A knowledge-based system for overall supply chain performance evaluation: a multi-criteria decision making approach

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Abstract

Purpose – Existing supply chain (SC) performance models are not able to cope with the potential of intensive SC digitalisation and establish a relationship between decisions and decision criteria. The purpose of this paper is to develop an integrated knowledge-based system (KBS) that creates a link between decisions and decision criteria (attributes) and evaluates the overall SC performance.

Design/methodology/approach – The proposed KBS is grounded on the fuzzy analytic hierarchy process (fuzzy AHP), which establishes a relationship between short-term and long-term decisions and SC performance criteria (short-term and long-term) for accurate and integrated Overall SC performance evaluation.

Findings – The proposed KBS evaluates the overall SC performance, establishes a relationship between decisions (long-term and short-term) and decision criteria of SC functions and provides decision makers with a view of the impact of their short-term or long-term decisions on overall SC performance. The proposed system was implemented in a case company where the authors were able to develop a SC performance monitoring dashboard for the company's top managers and operational managers.

Practical implications – The proposed KBS assists organisations and decision makers in evaluating their overall SC performance and helps in identifying underperforming SC functions and their associated criteria. It may also be considered as a tool for benchmarking SC performance against competitors. It can efficiently point to improvement directions and help decision makers improve overall SC performance.

Originality/value – The proposed KBS provides a holistic and integrated approach, establishes a relationship between decisions and decision criteria and evaluates overall SC performance, which is one of the main limitations in existing supply chain performance measurement systems.

Keywords Decision making, Integration, Fuzzy AHP

Paper type Research paper

1. Introduction

Advances in technology that allow organisations to collect, store, organise and use data information systems for efficient decision-making (DM) are ushering in a new era of SC performance evaluation (Fawcett *et al.*, 2007; Forslund, 2010). Artificial intelligence (AI) is gaining momentum across industries as a result of great strides seen in computing power and storage, the introduction of the Internet of Things (IoT) and Big Data (Rezaei *et al.*, 2017). AI helps in DM by bridging the gaps between experienced and inexperienced decision makers and allows real-time recommendations based on historical and current data analysis. Therefore, today, DM is not only "information-driven," but also "data-driven", which ensures greater precision in overall SC performance evaluation and DM (Sahay and Ranjan, 2008). Based on real-time data, fast decisions are essential to ensure more flexibility and rapid product delivery. Performance measurement is critical to the success of the SC. In managing the SC, many decisions must be taken at each level of DM (short-term or long-term) that has an impact on the overall SC performance. Therefore, it is essential for decision makers to understand the existing relationship

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between decisions, decision criteria and the overall SC performance.

SC integration plays a central role in the fulfilment of customer demand. It is based on alignment and efficient coordination within the SC. A SC integrates all activities, information and resources which are essential and involved from suppliers to customers to deliver the "right product" to the "right customer" at the "right time" in good quality while maximising the overall value generated. The value or the SC surplus is the difference between the value of the final product and the entire SC cost that is incurred in filling the customer demand (Chopra and Meindl, 2016). According to Charkha and Jaju (2014), SC as:

> A chain that links various entities, from the customer to the supplier, through manufacturing and services so that the flow of materials, money, and information can be effectively managed to meet the requirements.

The integration process in SC increases complexity for SC managers. Supply chain management (SCM) decisions play a significant role in the success or failure of an organisation. SCM is defined as comprising decisions related to the flow of information, products and funds. Usually, these decisions can be classified based on the frequency and the period during which a decision phase has an impact. In this context, it becomes more critical to have a sophisticated SC performance evaluation system to evaluate the impact of strategic, tactical and operational decisions on the SC performance in real time. These capabilities are particularly important in a dynamic environment where rapid SC decisions are critical.

Performance evaluation is a process or set of metrics used to quantify the efficiency or effectiveness of decisions and decision criteria. Many factors have an impact on the overall SC performance. However, it is quite challenging to identify the effect of decisions on overall SC performance precisely. Indeed, existing performance measurement systems (PMS), such as the dimension-based measurement system, are not able to reflect the underperforming criteria and their associated sub-criteria at any DM level (short-term and long-term) in the entire SC network because they focus mainly on the primary criteria (Agami *et al.*, 2012). For instance, the SCOR model focusses heavily on information flow and does not consider all SC processes. Moreover, the overall performance measurement is somewhat difficult to obtain and has less flexibility if we alter measures (Agami *et al.*, 2012). The balance score card (BSC) is a static model without the dimension of time and provides real-time information. The cause and effect relationship between different functions at different DM levels (short-term and long-term) are absent. Finally, most existing PMS face certain practical limitations in incorporating vague (linguistic) information/data when measuring the overall SC performance. Thus, to achieve greater integration between performance evaluation and DM, a link must exist between the two components to reduce errors and guarantee the achievement of the expected SC performance after execution. Therefore, the objectives of this paper are as follows:

- to study the relationship between short-term and long-term decisions and SC performance criteria (short-term and long-term) for accurate overall SC performance evaluation;
- to develop a knowledge-based system (KBS) that integrates knowledge from decision makers (top managers, planners, operations managers) and data from information collected from SC execution and evaluates overall SC performance; and
- to identify underperforming decision criteria in the short and long-term decision process to improve overall SC performance.

The remainder of the paper is organised as follows. Section 2 illustrates a comprehensive background based on a systematic literature review of existing SC performance evaluation systems and applications of fuzzy AHP in SC performance evaluation. Section 3 describes the problem statement and highlights the contribution of this study. Section 4 explains the proposed methodology to develop the KBS using the fuzzy AHP technique. Section 5 describes the implementation of the proposed methodology with an example from an automobile manufacturing company. Section 6 presents a discussion and practical implications of the proposed KBS. Section 7 concludes the paper and indicates the scope for future research.

2. Literature review

This literature review is divided into two main parts. In the first part, we will give an overview of the main existing supply chain performance measurement (SCPM) systems. In the second part, we will discuss the applicability of the fuzzy system in SCPM. Finally, we will identify research gaps.

2.1 Existing supply chain performance evaluation systems

The literature on SC performance management is considerably broad. Several authors have tried to examine major SC performance management systems from different perspectives. For example, Kurien and Qureshi (2011) condensed nine theoretical SC performance evaluation frameworks. Similarly, Agami *et al.* (2012) and Kurien and Qureshi (2011) organised SC performance evaluation frameworks and models into two main categories, namely, financial and non-financial and nine subcategories of non-financial categories. The Supply Chain Operation Reference (SCOR) model and the BSC are the most widely used performance evaluation systems. Most performance evaluation systems are specific to particular organisations and are not flexible. Financial performance evaluation systems focus mainly on economic indicators (Agami *et al.*, 2012; Kurien and Qureshi, 2011). The BSC system evaluates performance from four perspectives, namely, customer, financial, internal business and innovation. The BSC is a static model and provides real-time information. The cause-effect relationship between different functions at different DM levels (short-term and long-term) is not supported. Moreover, the cause-effect relationship between performance and decisions (long-term and short-term) is not obvious. Similarly, the SCOR model communicates between SC partners as the decision process related to SC functions, which are Plan, Source, Make and Deliver. However, it does not include all the processes and SC functions that are generally present in many organisations and as a result, overall performance evaluation is quite difficult and not easily modifiable when there is a change in assessment.

Dimension-based performance evaluation systems evaluate SC performance in terms of dimensions and do not reflect the performance of sub-criteria and their major associated criteria within the SC network (Agami *et al.*, 2012; Kurien and Qureshi, 2011). Perspective-based evaluation systems (PBMS) consider perspectives such as "system dynamics", "operations research", "logistics", "marketing", "organisation" and "strategy" and evaluate performance in terms of perspectives (Agami *et al.*, 2012; Kurien and Qureshi, 2011). The hierarchal-based evaluation system assesses performance at the different DM levels, namely, strategic, tactical and operational. However, no clear guidelines are provided to reduce the different levels of conflicts in the entire SC network (Agami *et al.*, 2012; Kurien and Qureshi, 2011). The function-based performance evaluation system evaluates specific SC function performance by focusing on each SC function separately/independently (Agami *et al.*, 2012; Kurien and Qureshi, 2011). The efficiency-based evaluation system for its part evaluates SC performance regarding efficiency (Agami *et al.*, 2012; Kurien and Qureshi, 2011). It evaluates the efficiency of SC functions as units, which are related to each other. However, it does not provide any relationship between each SC function. This creates ambiguity for the DM process.

Several key performance indicators (KPIs) were used with existing PMS to evaluate SC performance. Short-term and long-term decisions drive each KPIs. The long-term decision criteria for supplier selection are monetary value, supplier delivery performance (Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001), geographical location (Mondragon *et al.*, 2011) and environmentally friendly suppliers (Hu and Hsu, 2010). Decision drivers for these criteria are cost, supplier performance management, sourcing and sustainable suppliers. As for manufacturing, long-term decision criteria are: overall equipment effectiveness (OEE) (Mondragon *et al.*, 2011), capacity utilisation (Otto and Kotzab, 2003; Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001), inventory (Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001) and environmentally friendly operations (Hu and Hsu, 2010; Gunasekaran *et al.*, 2004). Decision drivers for the decision criteria are maintenance management, improving machine uptime, inventory policies and sustainable manufacturing. For warehousing, the decision criteria are storage utilisation (Otto and Kotzab, 2003; Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001), inventory count accuracy (Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001), order fulfilment (Bhagwat and Sharma, 2007; Gaudenzi and Borghesi, 2006); and inventory levels (Supply Chain Council, 2012; Gunasekaran *et al.*, 2004). Their associated decision drivers are size, design, automated storage and retrieval system (ASRS) of warehouses, inventory management systems, order management systems and finished product inventory policy, respectively. For logistics, long-term decision criteria are flexibility (Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001; Shepherd and Günter, 2011), delivery reliability and transportation cost (Gunasekaran *et al.*, 2004; Gunasekaran *et al.*, 2001) and environmentally friendly transportation (Hu and Hsu, 2010). Decision drivers for these decision criteria are fleet variety, transportation quality, long-term contract with the logistics service provider and sustainable transportation, respectively.

The list of short-term decision criteria and decision drivers of considered SC functions are summarised in Appendix 1. The proposed list for long-term and short-term decision criteria of the considered SC functions mentioned in Appendix 1 and Appendix 2 is based on a recent analysis of the literature in this field.

2.2 Fuzzy systems, analytic hierarchy process and supply chain performance evaluation

One of the main factors for improving the overall SC performance is the consideration of uncertainties among SC functions. Managing the SC in dynamic and uncertain environments, where information is unclear, and prediction is not easy, is also challenging. The fuzzy DM technique is useful in modelling complex and vague systems in which information is uncertain or unavailable and where the linguistic input is required from experts. Fuzzy decision-making (FDM) and its integration with other MCDM such as AHP have been applied at almost every level of the SC DM process and in the considered SC functions. FDM can easily be used in situations characterised by uncertainty and imprecision (Sirigiri *et al.*, 2012).

SC performance appraisal can be associated with actions of decision makers who are involving various (mostly immaterial) criteria/attributes, and hence, requires the subjective judgement of the decision maker. On the other hand, even a quantitative appraisal of SC performance metrics is difficult as performance evaluation systems are vague and ill-defined (Nomesh *et al.*, 2012). For instance, Jung (2011) proposed the fuzzy AHP Goal programming approach in manufacturing systems. Govindan *et al.* (2015) and Ocampo *et al.* (2015) used fuzzy systems and the fuzzy analytic network process (ANP) methodology in the manufacturing process. Tadic *et al.* (2014) proposed an integrated approach based on fuzzy AHP and TOPSIS in selecting logistics service providers. Ashrafzadeh *et al.* (2012) applied fuzzy TOPSIS in warehousing location selection. Khan *et al.* (2016) proposed the fuzzy AHP approach in warehouse performance evaluation. Several researchers, such as Kanda and Deshmukh (2007), Ohdar and Ray (2004), Chan and Qi (2003) and Unahabhokha *et al.* (2007) have used the fuzzy logic methodology to evaluate SC performance.

Some criteria have a more significant impact on the overall SC performance than others. The pairwise comparison of the AHP method, which ensures consistency among decision makers when assigning the importance of a given factor over another, is used to find the weights for these criteria. Bhagwat and Sharma (2007) used AHP to rank SCM metrics and other performance metrics levels. Chan *et al.* (2003) applied AHP as a DM tool to judge the rankings of performance evaluation criteria. Yang *et al.* (2011) came up with the logarithm triangular fuzzy number-AHP method to develop a SC performance evaluation system model. Askariazad and Wanous (2009) used the AHP methodology to carry out pairwise comparisons of SC functions, processes and criteria in a bid to develop a dependable framework for measuring the overall SC performance. To align BSC to petroleum industry SC strategy, Varma *et al.* (2008) used AHP in combination with BSC. Bhagwat and Sharma (2009) explained how an integrated AHP- preemptive goal programming (PHP) model could be used in performance evaluation while optimising the overall performance. Dobrota *et al.* (2015) applied fuzzy AHP in warehouse location selection. Dargi *et al.* (2014) used fuzzy ANP in supplier selection. Ding (2013) applied fuzzy systems in logistics network design. For optimal overall performance evaluation of SCM for SMEs, Bhagwat *et al.* (2008) applied AHP and linear programming techniques. Bhagwat and Sharma (2007) proposed a hierarchal model to prioritise SCM parameters. AHP has been successfully used in the supplier and reverse logistics service provider selection (Jain and Khan, 2017; Dweiri *et al.*, 2016). Drzymalski *et al.* (2010) developed a methodology using both the AHP and ANP techniques to gauge the SCM's performance based on two types of dependencies (intra-and inter-organisational) that exist in a multi-echelon SC.

2.3 Research gaps and discussion

Intensive digitalisation allows decision makers and managers to take fast decisions. Organisations should adopt more flexible ways of managing their SC. Existing PMS are not designed adequately to provide fast DM as they usually evaluate SC performance after operations have been completed. Moreover, existing SC PMS have some limitations to support the intensive integration among SC functions and stockholders at different DM levels. Finally, although the existing link between long-term and short-term decisions in many decision models, the explicit link between long-term and short-term SC evaluation criteria is absent (Khan, 2018) . Based on the literature review, we can summarise the limitations in existing SCPM systems, which are as follows:

- Existing SCPMS fail to establish a clear relationship between decisions (short-term and long-term), decision criteria and SC functions.
- There is an inadequate balance between financial and non-financial measurements in current SCPM systems and given the large number of existing SCPMs, it is quite difficult for decision makers to identify the most suitable performance management system to use to evaluate their SC performance.
- DM knowledge is not used efficiently to obtain a better evaluation of SC performance.

Thus, the proposed model will develop the integrated KBS to evaluate the overall SC performance. Designing a SC performance system that is sensitive to changes in the SC environment (stakeholders, decision makers, strategies and policies) is thus essential to appropriately adjust SC decisions at the right time and functions.

3. Problem statement

Advances in technology that allow organisations to collect, store, organise and use data and information for effective DM have opened new horizons and dimensions of SCPM (Khan, 2018). In managing SC, many decisions have to be taken at each scope (short-term or long-term). Further, many factors have an impact on the overall SC performance (Rezaei *et al.*, 2017). However, notwithstanding recent progress in the development of SC performance systems, it is still quite challenging to measure the exact effect of decisions on overall SC performance. Therefore, organisations must use technological advances and develop a performance system based on knowledge, and that integrates major functions of SC (Forslund, 2010). This study will answer the following research questions:

RQ1. How do we develop a KBS to identify the relationship between short-term and long-term decisions and SC performance decision criteria?

RQ2. How do we integrate and evaluate the overall SC performance?

RQ3. How do we identify underperforming SC performance criteria at different decision levels (long-term or short-term) to improve the overall SC performance?

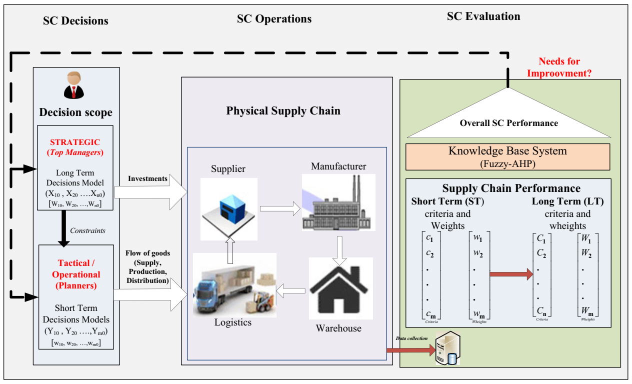
As shown in Figure 1, the vector (X_{10}, X_{20}, . . ., X_{n0}) represents the initial strategic (long-term/Investment) decisions made by top managers to design the SC based on a strategy characterised by specific long-term criteria (C_1, C_2, . . ., C_n) and their respective weights (W_{10}, W_{20}, . . ., W_{n0}). Once the SC network has been implemented, we will measure results based on different short-term attributes (c_1, c_2, . . ., c_n). These attributes are operational data collected from the company's information systems, such as enterprise resource planning, manufacturing execution system, transportation management system, order management system (OMS) and warehouse management system (WMS). These attributes are also the results of different initial decisions (Y_{10}, Y_{20}, . . ., Y_{n0}) at the tactical and operational levels of planning and their respective weights (w_{10}, w_{20}, . . ., w_{n0}).

By using long-term decision criteria (C_1, C_2, . . ., C_n) and their importance weights (W_1, W_2, . . ., W_n) and short-term decision criteria (c_1, c_2, . . ., c_m) and their importance weight (w_1, w_2, . . ., w_m), we will evaluate the overall SC performance based on the proposed KBS. If the overall SC performance is not up to the mark, we will go back to decisions taken at initial stages and calibrate the long-term and short-term ones by changing the weights for the long-term and short-term criteria (W_1, W_2, . . ., W_n; w_1, w_2, . . ., w_m) to improve the overall SC performance. This is a continuous process, where we will calibrate decisions until we achieve the desired overall SC performance.

4. A proposed methodology based on fuzzy analytic hierarchy process

The proposed approach considers the major SC functions (supplier, manufacturer, warehousing and logistics) available at many organisations. Also, it considers common SC

Figure 1 KBS for overall SC performance evaluation



performance criteria, which fulfil the purpose of overall SC performance evaluation for most of the organisations. Each criterion (long-term and short-term) of considered SC functions covers SC aspects, including reverse logistics, sustainability and sales and distribution. Therefore, we believe that the performance evaluation framework is general as it includes most SC functions and considers most of the standard criteria that are common to many organisations. Moreover, the generalised SC performance evaluation framework provides organisations with a shared performance evaluation platform, which allows information sharing among different SC functions and evaluates the overall SC performance. As the primary purpose of this paper is to develop an integrated SC performance evaluation framework that incorporates SC functions, establish a relationship between SC decision criteria and evaluate overall SC performance. A systematic and generalised methodology is introduced to most of the organisations examined. Figure 2 summarises the different steps required:

4.1 Step 1: Define supply chain functions

SC functions vary from one sector to another. In this step, we have to specify SC functions that are subject to evaluation. The selection of SC functions should be in line with specific SC activities (plan, source, make and deliver). Figure 3 shows the SC functions included in this study and that is common to many organisations.

Figure 2 Proposed methodology

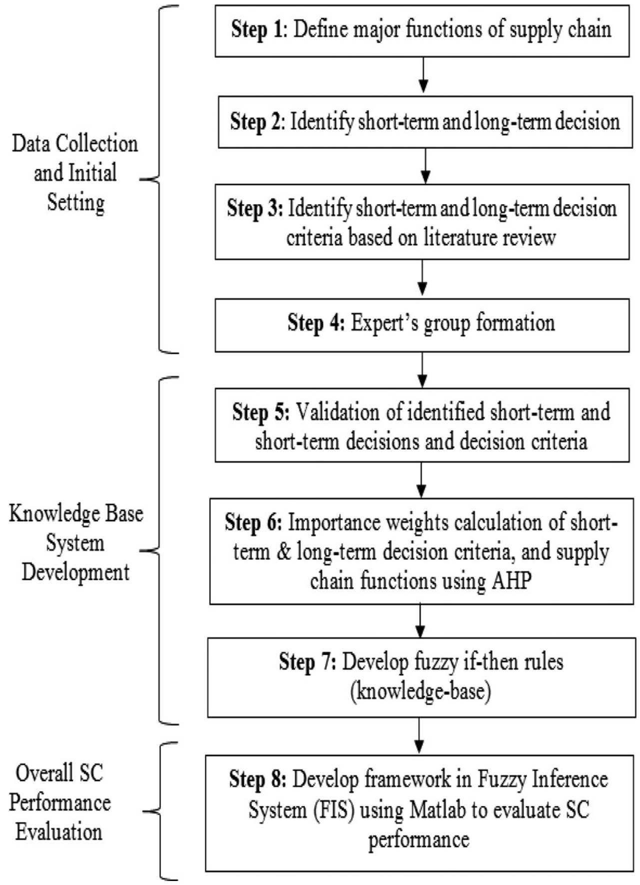
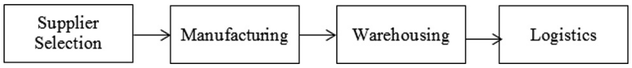


Figure 3 Considered SC functions



4.2 Step 2: Identify short-term and long-term decisions

As the primary purpose of the proposed KBS is to establish a relationship between short-term and long-term decisions and show their impact on the overall SC performance, we identified short-term and long-term decisions, as indicated in Appendix 1 and Appendix 2, respectively.

4.3 Step 3: Identify short-term and long-term decision criteria based on a literature review

In an integrated system, each decision is related to one another and each function of SC decisions has an impact on the overall SC performance. In this step, we can identify short-term and long-term decision criteria based on a literature review or using the most widely used performance indicators, as indicated in Appendix 1 and Appendix 2. The categorisation of criteria at particular decision levels (short-term and long-term) is based on the guidelines provided by Simchi-Levi *et al.* (2008) and is indicated in Appendix 3.

4.4 Step 4: Expert group formation

To implement the proposed methodology to evaluate the overall SC performance, we need experts to:

- validate identified criteria drawn from the literature and their relevance for most organisations;
- establish relationships between SC decision criteria;
- perform a pairwise comparison on identified decision criteria in the long-term and short-term; and
- develop KBS (fuzzy if-then rules).

4.5 Step 5: Validation of identified short-term and long-term decision criteria

A detailed and extensive survey similar to that in Step 4 should be done to review the classified criteria for short-term and long-term DM and to check their relevance with most of the different business segments such as manufacturing, service or process. In this step, either a group DM approach or an extensive survey could be used to review the classified criteria for short-term and long-term DM (identified in Step 3) and to check their relevance to the considered case company. Same approaches like group DM or extensive survey will be used to perform pairwise comparison and to develop KBS (fuzzy if-then rules) as describes in Step 4.

4.6 Step 6: Importance weights calculation of short-term and long-term decision criteria and supply chain functions using analytic hierarchy process

In this stage, similar to Step 4, we need to conduct a survey of experts and perform a pairwise comparison based on Saaty's scale to calculate the importance weights for short-term and long-term decision criteria. We also need to determine SC functions using AHP, and that applies to most organisations. According to Saaty (1980a, 1980b), "AHP is a common multi-criteria DM method. It is developed by Saaty (1980a, 1980b) to assist in solving complex decision problems by capturing both subjective and objective evaluation measures. It breaks a complex problem into hierarchy or levels".

Short-term and long-term decision criteria's importance weights have been calculated using pairwise comparisons. This pairwise comparison measures the relative weight for the criteria based on the main goal. The "inconsistency of the judgement" should be equal to zero and leads to a "perfect" score if quantitative data is available. Where the latter is not available, decision makers use qualitative judgement for a pairwise comparison (Dweiri *et al.*, 2015; Khan *et al.*, 2016). This qualitative pairwise comparison follows the importance scale suggested by Saaty (1980a, 1980b), as shown in Table I.

We also use the same pairwise comparison process to find the relative importance of different alternatives for each criterion (Dweiri *et al.*, 2015; Khan *et al.*, 2016). Each child (sub-criteria) has a "local priority" (immediate) and "global priority" (weight) with respect to the parent (major criteria). The sum of priorities for all the children of the parents "must be equal to 1". The global priority shows the relative importance of the alternatives with respect to the primary goal of the model.

4.7 Step 7: Develop fuzzy if-then rules (knowledge-based)

In this step, experts are asked through a survey to develop a fuzzy KBS (fuzzy if-then rules) and the relationship between SC decision criteria for the short- and long-terms based on their experience. In general, there are many possible relationships between the considered SC functions, as shown in Figure 4.

As illustrated in Figure 4, the supplier selection function may be related to manufacturing, warehousing and logistics. Similarly, manufacturing may be related to warehousing and logistics and warehousing may be related to logistics. Likewise, each considered function of the SC long-term decision criteria (C_1, C_2, …, C_n) is connected to others considered SC functions' (manufacturing, warehousing and logistics) long-term decision criteria. Correspondingly, each considered function of SC short-term decision criteria (c_1, c_2, …, c_m) is related to other considered SC functions' (manufacturing, warehousing and logistics) short-term decision criteria. These links can be developed using a fuzzy KBS (fuzzy if-then rules). The basic structures of the fuzzy KBS (if-then rules) for Phases I, II and III are shown in Tables II-IV, respectively.

Table I Importance scale of factors in pairwise comparison (Saaty's, 1980a, 1980b)

Importance scale	Importance description
1	Equal importance of 'i' and ' j'
3	Week importance of 'i' over 'j'
5	Strong importance of 'i' over 'j'
7	Demonstrated importance of 'i' over 'j'
9	Absolute importance of 'i' over 'j'

Note: 2, 4, 6 and 8 are intermediate values

Figure 4 Generalised structure of relationships among SC functions

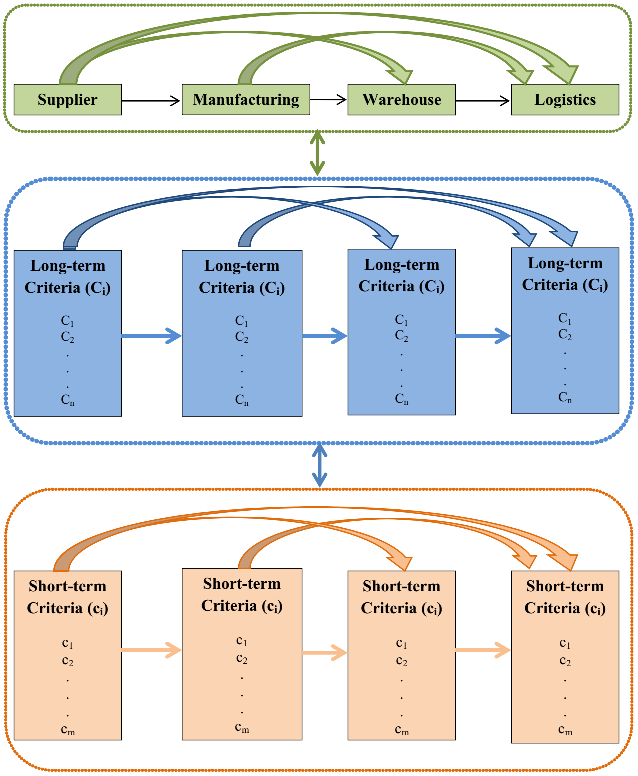


Table II Generalised structure of fuzzy KBS (fuzzy if-then rules) for Phase I

Phase I				
		Long-term decision criteria (C_1, C_2, . . . C_n)		
		Short-term decision criteria weights (w_1,w_2, . . . w_m)		
		L	M	H
Short-term decision criteria value (c_1, c_2, . . . c_m)	L	a_1	a_2	a_3
	M	a_4	a_5	a_6
	H	a_7	a_8	a_9

Table II shows the generalised structure of the fuzzy if-then rules of Phase I where the relationship between short-term decision criteria values (c_1, c_2, …, c_m) and their importance weights (w_1, w_2, …, w_m) with long-term decision criteria values (C_1, C_2, …, C_n). a_1, a_2, …, a_6 are the values of the specific rules. The generalised structure of fuzzy if-then rules is based on the expert's decision makers knowledge and experience and their linguistic (L, M, H) decisions. It can be interpreted as follows:

> IF short-term decision criteria value (c1, c2, ., cm) is "L" and its importance weights (w1, w2,…, wm) is "M" THEN long-term decision criteria value (C1, C2, …, Cn) value will be a2.

> IF short-term decision criteria value (c1, c2, ., cm) is "M" and its importance weights (w1, w2,…, wm) "H" THEN long-term decision criteria value (C1, C2, …, Cn) value will be a6.

We can interpret Tables III and IV similarly. All rules developed by experts and decision makers in this step follow the same structure. They represent the relationship between one decision criterion and its importance weights with one long-term decision criterion value at a time. These KBS (fuzzy if-then rules) will apply to most organisations.

Table III Generalised structure of fuzzy KBS (fuzzy if-then rules) for Phase II

Phase II

		Performance of SC functions ((f$_1$, f$_2$, . . . f$_i$) Long-term decision criteria weights (W$_1$, W$_2$, . . . W$_n$)		
Long-term decision criteria value (C$_1$, C$_2$, . . . C$_n$)		L	M	H
	L	b_1	b_2	b_3
	M	b_4	b_5	b_6
	H	b_7	b_8	b_9

Table IV Generalised structure of fuzzy KBS (fuzzy if-then rules) for Phase III

Phase III

		Overall SC performance (X) Performance weights of SC functions (W$_1$, W$_2$, . . . W$_j$)		
Performance value of SC functions (f$_1$, f$_2$, . . . f$_i$)		L	M	H
	L	A_1	A_2	A_3
	M	A_4	A_5	A_6
	H	A_7	A_8	A_9

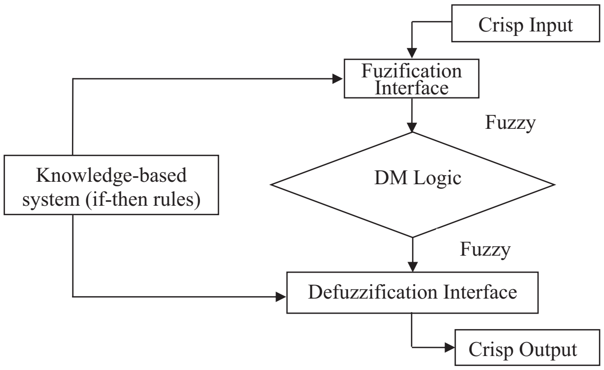
4.8 Step 8: Develop a framework in fuzzy inference system using matlab to evaluate overall supply chain performance

To develop the integrated fuzzy inference system (FIS) for evaluating the overall SC performance, we need to build an inference system in three phases. In Phase I, we develop a FIS to see the impact of short-term decision criteria on long-term decision criteria for each function of the considered SC function. In Phase I, the impact of each short-term decision criteria on long-term decision criteria will be estimated. We will develop a FIS based on operational value (actual data) and decision criteria weights (which was calculated based on expert opinion using AHP) and fuzzy (if-then rules) as mentioned in Step 6. In Phase II, we estimate the effects of long-term decision criteria by developing a FIS on each function of SC based on the input value (calculated through Phase I) and decision criteria weights (calculated based on expert opinion through AHP) and the relationship developed in Step 6. In Phase III, we integrate each function of a considered SC function into the overall SC performance by developing a FIS. We will enter input values (calculated through Phase II) and considered SC function weights (calculated based on expert opinion through AHP) and the relationship developed in Step 6.

At this level, we are ready to introduce fuzzy the inference system (FIS). "Fuzzy logic is a problem-solving methodology that provides a simple way of definite conclusions from vague and imprecise information" (Zadeh, 1988). Figure 5 indicates the framework for the fuzzy decision-making system (FDMS).

FDMS is composed of four main components: a fuzzification interface, a KBS, DM logic and a defuzzification interface (Dweiri, 1999; Lee-Kwang and Lee, 1999) as shown in Figure 5. In essence, an "FDMS is a fuzzy expert system (FES). FES is oriented towards numerical processing where conventional expert systems are mainly symbolic reasoning engines" (Kandel, 1992; Yang *et al.*, 2001; Zadeh, 1988). Figure 5 provides a general framework for the interrelationships between the four components that constitute an FDMS (Dweiri and Kablan (2006). These four components are:

Figure 5 FDM system



Sources: Dweiri and Kablan (2006); Khan *et al*. (2016)

1 The fuzzification interface, where "we measure the characteristics of input variables on their associated membership functions to measure the degree of belongings for each rule premise"(Dweiri and Kabla, 2006; Dweiri and Kablan, 2006; Dweiri and Kablan, 2006; Dweiri and Kablan, 2006; Dweiri and Kablan, 2006; Dweiri and Kablan, 2006; Dweiri and Kablan, 2006).
2 The KBS, which includes experts' knowledge of application areas and the decision rules that control the relationship between inputs and outputs. Experts' experience and their knowledge of the system help in designing membership functions of inputs and outputs".
3 The decision-making logic that is identical to mimicking human DM in ascertaining fuzzy control actions and establishing rules of inference in fuzzy logic. The assessment of the rule depends on evaluating the truth value of its premise part and uses it to its conclusion part. Thus, one fuzzy subset is assigned to each output variable of the rule. Similarly, in inferencing, the whole strength of the rule is treated as a minimum membership value of the input variables' membership values" XXX.
4 The defuzzification interface, which converts a "fuzzy control action (a fuzzy output) into a fuzzy control action (a crisp output). The most commonly used method in defuzzification is the centre of area method (COA). The COA method computes the crisp value as the weighted average of a fuzzy set" (Dweiri and Kablan, 2006).

5. A case study of an automobile manufacturing company

5.1 Data collection and initial settings

In this section, we will focus on the applicability of the proposed fuzzy KBS for the overall SC performance evaluation via a case study. XYZ Company is located in the southern part of a developing country and is one of the largest automotive car manufacturers in an emerging economy. It was established in 1989, in technical collaboration with Toyota Tsusho Corporation (TTC), Japan. The manufacturing facility and offices are located at a 105-acre site in the south, while the product is delivered to end customers nationwide through a strong network of 41 independent 3S dealerships spread across the country. The company manufactures, imports and distributes passenger cars, sport-utility vehicle's, four-wheel drive cars and commercial vehicles from Japan and Thailand. The company workforce is over 2,300, including management employees. The management of XYZ Company is interested in building an FDMS that evaluates their overall SC performance. We implemented the proposed methodology step by step, as shown in Figure 2.

In Step 1, we enquire about the SC functions to consider in the study, and the case company stated that they have the same functions of SC as indicated in Figure 3.

In Steps 2 3, we consider the case company the same identified short-term and long-term decisions (Appendix 1). Moreover, we decide to use the same short-term and long-term decision criteria that are identified from the literature (Appendix 2). In Step 4, we adopt a group DM process that assists us in developing a fuzzy AHP-based overall SC performance framework. Stakeholders of the automobile manufacturing firms are selected from the following departments: Procurement, Manufacturing, Logistics, Warehouse and Operations. Five key actors are selected from each stakeholder for participation in the interviews. Interviewers from each stakeholder department comprised one manager (15+ years of experience), one deputy manager (12+ years of experience), one assistant manager (11+ years of experience) and three key officers (5+ years, 7+ years and 8+ years of experience within the company). All group members have more than eight years of experience and have been with the company for at least three years. Selected experts were used to perform four tasks, as mentioned in Step 4.

During the company's group DM process, we find many decision points and variables that require the involvement of all stakeholders. Firstly, we brief them on the objectives of this exercise (evaluate overall SC performance) and explain the SC performance method, which includes the rationale for each construct and their interrelationships. Secondly, the fuzzy AHP method was described. This was to show not only how to evaluate the overall SC performance, but also to give them an idea of the rationale for particular selections. Thirdly, the participants are asked to perform the pairwise comparison on Saaty's scale, as mentioned in Table I, develop if-then-else rules and define the membership functions. The group form a consensus decision and come up with one value/result under the leadership of the operational director of the company. We answer some questions that are raised by a few members by explaining the whole procedure.

5.2 Knowledge-based system development

In Step 5, experts are asked to review the identified criteria for short-term and long-term decisions and decision criteria as indicated in Appendix 1 and Appendix 2. After thorough discussions among each group, they approve and validate the short-term and long-term decisions and decision criteria.

In Step 6, experts are asked to perform a pairwise comparison based on Saaty's scale for the identified short-term and long-term decision criteria importance and SC functions. We enter these values in the AHP software. Tables V and VI summarise the importance weights for short-term and long-term decision criteria, and Table VII summarises the importance weights for the considered SC functions.

In Step 7, experts and DMs are asked to develop the fuzzy KBS (if-then rules) using their experience. They follow the same structure of rules as described in Table II for Phase I, Table III for Phase II and Table IV for Phase III, and consider the relationship between one decision criterion and its importance weights at a previous time. Experts and decision makers consult with each other and provide the rules. They consider only the horizontal relationships between the SC functions criteria. They develop a total of 558 rules in Phase I, followed by 128 rules in Phase II and 36 rules in Phase III. Examples of rules developed in each phase (Phase I, Phase II and Phase III) by the experts and decision makers are shown in Table VIII for Phase I, Table IX for Phase II and Table X for Phase III.

Rules mentioned above for Phase I and shown in Table VIII can be interpreted as follows:

Table V Importance weights for short-term decision criteria of considered SC

Supplier selection		Manufacturing		Warehousing		Logistics	
Short-term criteria ($c_1, c_2, \ldots c_m$)	Wt. (AHP) ($w_1, w_2, \ldots w_m$)	Short-term criteria ($c_1, c_2, \ldots c_m$)	Wt. (AHP) ($w_1, w_2, \ldots w_m$)	Short-term criteria ($c_1, c_2, \ldots c_m$)	Wt. (AHP) ($w1, w2, \ldots w_m$)	Short-term criteria ($c_1, c_2, \ldots c_m$)	Wt. (AHP) ($w_1, w_2, \ldots w_m$)
On-time delivery	0.324	Productivity	0.248	Order accuracy	0.369	Quality of goods delivered	0.351
Price	0.201	Cost/Operation hour	0.233	Order fill rate	0.216	Faulty deliveries	0.248
Rejection rate	0.194	Defect%	0.222	Cost/Order	0.134	On-time delivery	0.165
Air/Water/ Land emission	0.142	Air/Water/ Land emission	0.130	On-time delivery	0.125	Cost/Unit delivered	0.109
Lead time	0.091	On-time delivery	0.096	Inventory turn	0.097	Return product cost/unit	0.073
Delivery flexibility	0.047	% of Reused material	0.071	Damaged inventory	0.057	Air/Water/Land emission	0.053

Table VI Importance weights for long-term decision criteria of considered SC

Supplier selection		**Manufacturing**		**Warehousing**		**Logistics**	
Long-term criteria ($C_1, C_2, \ldots C_n$)	**Wt. (AHP) ($W_1, W_2, \ldots W_n$)**	**Long-term criteria ($C_1, C_2, \ldots C_n$)**	**Wt. (AHP) ($W_1, W_2, \ldots W_n$)**	**Long-term criteria ($C_1, C_2, \ldots C_n$)**	**Wt. (AHP) ($W_1, W_2, \ldots W_n$)**	**Long-term criteria ($C_1, C_2, \ldots C_n$)**	**Wt. (AHP) ($W_1, W_2, \ldots W_n$)**
Monetary value	0.403	Inventory level	0.511	Order fill rate	0.358	Flexibility	0.068
Supplier delivery performance	0.187	Environmentally friendly operation	0.247	Inventory level	0.317	Delivery reliability	0.303
Geographical location	0.101	Capacity utilisation	0.131	Storage utilisation	0.260	Transportation cost	0.377
Environmentally friendly supplier	0.310	OEE	0.111	Inventory count accuracy	0.064	Environmentally friendly transportation	0.252

Table VII Importance weights for considered SC functions

Supplier selection	0.230	Manufacturing	0.371	Warehousing	0.111	Logistics	0.288

Table VIII If-then-else rules examples (Phase I)

		Monetary value		
		Rejection rate Wt.		
Rejection rate		L	M	H
	L	*H*	*H*	*M*
	M	*L*	*M*	*L*
	H	*M*	*M*	*L*

Table IX If-then-else rules examples (Phase II)

		Supplier selection performance		
		Monetary value Wt.		
Monetary Value		L	M	H
	L	*L*	*M*	*M*
	M	*M*	*M*	*H*
	H	*M*	*H*	*H*

Table X If-then-else rules examples (Phase III)

		Overall SC performance		
		Supplier selection performance Wt.		
Supplier selection performance value		L	M	H
	L	*L*	*M*	*M*
	M	*M*	*M*	*H*
	H	*M*	*H*	*H*

Notes: PS: L = Low; M = Medium; H = High

> IF rejection rate is "L" and its weight is "L" THEN monetary value will be "H".
>
> IF rejection rate is "M" and its weight is "H" THEN monetary value will be "L".

Similarly, Phase II, shown in Table IX, can be interpreted as follows:

> IF monetary value is "H" and its weight is "M" THEN supplier selection performance value will be "H".
>
> IF monetary value is "L" and its weight is "H" THEN supplier selection performance value will be "M".

Also, Phase III, shown in Table X, can be interpreted as follows:

> IF supplier selection performance value is "M" and its weight is "L" THEN overall SC performance value will be "M".
>
> IF supplier selection performance value is "H" and its weight is "H" THEN, overall SC performance value will be "H".

In Step 8, we built a FIS in three phases, as explained above in Step 7 of Section 3. Examples of FIS are mentioned in Figure 6.

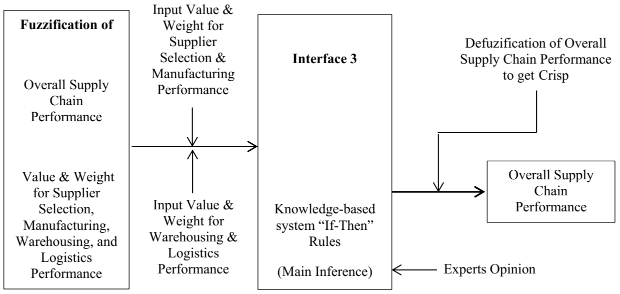
The structure of the integrated framework for evaluating the overall SC performance in each phase is shown in Appendix 4.

5.3 Overall supply chain performance evaluation

Now we have all the necessary inputs needed to determine the overall SC performance, we can build an FDMS for the evaluation of the overall SC performance according to the following steps.

Step (a): Figure 6 illustrates the intended FDMS for the overall SC performance. We have six inputs for supplier selection (short-term decision criteria and their weights) and

Figure 6 FIS of integrated system to measure the overall SC performance

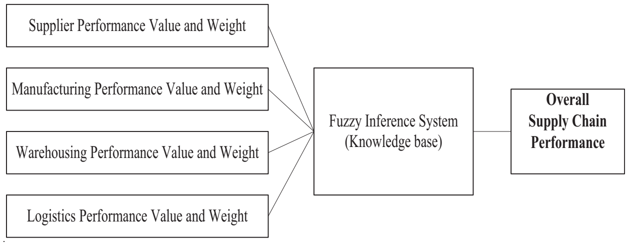


four outputs (long-term decision criteria). Similarly, we have six inputs for manufacturing, warehousing and logistics (short-term decision criteria and their weights) and four outputs (long-term decision criteria). To evaluate the overall SC performance by the integrated system, as mentioned in Appendix 4, we develop the same FDMS for Phases II and III. In general, the value of long-term decision criteria of each SC function is determined by aggregating the following three components:

1 *The combined impact of short-term decision criteria of supplier selection (price and weight for the price) on long-term decision criteria (monetary value, supplier delivery performance, geographical location and environmentally friendly supplier) operation*: This combined impact can be evaluated using a set of fuzzy "if-then" rules. These rules should usually be based on the expert's knowledge and experience in the case company. The rules for supplier selection are developed for short-term criteria (rejection rate, on-time delivery, lead time, delivery flexibility, air/water/land emission and their associated weights) and long-term criteria (monetary value, supplier delivery performance, geographical location and environmentally friendly supplier).
2 *The combined influence of long-term supplier selection, manufacturing, warehousing and logistics decision criteria (a value we got from Step 1, along with the respective weights) on the performance of supplier selection, manufacturing, warehousing and logistics functions*: This combined impact can be evaluated using a set of fuzzy "if-then" rules. Usually, these rules should be based on the expert's knowledge and experience in the case company. These rules have been developed for long-term criteria of SC functions (supplier selection, manufacturing, warehousing and logistics) performance of considered SC functions as mentioned in Figure 3.
3 *Similarly, the combined impact of the performance of the considered SC function (supplier selection, manufacturing, warehousing and logistics) on the overall SC performance*: This can be evaluated using a set of fuzzy if-then rules, as indicated in Figure 7.

Step (b): Fuzzify the input variables and the output variable in Phases I, II and III based on the expert's knowledge and experience (Appendix 4). Membership functions, in general, are developed using expert's knowledge and experience. Experts usually suggest the boundaries and the shape of each subset. We decided to use the following fuzzy subsets to fuzzify the input variables: Low (L), Medium (M) and High (H). Also, we chose to use trapezoidal membership functions. Similarly, the other input variables and the output variable were fuzzified.

Figure 7 Intended FDMS for overall performance



Step (c): Enter if-then decision rules into the software. The "if-then" rules used in our case study are assumed to be based on "heuristic knowledge" and on the experts' experience. They are conveniently tabulated in the form of lookup tables, as mentioned above in Tables VIII-X, respectively. The total number of rules for all three phases is 722. These rules are entered into the software, accessed and their "truth-ness" is evaluated during the "inferencing process." At this point, the construction of the FDMS is complete because inferencing and defuzzification are built-in functions in the software.

Now, the FDMS is ready to accept input values. In Phase I, if we feed the system with the input short-term criteria attributes and weights for short-term criteria of each function of SC (supplier selection, manufacturing, warehousing, logistics), as mentioned in Table V, FDMS will relate input values to their fuzzy sets, the decision rules are applied and the fuzzy results of the output variable (long-term decision criteria) in Phase I for each function of SC is composed and defuzzified using the COA method. The output of each SC function of long-term decision criteria is obtained based on input values of short-term decision criteria (operational data) from the case company and weights from AHP process (calculated using pairwise comparison as mentioned in Step 6). Table XI below shows the Phase I results:

Similarly, Table XII shows the values of long-term decision criteria values that we got after Phase I and their importance weights that we obtained from AHP (Table VI). FDMS will relate input values to their fuzzy sets, the decision rules will be applied and the fuzzy results of the output variable (performance) in Phase II for each function of SC will be composed and defuzzified using the COA method.

Table XIII shows the performance of each SC function (supplier, manufacturing, warehousing and logistics) based on long-term decision criteria values that we got after Phase II (Table XII) and their importance weights that we got from AHP (Table V). FDMS will relate input values to their fuzzy sets, the decision rules will be applied and the fuzzy results of the output variable (performance) in Phase II for each function of SC will be composed and defuzzified using the COA method.

Table XIV shows the overall SC performance based on the performance values of the considered SC functions (supplier selection, manufacturing, warehousing and logistics) that we got in Phase III (Table XIII) and its importance weights from AHP (Table VII). FDMS will relate input values to their fuzzy sets, the decision rules will be applied and the fuzzy results of the output variable (Overall SC performance) in Phase III for the performance of each function of SC will be composed and defuzzified using the COA method.

Based on short-term criteria attributes that we got from the case company (information system), we can see that the supplier selection performance is 66.4 per cent, manufacturing is 65 per cent, warehousing is 41.4 per cent and logistics is 37.8 per cent. Also note that as per company experts and based on their pairwise comparison, the importance of supplier selection in evaluating overall SC performance is 23 per cent, followed by 37.1 per cent for manufacturing, 11.1 per cent for warehousing and 28.8 per cent for logistics. These values rely on the company's experts and the developed KBS. For the considered case company, the overall SC performance is 50.7 per cent. The case company's decision makers provide target values for each considered SC function based on their past

Table XI Short-term decision criteria values and weights (Phase I)

Supplier Selection			Manufacturing			Warehousing			Logistics		
Short-term criteria (c_m)	**Attribute**	**Wt. (AHP) (w_m)**	**Short-term criteria (c_m)**	**Attribute**	**Wt. (AHP) (w_m)**	**Short-term criteria (c_m)**	**Attributes**	**Wt. (AHP) (w_m)**	**Short-term criteria (c_m)**	**Attributes**	**Wt. (AHP) (w_m)**
On-time delivery	0.90	0.324	Productivity	0.85	0.248	Order accuracy	0.95	0.369	Quality of goods delivered	0.93	0.351
Price	75	0.201	Cost/ operation hour	45	0.233	Order fill rate	0.97	0.216	Faulty deliveries	0.04	0.248
Rejection rate	0.10	0.194	Defect %	0.07	0.222	Cost/ Order	26	0.134	On-time delivery	0.91	0.165
Air/ Water/ Land emission	60	0.142	Air/ Water/Land emission	54	0.130	On-time delivery	0.93	0.125	Cost/Unit delivered	36	0.109
Lead time	12	0.091	On-time delivery	0.90	0.096	Inventory turn	7	0.097	Return product cost/ unit	31	0.073
Delivery flexibility	6	0.047	% of reused material	0.08	0.071	Damaged inventory	0.038	0.057	Air/Water/Land emission	60	0.053

Table XII Long-term decision criteria values based on short-term decision criteria and weights (Phase II)

Supplier Selection			Manufacturing			Warehousing			Logistics		
Long-term criteria (C_n)	**Value**	**Wt. (AHP) (W_n)**	**Long-term criteria (C_n)**	**Value**	**Wt. (AHP) (W_n)**	**Long-term criteria (C_n)**	**Value**	**Wt. (AHP) (W_n)**	**Long-term criteria (C_n)**	**Value**	**Wt. (AHP) (W_n)**
Monetary value	0.540	0.403	Inventory level	0.311	0.511	Order fill rate	0.576	0.358	Flexibility	0.375	0.068
Supplier delivery performance	0.546	0.187	Environmentally friendly operation	0.302	0.247	Inventory level	0.506	0.317	Delivery reliability	0.493	0.303
Geographical location	0.357	0.101	Capacity utilisation	0.337	0.131	Storage utilisation	0.618	0.260	Transportation cost	0.658	0.377
Environmentally friendly supplier	0.478	0.310	OEE	0.487	0.111	Inventory count accuracy	0.569	0.064	Environmentally friendly transportation	0.487	0.252

Table XIII SC Function values based on long-term decision criteria values and weights

SC functions ($f_1, f_2, \ldots f_i$)	Value
Supplier selection	0.664
Manufacturing	0.650
Warehousing	0.414
Logistics	0.378

Table XIV Considered performance of SC functions (Phase III)

SC functions ($f_1, f_2, \ldots f_i$)	Value	Weight (AHP) ($W_1', W_2', \ldots W_j'$)	Overall SC performance
Supplier Selection	0.664	0.230	0.507
Manufacturing	0.650	0.371	
Warehousing	0.414	0.111	
Logistics	0.378	0.288	

performance evaluation. For example, functional performance (Logistics, Warehousing, Manufacturing and Supplier Selection) targets (T) are initially set to at least 40 per cent.

Similarly, for the overall SC performance, it is set as 75 per cent. As the considered case company has implemented the proposed KBS, they decided to start with these values and later (after a few months); they will adjust the target values after identifying the underperformed criteria and the ways of improvement. For long-term supplier selection, manufacturing, warehousing and logistics decision criteria; they are 40 per cent, 30 per cent, 55 per cent and 45 per cent, respectively. These values are obtained by considering existing facilities at each SC function, trained and experienced personnel working in the company, and based on the experience of decision makers and experts with each SC function.

For a better presentation of the results, a SC-monitoring dashboard is shown below. The dashboard is useful for top managers and operational managers (planners) and allows them to visualise the overall performance. Moreover, it also helps decision makers in setting targets and monitoring the overall SC performance over a given period. Furthermore, the SC-monitoring dashboard is helpful for looking at the current performance and comparing it with previous ones. It is also helpful for all decision makers (long-term and short-term decision makers) for monitoring their criteria performance and taking immediate action to improve the overall SC performance (Figure 8).

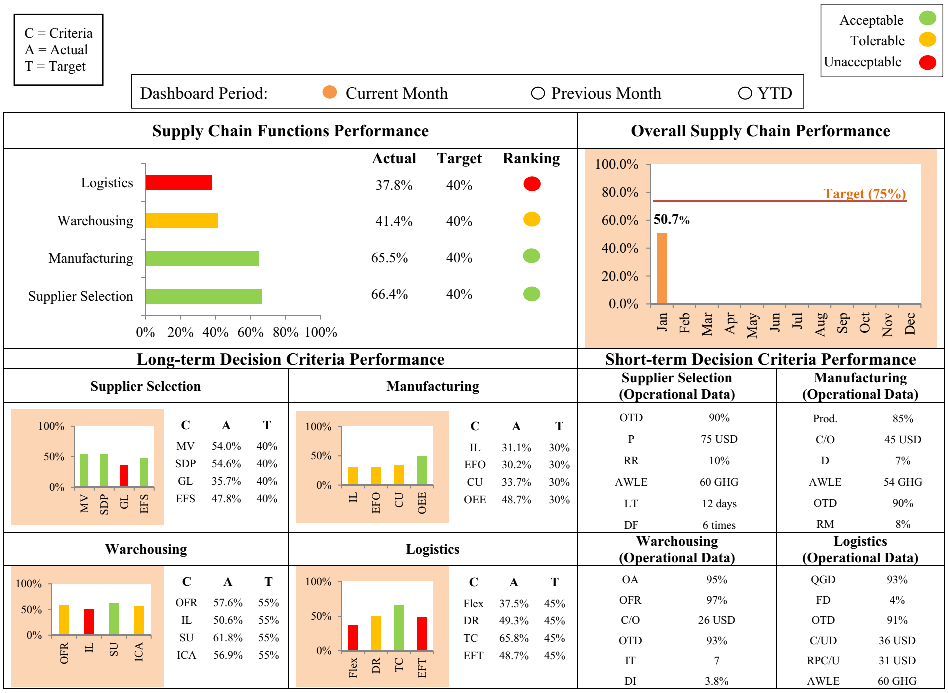
5.4 Sensitivity analysis

The Section 7 highlights the implementation of the proposed methodology based on the case study and information collected from the different experts and considers the horizontal relationship among decision criteria (short-term and long-term) and their respective SC functions. As the proposed methodology is also able to capture the cross-function relationships (Figure 4) as well, we generated additional scenarios to evaluate the effect of the overall SC performance as follows:

- *Scenario 1*: In this scenario, we considered the impact of the cross-functional relationship of two SC functions (supplier selection and manufacturing) on the overall SC performance. We modified the KBS (fuzzy if-then rules) by adding 18 new rules to establish the relationship between the two considered SC functions on overall SC performance. After running the proposed KBS as per the steps mentioned in Phase III, the overall SC performance changed to 40.8 per cent.
- *Scenario 2*: In this scenario, we considered the impact of the cross-functional relationship of two SC functions (supplier selection and logistics) on the overall SC performance. We modified the KBS (fuzzy if-then rules) by adding 17 new rules to establish the relationship between the two considered SC functions. After running the proposed KBS as per the steps mentioned in Phase III, the evaluated overall SC performance was 49.9 per cent.
- *Scenario 3*: In this scenario, we considered the impact of the cross-functional relationship of three SC functions (manufacturing, warehousing and logistics) on overall SC performance. We modified the KBS (fuzzy if-then rules) by adding 17 new rules to establish the relationship among the three considered SC functions. After running the proposed KBS as per the steps mentioned in Phase III, the evaluated overall SC performance was 26.6 per cent.
- *Scenario 4*: In this scenario, we considered the impact of the cross-functional relationship of three SC functions (supplier selection, manufacturing and warehousing) on overall SC performance. We modified the KBS (fuzzy if-then rules) by adding 20 new rules to establish the relationship among the three considered SC functions. After running the proposed KBS as per the steps mentioned in Phase III, the evaluated overall SC performance was 39.1 per cent.
- *Scenario 5*: In this scenario, we considered the impact of the cross-functional relationship among all considered SC functions (supplier selection, manufacturing, warehousing and logistics) on overall SC performance. We modified the KBS (fuzzy if-then rules) by adding 27 new rules to establish the relationship among the considered SC functions on overall SC performance. After running the proposed KBS as per the steps mentioned in Phase III, the overall SC performance was evaluated at 66.4 per cent.

All the above-mentioned considered scenarios were based on experts' judgement as they wanted to see the effect and importance of cross-functional relationship on overall SC performance. Based on the above scenarios, the highest overall

Figure 8 SC performance dashboard



Dashboard Period: ● Current Month ○ Previous Month ○ YTD

Supply Chain Functions Performance

	Actual	Target	Ranking
Logistics	37.8%	40%	🟥
Warehousing	41.4%	40%	🟨
Manufacturing	65.5%	40%	🟩
Supplier Selection	66.4%	40%	🟩

Long-term Decision Criteria Performance

Supplier Selection

C	A	T
MV	54.0%	40%
SDP	54.6%	40%
GL	35.7%	40%
EFS	47.8%	40%

Manufacturing

C	A	T
IL	31.1%	30%
EFO	30.2%	30%
CU	33.7%	30%
OEE	48.7%	30%

Warehousing

C	A	T
OFR	57.6%	55%
IL	50.6%	55%
SU	61.8%	55%
ICA	56.9%	55%

Logistics

C	A	T
Flex	37.5%	45%
DR	49.3%	45%
TC	65.8%	45%
EFT	48.7%	45%

Short-term Decision Criteria Performance

Supplier Selection (Operational Data)		Manufacturing (Operational Data)	
OTD	90%	Prod.	85%
P	75 USD	C/O	45 USD
RR	10%	D	7%
AWLE	60 GHG	AWLE	54 GHG
LT	12 days	OTD	90%
DF	6 times	RM	8%

Warehousing (Operational Data)		Logistics (Operational Data)	
OA	95%	QGD	93%
OFR	97%	FD	4%
C/O	26 USD	OTD	91%
OTD	93%	C/UD	36 USD
IT	7	RPC/U	31 USD
DI	3.8%	AWLE	60 GHG

SC performance is observed in Scenario 5 (considering the relationship among all the functions), which is 66.4 per cent. Similarly, the lowest overall SC performance is reported in Scenario 3 (considering the relationship among three SC functions), which is 26.6 per cent. This result shows that it is essential for decision makers and SC managers to identify the potential cross-functional relationship because it might have a direct impact on the overall SC performance. Moreover, sensitivity analysis demonstrates clearly that the proposed KBS allow decision makers and experts to see the impact of cross-functional relationship on overall SC performance. Finally, experts should be ready to change the associated weight for each criterion (long-term and short-term) to adjust the appropriate decisions (long-term and short-term decisions) to achieve the performance targeted for each function and the overall performance.

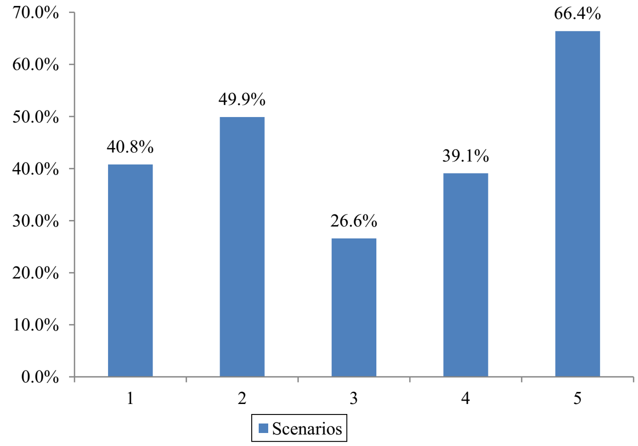
All the scenarios mentioned above are represented in Figure 9.

6. Discussion and practical implications

The proposed methodology is general and can be implemented in different sectors with a few modifications, such as a change in criteria (short-term and long-term) and weights, which would reflect changes in SC strategies and policies. In the case automobile manufacturing company, experts approved the identified criteria and SC functions and the proposed methodology were implemented to evaluate the overall SC performance. There could be a cross-functional relation between short-term decision criteria across considered SC functions and a fuzzy KBS should allow decision makers to establish such relations based on their individual experiences. Decision makers and experts can develop any relationships they deem possible and relevant to their SC. In the case company, experts considered the horizontal relationship between the decision criteria as mentioned in Table VII. SC Managers and decision makers are now able to precisely evaluate SC performance based on the knowledge system that provides them to use operational data from data management systems.

Another purpose of this study was to integrate and evaluate overall SC performance. The proposed methodology can integrate the considered SC functions and their associated short-term and long-term decision criteria in three different phases, as mentioned in Appendix 4. We can see from this appendix that in Phase I, we calculated the long-term decision criteria values based on short-term decision criteria attributes (which we got from the case company information system) and weights (which we got from AHP). In Phase II, we calculated the performance of considered SC functions (supplier selection, manufacturing, warehousing and logistics) based on long-term decision criteria values that we got in Phase I and weights that we calculated using AHP. In Phase III, the overall SC performance was evaluated based on the considered performance of SC functions obtained in Phase II and importance weights using AHP. Thus, every decision and decision criteria are interrelated and have an impact on overall SC performance. The proposed KBS uses experts' knowledge and experience to develop the relationship between decisions and decision criteria (short-term and long-term) and determine their impact on the overall SC performance.

Figure 9 Sensitivity analysis of considered SC cross-function relationship in overall SC performance



The third purpose of this study was to identify underperforming decision criteria at different decision levels (long-term or short-term) to improve overall SC performance. After our proposed knowledge-based SC performance evaluation system was implemented, we noticed that the overall SC performance of the case company was 50.7 per cent, and needed improvement. The proposed methodology should help decision makers in finding underperforming functions. In this case, with a score of 0.378 logistics is the lowest performing function among the entire SC functions. The weight associated with the overall SC performance is 0.288, which is significant. Also, the second-lowest SC function performance is warehousing, which is 0.414. In addition to that, decision makers must now decide to improve the logistics performance as a first step in improving the overall SC performance, as it is the lowest among all SC functions. As mentioned previously, we need decisions and decision criteria related to logistics both in the long- and short-terms. In this case, we can see from Table XI that "Flexibility," a long-term decision criterion and its associated decision; "Fleet Variety," have a low value (0.375) and its importance weight is 0.068; it is followed by "Environmentally friendly transportation," a long-term criterion and its associated decision, "Sustainable transportation," which is 0.487 and its importance weight is 0.252. Here, the decision maker has the option to choose either flexibility or environmentally friendly transportation decision criteria and decisions, which are fleet variety and sustainable transportation to improve the overall SC performance. For example, if we want to take long-term decisions to improve logistics performance, which will lead to an improvement of the overall SC performance, we have to increase fleet variety by selecting transportation service providers with a variety of fleets. This will improve flexibility (long-term decision criterion) and eventually will improve overall SC performance. To show the flexibility of the proposed system and how the improvement of the lowest long-term decisions (fleet variety and sustainable transportation criteria) will impact the overall SC performance, we run the model while increasing the fleet variety value from 0.375 to 0.47 and increasing sustainable transportation performance (environmentally friendly transportation) from 0.487 to 0.587. Using the KBS, we observe an improvement of the overall SC performance from 0.507 to 0.515. These results mainly show that the proposed KBS can quickly provide directions for improvements and identify decisions and decision criteria that are underperforming, and finally, it helps decision makers improve the overall SC performance.

The SC performance evaluation dashboard allows decision makers and SC managers to visualise the overall SC performance. The proposed KBS automatically updates the information on the dashboard by integrating new changes in policy and strategy into operational results. Thus, to improve the overall SC performance, decision makers and SC managers need to identify the function and criteria (long-term or short-term) needing extra focus and attention. In this case, the proposed KBS can identify underperformed decision (long-term or short-term) criteria easily.

7. Conclusion and future research

Existing SC performance models are not effectively aligned with the intensive SC digitalisation to establish a clear relationship between decisions and decision criteria. Every industry segment SC is different. Therefore, we need a holistic and integrated knowledge-based SC performance evaluation system that evaluates overall SC performance, establishes a relationship between decisions (long-term and short-term) and decision criteria of SC functions and allows decision makers to see the impact of their short-term or long-term decisions on overall SC performance. This study developed a KBS that establishes relationships between short-term and long-term decisions and decision criteria and evaluates overall SC performance. The proposed KBS can be implemented in any industry and experts can develop a relationship between the decisions and decision criteria. This relationship can cascade or go across the SC functions, as mentioned in Figure 3. According to the proposed approach, the relationships between decisions and decision criteria and overall SC performance are determined by the integration of the following three impacts:

1 the combined impact of short-term decision criteria attributes (from case company) and the importance weights (from AHP) of considered SC functions (supplier selection, manufacturing, warehousing, logistics) on the long-term decision criteria of the considered SC. (Phase 1);
2 the combined impact of long-term decision criteria values (from Phase I) of considered SC functions and the importance weight factor (from AHP) on the performance of each function of the considered SC. (Phase 2); and
3 the combined impact of the performance value of considered SC functions (from Phase II) and the importance weight factor (from AHP) on the overall SC function.

The proposed integrated KBS for overall SC performance evaluation is illustrated via a case study. A FDMS is designed and implemented using MATLAB for overall SC performance evaluation. Furthermore, the AHP and Expert Choice (EC) are used for the evaluation of the priorities of short-term and long-term decision criteria and functions of considered SC. The development of an FDMS for overall SC performance evaluation is easily implemented using MATLAB.

Our proposed KBS is based on experts' knowledge and their experience. The latter was used in determining the membership functions of all input and output variables and establishing decision rules (if-then-else) to govern the relationship between inputs and outputs. Our proposed KBS can be considered as a FDM expert system and can be useful in preserving the knowledge of decision makers and experts in any organisation.

Finally, our proposed system can absorb the effect of changing the behaviour of customers due to the digital transformations of SC. It creates a relationship between each function of SC decisions and decision criteria and SC functions and provides a holistic and integrated approach to evaluate overall SC performance, which is lacking in existing SC performance evaluation systems. Therefore, we believe that the proposed KBS and the successful implementation in an automobile manufacturing company contribute to answering the main research questions that were raised at the end of Section 2.

The proposed KBS can benefit from the following future research:

- Short-term and long-term decision criteria are selected using the literature review and also validated by the case company. However, a survey of different companies should be carried out to validate the necessary short-term and long-term criteria to include in the KBS.
- The fuzzy KBS (if-then rules) was developed based on feedback from case company experts. However, it is recommended that we validate these rules using different companies' experts through extensive surveys.
- The relationship between decision criteria in a case company considered in a cascaded fashion (horizontal). In the future, it is recommended to implement the proposed KBS by establishing relationships across different SC functions.
- In this study, we adopted three linguistic scales (Low, Medium and High) in the development of the fuzzy KBS. It is also recommended to use five linguistic scales (Very low, Low, Medium, High and very high) and to then compare the results. Five-point Linguistic scale will be able to capture small variations in the decision strategies and be more sensitive to the changes.
- We implemented the proposed methodology for an automotive company in the manufacturing sector. However, to obtain external validity, it is recommended to implement the proposed system in other manufacturing and service sectors, and perhaps with slight modifications.

Notwithstanding, the above-mentioned limitations and future research recommendations, we believe that the proposed KBS is general and can be implemented in any organisation regardless of the business sector, with slight modifications. Also, we believe that this research establishes a stepping stone in SC performance evaluation literature, as we introduced the concept of the relationship between SC performance decision criteria and evaluating overall SC performance by using integrated SC functions. Decision makers and managers can use the proposed system to monitor their overall SC performance and take appropriate actions based on the continuous data monitoring.

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Appendix 1

Table AI Short-term decision criteria

SC Function	Decisions Drivers	Decision Criteria	Reference
Supplier selection	Cost	Price	Kaplan and Norton (1992), Lambert and Pohlen (2001), Shepherd and Günter (2011)
	Supplier delivery Performance	Rejection rate	Kaplan and Norton (1992)
		On-time delivery	Gaudenzi and Borghesi (2006) Gunasekaran *et al.* (2004) Supply Chain Council (2012)
		Lead time	Otto and Kotzab (2003) Bhagwat and Sharma (2007) Gaudenzi and Borghesi (2006)
		Delivery Flexibility	Otto and Kotzab (2003) Bhagwat and Sharma (2007) Gaudenzi and Borghesi (2006) Shepherd and Günter (2011)
	Supplier sustainability	Air/Water/Land Emission	Agarwal *et al.* (2011) Agarwal and Vijayvargy (2012)
Manufacturing	Meeting production target	On-time delivery/cycle time	Otto and Kotzab (2003) Gunasekaran *et al.* (2004)
	Quality of manufactured product	% Defect	Gunasekaran *et al.* (2004) Gaudenzi and Borghesi (2006) Bhagwat and Sharma (2007)
	Cost	Cost/operation hour	Beamon (1999) Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001) Shepherd and Günter (2011)
	Effective utilisation of resources	Productivity	Gunasekaran *et al.* (2004)
	Sustainable operations	Air/Water/Land emission or Solid/ Hazardous/ Water waste	Azzone and Noci (1998) Agarwal *et al.* (2011) Agarwal and Vijayvargy (2012)
		% of crushed material	Gunasekaran *et al.* (2001) Hu and Hsu (2010) Rao and Holt (2005)
Warehousing	Cost	Cost/order	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001) Otto and Kotzab (2003) Shepherd and Günter (2011)
	Material handling	Damaged Inventory	Supply Chain Council (2012) Gunasekaran *et al.* (2004)
	Delivery performance	On-time delivery	Gunasekaran *et al.* (2004) Gaudenzi and Borghesi (2006) Shepherd and Günter (2011)
		Order fill rate	Gunasekaran *et al.* (2004) Supply Chain Council (2012) Gaudenzi and Borghesi (2006)
		Order accuracy	Bhagwat and Sharma (2007) Supply Chain Council (2012) Kaplan and Norton (1992)
	Inventory management	Inventory turn	Beamon (1999)

(*continued*)

Table AI

SC Function	Decisions Drivers	Decision Criteria	Reference
Logistics	Performance of goods delivered	Quality of Goods Delivered	Gunasekaran *et al.* (2004)
		Faulty Deliveries	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001) Gaudenzi and Borghesi (2006)
		On-time Delivery	Gunasekaran *et al.* (2004) Gaudenzi and Borghesi (2006) Shepherd and Günter (2011)
	Operation cost	Cost/unit delivered	Gaudenzi and Borghesi (2006) Shepherd and Günter (2011)
	Sustainability cost	Cost/unit delivered of RL	Diabat and Govindan (2011) Mondragon *et al.* (2011)
	Sustainable transportation	Air/water/land emission or Solid/ Hazardous/ water waste	Azzone and Noci (1998) Agarwal *et al.* (2011) Agarwal and Vijayvargy (2012)

Appendix 2

Table AII Long-term decision criteria

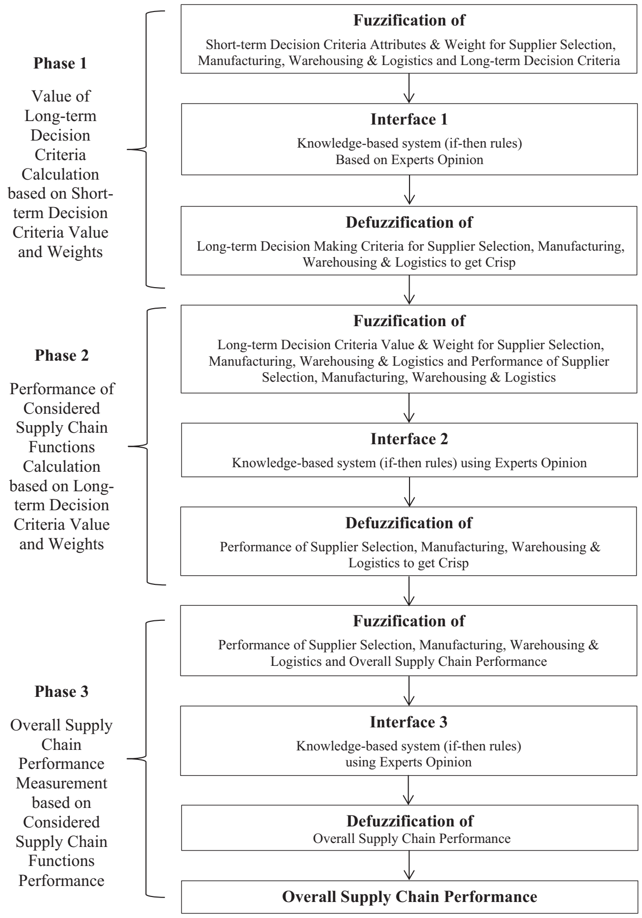
SC function	Decisions drivers	Decision criteria	References
Supplier selection	Cost	Monetary value	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Supplier performance management	Supplier delivery performance	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Sourcing	Geographical location	Mondragon *et al.* (2011b)
	Sustainable supplier	Environmentally friendly upplier	Hu and Hsu (2010)
Manufacturing	Maintenance management	OEE	Mondragon *et al.* (2011b)
	Improving machine uptime	Capacity utilisation	Otto and Kotzab (2003) Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Inventory policies	Inventory	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Sustainable manufacturing	Environmentally friendly operations	Hu and Hsu (2010) Gunasekaran *et al.* (2004)
Warehousing	Size, design, ASRS of warehouse	Storage utilisation	Otto and Kotzab (2003) Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Inventory management systems	Inventory count accuracy	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Order management system	Order fulfilment	Bhagwat and Sharma (2007) Gaudenzi and Borghesi (2006)
	Finished oroduct inventory policy	Inventory level	Supply Chain Council (2012) Gunasekaran *et al.* (2004)
Logistics	Fleet variety	Flexibility	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001) Shepherd and Günter (2011)
	Transportation quality	Delivery reliability	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Long-term contract with logistics service provider	Transportation cost	Gunasekaran *et al.* (2004) Gunasekaran *et al.* (2001)
	Sustainable transportation	Environmentally friendly transportation	Hu and Hsu (2010)

Appendix 3

Table AIII Level of DM and timeline (Simchi-Levi *et al.*, 2008)

Level of DM	Considered DM level	Description of decisions	Type of Decision made
Strategic **Tactical**	Long-term DM	The strategic level includes decisions that have a long-lasting effect on the firm	This includes decisions related to the warehouse location, the capacity of the warehouse and distribution centres, manufacturing decisions such as automated or manual, SC network design
Operational	Short-term DM	The operational level includes decisions, which are usually day-to-day, such as loading/ unloading, daily production plan, etc.	These include decisions related to satisfying daily and weekly forecasting, settling damages or losses with suppliers, vendors and clients and monitoring logistics activities for contract and order fulfilment

Appendix 4



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