14 days	N(14,4.2)	14 days	N(14,4.2)
Productivity	Infinite	Infinite	UNIF(15,48)	UNIF(15,48)
Product quality	100%	100%	90%	90%
Customer demand	8	8	N(8,2.4)	N(8,2.4)
The interval between customers' arrival	7 days	7 days	EXPO(7)	EXPO(7)

Table 3
S/N ratio of total inventory cost.

Total inventory cost (unit: $) Strategy	N_1	N_2	N_3	N_4	SN
Supply chain with distributor removed	252.86	274.63	367.70	333.68	−49.84
Emergency transshipments	334.29	359.82	492.92	463.83	−52.43
EPOS	338.57	362.09	481.33	467.85	−52.41
EPOS with distributor removed	259.29	274.62	320.06	307.92	−49.29
EPOS-integrated emergency transshipments	340.71	361.99	421.41	400.99	−51.65
EPOS-integrated emergency transshipments with distributor removed	263.57	274.26	279.66	287.33	−48.83
e-Shopping	130.71	135.24	142.93	141.39	−42.78
Reduced	287.14	306.92	366.90	325.72	−50.18
Traditional	332.14	359.89	510.12	515.99	−52.82
VMI	287.14	317.58	404.63	397.29	−51.01

Table 4
S/N ratio of customer service level.

Customer service level (unit: %) Strategy	N_1	N_2	N_3	N_4	SN
Supply chain with distributor removed	100	100	73.24	80.88	−1.30
Emergency transshipments	100	100	83.92	84.07	−0.82
EPOS	100	100	73.20	75.76	−1.47
EPOS with distributor removed	100	100	78.03	79.48	−1.16
EPOS-integrated emergency transshipments	100	100	85.88	84.97	−0.74
EPOS-integrated emergency transshipments with distributor removed	100	100	87.40	86.46	−0.65
e-Shopping	100	100	94.51	95.40	−0.23
Reduced	100	99.71	77.21	84.94	−1.03
Traditional	100	99.95	81.67	80.63	−1.00
VMI	100	60.24	27.73	29.64	−8.47

Table 5
Rankings for three multi-criteria decision methods.

Strategy	SMART	TOPSIS	GRA
Supply chain with distributor removed	4	4	7
Emergency transshipments	7	7	6
EPOS	9	9	9
EPOS with distributor removed	3	3	4
EPOS-integrated emergency transshipments	6	6	3
EPOS-integrated emergency transshipments with distributor removed	2	2	2
e-Shopping	1	1	1
Reduced	5	5	5
Traditional	8	8	8
VMI	10	10	10

4.5.2. *Multi-criteria decision-making methods*

After obtaining the S/N ratio of total inventory cost and customer-service level, the multiple criteria decision-making (MCDM) method was used to assess overall performance. Three MCDMs were utilised, as presented in Table 5.

As presented in Table 5, the numerical results for the three MCDMs were very similar. e-Shopping had the better overall performance and the most robust performance. From Table 5, it can be seen that the strategies with fewer echelons, such as (i) e-shopping, (ii) EPOS-integrated emergency transshipments with distributor removed, (iii) EPOS with distributor removed, and (iv) supply chain with distributor removed and reduced, had better overall performance and robust performance. The explanation for this is that the lower total cost can be obtained for those strategies with fewer echelons and the reduction of the echelons of supply chain is equivalent to the reduction of possible variation points. Consequently, the uncertainty of supply chain is then reduced.

It is apparent that an improved performance cannot be achieved by using EPOS or an emergency transshipments strategy alone. However, the robust characteristics of a supply chain can be improved by employing a combination of two or more strategies. For example, EPOS with distributor removed and EPOS-integrated emergency transshipments, and EPOS-integrated emergency transshipments with distributor removed, in particular, showed good performance. Since the Bullwhip Effect can be reduced through information-sharing, an emergency transshipments strategy allows a quick response to customer demand along a dynamic supply chain. Therefore, the robust characteristics of a supply chain can be potentially improved.

The rankings showed that VMI had the worst result. From Table 3, it can be seen that VMI had a lowest total inventory cost, but it had the worst customer-service level among all the strategies with four echelons. This is, arguably, due to the decrease in adaptability of VMI to a changing environment, while having a better control of inventory. VMI strategy is different from the other strategies which let the vendor to order more inventories for coping with uncertainty. The decreased inventory in VMI is replenished by the vendor within the lead-time. Therefore, the inventory can be replenished quickly only if the lead time is short enough. However, based on the present beer game settings that both the lead-time is not short enough and the inventory level is not high enough, VMI cannot provide a satisfactory service level under the uncertain demands.

4.5.3. *Comparison of results*

Experiments under different target inventory levels have been carried out in this study. The S/N ratio of total inventory cost decreased as the target inventory level increased. Because the objective function of S/N ratio is obtained by optimizing both the mean and standard deviation of the optimal inventory cost, the increase in the target inventory level might, arguably,

Table 6
S/N ratio of total inventory cost under different parameter settings.

Total inventory cost Strategy	1	2	3	4
Supply chain with distributor removed	−49.84	−50.81	−49.80	−49.91
Emergency transshipments	−52.43	−52.90	−52.19	−52.05
EPOS	−52.41	−54.09	−51.83	−52.54
EPOS with distributor removed	−49.29	−49.86	−49.56	−49.45
EPOS-integrated emergency transshipments	−51.65	−51.74	−51.94	−51.27
EPOS-integrated emergency transshipments with distributor removed	−48.83	−48.65	−49.58	−48.63
e-Shopping	−42.78	−42.20	−43.74	−42.32
Reduced	−50.18	−51.69	−50.69	−50.53
Traditional	−52.82	−56.37	−51.89	−53.58
VMI	−51.01	−52.01	−51.31	−51.16

Table 7
S/N ratio of customer-service level under different parameter settings.

Customer service level Strategy	1	2	3	4
Supply chain with distributor removed	−1.30	−1.29	−1.09	−1.00
Emergency transshipments	−0.82	−0.89	−0.63	−0.76
EPOS	−1.47	−1.22	−1.01	−1.13
EPOS with distributor removed	−1.16	−1.13	−0.79	−0.94
EPOS-integrated emergency transshipments	−0.74	−0.90	−0.61	−0.74
EPOS-integrated emergency transshipments with distributor removed	−0.65	−0.84	−0.52	−0.66
e-Shopping	−0.23	−0.37	−0.06	−0.27
Reduced	−1.03	−1.21	−1.10	−0.89
Traditional	−1.00	−1.20	−0.87	−0.95
VMI	−8.47	−7.88	−8.24	−7.99

Table 8
S/N ratio analysis by using SMART under different parameter settings.

Strategy	1	2	3	4
Supply chain with distributor removed	4	4	4	4
Emergency transshipments	7	7	8	7
EPOS	9	8	9	8
EPOS with distributor removed	3	3	3	3
EPOS-integrated emergency transshipments	6	5	6	6
EPOS-integrated emergency transshipments with distributor removed	2	2	2	2
e-Shopping	1	1	1	1
Reduced	5	6	5	5
Traditional	8	9	7	9
VMI	10	10	10	10

Table 9
S/N ratio analysis using TOPSIS under different parameter settings.

Strategy	1	2	3	4
Supply chain with distributor removed	4	4	4	4
Emergency transshipments	7	7	8	7
EPOS	9	8	9	8
EPOS with distributor removed	3	3	3	3
EPOS-integrated emergency transshipments	6	5	6	6
EPOS-integrated emergency transshipments with distributor removed	2	2	2	2
e-Shopping	1	1	1	1
Reduced	5	6	5	5
Traditional	8	9	7	9
VMI	10	10	10	10

Table 10
S/N ratio analysis using GRA under different parameter settings.

Strategy	1	2	3	4
Supply chain with distributor removed	7	6	6	6
Emergency transshipments	6	5	5	7
EPOS	9	8	9	9
EPOS with distributor removed	4	3	3	3
EPOS-integrated emergency transshipments	3	4	4	4
EPOS-integrated emergency transshipments with distributor removed	2	2	2	2
e-Shopping	1	1	1	1
Reduced	5	7	8	5
Traditional	8	9	7	8
VMI	10	10	10	10

cause the increase in the total inventory cost; and resulting in the decreased S/N ratio. On the contrary, the S/N ratio of customer-service level increased as the target inventory level increased. The S/N ratio will increase because it can provide a better service level under an uncertain environment, as the target inventory level increased. Tables 3 and 4 present that VMI possesses low inventory cost and a high customer-service level simultaneously under a stable environment. However, it had the worst ranking from the analysis of the three MCDMs in an uncertain environment. By conducting sensitivity analysis and comparing with other strategies, VMI was found to be capable of significantly improving robustness by increasing the target inventory level. The underlying reason is that the increase in target inventory level can improve the adaptability of VMI, which was sacrificed while the inventory level is controlled under a changing environment. Therefore, it could increase the robustness of the system.

Because of the different directions (that is, an increase or decrease) of inventory cost and customer-service level, it was necessary to find a compromise solution by using MCDMs. There was no significant difference in the rankings for different target inventory levels. Specifically, e-shopping showed the best overall performance. VMI had the worst rankings.

4.5.4. *Sensitivity analysis*

The S/N ratios of supply chain information-sharing strategies under different parameter settings are presented in Tables 6 and 7.

The S/N ratio analyses using three MCDMs under different parameter settings are presented in Tables 8–10.

It can be seen that strategies did not show any significant change in the rankings for the four different parameter settings. Moreover, e-shopping still showed the best overall performance. However, VMI had the worst rankings.

5. Conclusions and future research opportunities

5.1. Conclusions

To resolve the difficulties involved in selecting an appropriate supply chain information-sharing strategy in the context of uncertainty arising from a dynamic business environment, eleven (11) supply chain information-sharing strategies were examined in the present study. The aim was to provide a systematic and efficient evaluation of robust supply chain information-sharing strategies with a view to improve the quality of decision-making, reducing costs, and minimising risk.

The study has found that e-shopping showed the better overall performance, according to the rankings of the numerical methods employed. In general, the strategies with fewer echelons had better overall performances and robust performances. The robust performances of a supply chain can be improved by employing a combination of two or more strategies—such as EPOS with distributor removed and EPOS-integrated emergency transshipments, and, in particular, EPOS-integrated emergency transshipments with distributor removed showed good performance.

By applying three MCDMs, the study identified that VMI had the worst performance. While VMI showed low inventory cost and high customer-service level under a stable environment, it had the worst ranking when evaluated under an uncertain environment. The robustness of the VMI strategy can be enhanced with improved target inventory level.

From the sensitivity analysis of different target inventory values, it was apparent that the S/N ratio of inventory cost decreased with an increased target inventory level, but the S/N ratio of service level increased with increased target inventory level.

Parameter settings did not affect, in general, the robustness ranking of supply chain information-sharing strategies. Moreover, e-shopping always ranked first. The remainder of the strategies only marginally changed.

From the perspective of total cost, the supply chain strategies with fewer echelons generally present a lower total cost. Consequently, the e-shopping alternative is preferable as it has the minimum echelons (only two echelons). However, the remaining supply chain strategies, with more echelons, are more industrially applicable. In reality, it is not possible for all business activities to be fulfilled by using the strategy with a minimum number of echelons, such as with an e-shopping strategy. Therefore, many supply chain strategies (such as the eleven (11) supply chain strategies described above) were developed to satisfy alternative business models. Each criterion has been assessed for each echelon of the different supply chain strategies. This gave a total result per criterion for the total supply chain. The underlying assumption with the assessment of results is that all criteria and all echelons in the supply chain are equally weighted.

This study evaluates both the total inventory cost and the customer service-level as performance measures. To solely compare different strategies, aiming towards finding 'the best strategy' in all situations, is not possible, useful or realistic. However, an important contribution of this study is that we present a method by which a company, in a specific (uncertain) setting, can identify the preeminent SCM strategy.

5.2. Future research opportunities

In this study, three multi-criteria decision methods were utilised to assess the overall robust performance of each supply chain information-sharing strategy. Future researchers might obtain a different result by choosing any one appropriate multi-criteria decision method based on their own needs. Two performance criteria, inventory cost and customer service were used in this study. Improved results might be gained by developing alternative performance criteria and to consider the weightings of each criterion for evaluating the system. In this study, the order quantity is set based on APIOBPCS. A different ordering strategy may have a different influence on the robustness of supply chain information sharing. Therefore, a study of robustness of supply chain information sharing strategies under different ordering strategies could be a worthwhile topic for future study.

Inventory cost is not the sole criterion to be considered. Other criteria, such as ordering cost and transportation cost, could be considered. The traditional beer game adopted here is to identify the performance index, only recognizes one cost parameter, an inventory cost composed of shortage cost and holding cost. This study simulated the information-sharing strategies by utilizing the traditional beer game. Consequently, the inventory cost was used as the cost parameter in this study. A future research opportunity would be to include other cost criteria to establish an extended-beer game.

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