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Developing a practical evaluation framework for identifying critical factors to achieve supply chain agility

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ABSTRACT

Supply chain agility is a key determinant of competitiveness in today's dynamic and turbulent business environment. This paper develops a practical evaluation framework that serves to identify critical factors for achieving supply chain agility. First, we construct a reference framework of the factors that contribute to achieving agility in supply chain based on a systematic analysis of the related literature. Then, we develop a hybrid evaluation method that integrates fuzzy logic, DEMATEL (decision making trial and evaluation laboratory), and ANP (analytic network process). The proposed framework is implemented in an automotive company that is seeking to improve agility of its supply chain. It provides a systematic approach to explore and analyze influential relationships between agile-enabling factors and assigns a weight to each factor representing its relative importance. It also captures ambiguities, uncertainties, and vagueness inherent in evaluating the factors and their relationships and provides an efficient mechanism for group evaluation.

1. Introduction

The concept of supply chain agility has been introduced in the late 1990s due to parallel developments in the areas of agile systems and manufacturing as well as supply chain management [1]. It is defined as the supply chain's alertness to internal and environmental changes and the supply chain's capability to use resources in responding to these changes in a timely and flexible manner [2]. The fact that competition between supply chains has replaced the traditional competition between companies [3] implies that supply chain agility is a key element to establish a superior competitive position [4,5]. It has been widely recognized as a key determinant of long-term success and survival and has been advocated as the 21st century supply paradigm [6].

Among the critical questions regarding supply chain agility that have not been adequately addressed in the literature is how such capability can be built [1,4]. According to Christopher [7], supply chain agility is a broad, multi-dimensional, and business-wide capability. Thus, the development of agility in supply chain is a challenging and complex task and various factors may facilitate or hamper to its attainment. Identifying and evaluating such factors is of particular importance to understand the required preconditions of supply chain agility and to provide a practical guide to successful development of a truly agile supply chain. However, scholarly research on this topic is very limited [8].

This paper develops a novel evaluation framework that systematically incorporates the factors that contribute to achieving supply chain agility and reflects a holistic and integrated view of the fundamental agile-enabling

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elements in the supply chain. It utilizes fuzzy logic, decision making trial and evaluation laboratory (DEMATEL), and analytic network process (ANP) methodologies in a hybrid model in order to analyze the influential relationships among the factors and calculate their relative importance. The purpose of this evaluation is to identify critical factors that should be focused in order to achieve supply chain agility, using a practical approach.

The remainder of this paper is organized as follows: Section 2 provides a review of the related literature and provides a reference framework of the factors that contribute to achieving supply chain agility. Section 3 describes the proposed fuzzy-DEMATEL-ANP evaluation method. Section 4 discusses application of the model to a case study of an automotive company that is seeking to improve the agility of its supply chain. Finally, Section 5 summarizes the paper and gives concluding remarks.

2. Factors that contribute to achieving supply chain agility

2.1. Related literature

Currently, in the literature, there is no systematic and comprehensive framework of the factors that contribute to achieving supply chain agility. There are only a few papers seeking to establish a set of enablers, drivers, or influential factors of agility in the supply chain. Power et al. [9] have investigated some critical factors that differentiate more agile from less agile organizations in managing their supply chains. In addition, Agarwal et al. [10] and Kisperska-Moron and Swierczek [11] have identified some strong drivers of supply chain agility in their proposed frameworks.

Several studies have focused on specific antecedent(s)/enabler(s) of agility in the supply chain. These include emergent information systems and technologies (IS/IT) [12,13], IT integration and supply chain flexibility [4,14], and market and learning orientation [15]. Empirical evidence has been also provided for the impact of strategic sourcing [16], supply chain competencies [17], logistics, coordination, and information management capabilities [7,18], technical and relational factors [19] and behavioral characteristics [20] on supply chain agility.

Some authors have studied the design and development of agile supply chains. Ismail and Sharifi [1] have proposed a framework for agile supply chain development that integrates supply chain design with product design. Baramichai et al. [21] have developed the agile supply chain transformation matrix as a tool to achieve agility in supply chain. Several other authors have proposed mathematical models to design agile supply chain networks [e.g. 22,23]. These studies highlight some necessary prerequisites and key considerations that should be taken into account when moving towards an agile supply chain.

In some other studies, a conceptual understanding of supply chain agility has been provided. Christopher [7] has identified the key characteristics of truly agile supply chains. Li et al. [2] have reviewed some previously proposed definitions of supply chain agility and developed a theory-driven model that describes supply chain agility at various work design levels. Gligor et al. [24] have indicated that supply chain agility is composed of alertness, accessibility, decisiveness, swiftness, and flexibility. Some factors that contribute to achieving agility in supply chain can be identified based on the fundamental elements of supply chain agility identified in these studies.

Furthermore, studies that have focused on the measurement and assessment of agility in the supply chain help address some agile-enabling factors. Lin et al. [6] have developed a measurement framework that comprises agile capabilities and agility-enabled attributes. Jain et al. [25] have identified a set of eight key attributes of supply chain agility. Vinodh and Prasanna [26] and Samantra et al. [27] have also contributed to this topic. The agile attributes/capabilities identified in these studies provide a basis to further address the factors that contribute to achieving supply chain agility.

2.2. A reference framework

We explored the factors that contribute to achieving supply chain agility in the mentioned research areas using grounded theory (GT). The GT is an inductive methodology that serves as a useful tool for exploratory research and qualitative data analysis. It involves continuous interplay between data collection and analysis and applies the analytical procedures of coding, constant comparison, theoretical sampling, and theoretical memoing for conceptualizing the data [28,29].

The systematic review and analysis of the related literature using GT resulted in a reference framework incorporating 11 factors that contribute to achieving supply chain agility. The reference framework, given in Table 1, divides the identified factors into three main inductively-derived dimensions, namely, strategic commitment to supply chain agility, agile-enabling infrastructures and mechanisms, and human/cultural competence. These dimensions are inter-related in nature and provide a higher-level abstraction of the identified factors based on their thematic similarities. The framework was further assessed through interviews with five supply chain experts and refined based on the feedback from the interviews.

3. Proposed evaluation method

The factors in the proposed reference framework are evaluated in order to identify those that are critical for achieving supply chain agility. The main features of the proposed evaluation method are: (1) capturing the ambiguities, uncertainties, and vagueness inherent in evaluators' judgments by using fuzzy logic; (2) systematically identifying the causal relationships among the factors by using decision making trial and evaluation laboratory (DEMATEL); (3) determining the relative importance of the factors by using analytic network process (ANP).

3.1. Fuzzy logic

The factors identified in the presented reference framework are subjective and qualitative in nature. Thus, it is

Table 1
A reference framework of the factors that contribute to achieving supply chain agility.

Dimensions	Factors	Description	References
Strategic commitment (D_1)	Well-recognized need for agility (C_1)	Recognizing the required agile capabilities, understanding the characteristics of the business environment and the supply chain itself, understanding the uncertainties, changes, and pressures that lead the supply chain to embrace the agile paradigm	[30–33]
	Integration of agility into the strategic context of the supply chain (C_2)	Incorporating agility into the strategic vision and objectives of the supply chain, supply chain operation strategies, supply chain strategic decisions, and each member of the network's strategy	[1,22,23,25,31,34]
	Management commitment and support (C_3)	A strong belief in the value of supply chain agility, providing necessary technical and financial support, commitment and involvement in reengineering the supply chain and logistics and creating an agile-supporting culture	[12,17,35–38]
Infrastructures & mechanisms (D_2)	Intra-organizational collaboration (C_4)	Inter-functional and inter-departmental integration, collaborative and cooperative relationships and effective communications between organizational units, cross-functional alignment, openness and teamwork within the organization	[15,33,35–37]
	Collaboration between supply chain partners (C_5)	Strong, long-term collaborative relationships between all supply chain partners at upstream, midstream, and downstream echelons, integrating inter-organizational processes, providing feedback to the partners and relying on the feedback from the partners to enhance supply chain operations, high corporate level communication and inter-organizational trust, collaboration in the design and development of new products/services, strategy determination, planning, problem-solving, and inventory management, synchronized supply	[2,6,10,15,17,37,39,40]
	Information flow within the supply chain (C_6)	Extensive sharing of accurate, timely information, strong information integration, access to information, transparency of information across the supply chain	[6,7,9,11,12,14,15,17,19,36]
	Continuous monitoring of the supply chain and business environment (C_7)	Timely identification of changes in the market and the overall business environment, changes in competition patterns and customers' requirements, changes in supply sources, early warning and detection of disturbances in supply chain and situations that require quick response	[2,32,36,41]
	Use of agile-enabling technologies (C_8)	Use of information and communication technologies to facilitate communication and information flows, IT integration and flexibility, use of computer-assisted technologies pertaining to design, planning, and production systems to enhance adaptability and flexibility of supply chain processes	[4,7,9,10,12–14,17,19,38,42]
Human/cultural competence (D_3)	Management competence (C_9)	Making appropriate response to market changes in a timely and cost-efficient manner, participating in strategy formulation and planning, working proactively across business units and organizations to identify opportunities, using inter-organizational collaboration as a lever of marketing strategy, competence in change management and managing supply chain resources	[2,9,17,31,32,36,41]
	Competence of employees (C_{10})	The ability of employees to support top management's plans and strategies and implement the organizational response to internal and environmental changes	[17,31,38,43]
	Creation of a culture of learning and change (C_{11})	A continuous improvement-focused approach in meeting customer requirements, continually seeking the processes of learning, behavior change, and performance improvements, commitment to learning, consensus on the focus and direction of learning among supply chain members, willingness to critically evaluate supply chain operations, continually update and revise the strategies, and accept new ideas, minimizing resistance to change	[9,10,15,17,36]

very difficult to express their influential relationships using exact numerical values. Instead, the evaluators express their assessments using lingual expressions which are vague and ambiguous concepts. Moreover, there are some degrees of uncertainty inherent in the subjective assessments. Therefore, fuzzy logic is used to deal with these ambiguities, vagueness, and uncertainties. Fuzzy logic can properly deal with the vagueness and uncertainties inherent in the evaluators' judgments [44,45]. It can handle the ambiguities in linguistic estimations by converting the linguistic terms into fuzzy numbers [46].

A triangular fuzzy number (TFN) $\tilde{N}$ can be defined as a triplet (l, m, r), $l \leqslant m \leqslant r$, where l, m, and r are real numbers. Since the TFNs can be used in matrix operations, a defuzzification method is required to convert them into crisp scores [47]. Herein, we apply the CFCS (converting fuzzy data into crisp scores) defuzzification method developed by Opricovic and Tzeng [48] as described below.

Consider a group of K evaluators and $\tilde{X} = (a^k_{1ij}, a^k_{2ij}, a^k_{3ij})$ be the fuzzy evaluation of the effect of the ith factor on the jth factor, given by the kth evaluator. The normalization is done using Eqs. (1)–(3).

$$xa^k_{1ij} = (a^k_{1ij} - \min\ a^k_{1ij})/\Delta^{\max}_{\min} \tag{1}$$
$$xa^k_{2ij} = (a^k_{2ij} - \min\ a^k_{1ij})/\Delta^{\max}_{\min} \tag{2}$$
$$xa^k_{3ij} = (a^k_{3ij} - \min\ a^k_{1ij})/\Delta^{\max}_{\min} \tag{3}$$

where $\Delta^{\max}_{\min} = \max a^k_{3ij} - \min\ a^k_{1ij}$. The left and right normalized values and the total normalized crisp value are calculated as given in Eqs. (4)–(6).

$$xls^k_{ij} = xa^k_{2ij} / \left(1 + xa^k_{2ij} - xa^k_{1ij}\right) \tag{4}$$
$$xrs^k_{ij} = xa^k_{3ij} / \left(1 + xa^k_{3ij} - xa^k_{2ij}\right) \tag{5}$$
$$z^k_{ij} = \left[xls^k_{ij}\left(1 - xls^k_{ij}\right) + xrs^k_{ij} xrs^k_{ij}\right] \Big/ \left[1 - xls^k_{ij} + xrs^k_{ij}\right] \tag{6}$$

The crisp score corresponding to the fuzzy evaluation $\tilde{X}$ is then obtained using Eq. (7).

$$x^k_{ij} = \min\ a^k_{1ij} + z^k_{ij}\Delta^{\max}_{\min} \tag{7}$$

Finally, the crisp scores from defuzzification of K evaluations are averaged to produce an aggregated score as shown in Eq. (8).

$$c_{ij} = \frac{1}{K}\sum\nolimits_{k=1}^{K} x^k_{ij} \tag{8}$$

3.2. DEMATEL

The DEMATEL is an analytical method which is especially useful to identify the strength of influences of the elements of complex systems and visualize the structure of complicated causal relationships. The findings of the DEMATEL divide system elements into cause group and effect group and provide insights into those elements that most significantly influence the others [49,50]. The DEMATEL has been successfully applied in many situations which assume interdependence relationships within a system of factors [e.g. 51,52]. In the proposed evaluation framework, the DEMATEL is used to explore and structure the complex causal relationships between the identified agile-enabling factors and evaluate the strength of their influential effects. The method can be summarized as follows:

Assuming a set of n factors, the initial direct-influence matrix $A = [a_{ij}]_{n\times n}$ is established by pair-wise comparisons in terms of influences between the factors in which a_{ij} denotes the degree to which the factor i affects the factor j. The diagonal elements of the matrix are all set to zero.

The normalized direct-influence matrix $\boldsymbol{D} = [d_{ij}]_{n\times n}$, $0 \leqslant d_{ij} \leqslant 1$, is then obtained as follows.

$$\boldsymbol{D} = k \times \boldsymbol{A} \tag{9}$$

$$k = \min\left\{1/\max_i \sum_{j=1}^{n} a_{ij}, 1/\max_j \sum_{i=1}^{n} a_{ij}\right\},\ i,j \in \{1,2,\ldots,n\} \tag{10}$$

The total-influence matrix $\boldsymbol{T} = [t_{ij}]_{n\times n}$ is calculated using Eq. (11). $\boldsymbol{I}$ is an $n \times n$ identity matrix.

$$\boldsymbol{T} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{D})^{-1} \tag{11}$$

The sum of rows and the sum of columns, denoted by $\boldsymbol{R}$ and $\boldsymbol{C}$, are obtained as in Eqs. (12) and (13), respectively. The superscript in Eq. (13) denotes transposition.

$$\boldsymbol{R} = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \tag{12}$$

$$\boldsymbol{C} = [c_j]_{n\times 1} = \left[\sum_{i=1}^{n} t_{ij}\right]'_{1\times n} \tag{13}$$

When $j = i$, $(r_i + c_i)$ shows all effects given and received by factor i. Thus, it indicates the degree of the total influences of factor i in the entire system. In addition, if $(r_i - c_i)$ is positive, then factor i is affecting other factors, and if it is negative, then factor i is being influenced by other factors [49,50]. A network relation map (NRM) is also achieved by mapping the dataset of $(\boldsymbol{R} + \boldsymbol{C}, \boldsymbol{R} - \boldsymbol{C})$ and based on the total-influence matrix $\boldsymbol{T}$ [52].

3.3. Combining DEMATEL and ANP

The ANP is a multi-criteria decision making (MCDM) method and a generalization of the analytic hierarchy process (AHP) that can systematically overcome all types of dependences. The method is an effective tool where the interactions among system elements form a network structure. It handles inter-relationships between system elements by identifying composite weights through developing a supermatrix [45,53]. Herein, the ANP is combined with DEMATEL to obtain the weights of the factors identified in the presented reference framework while considering their inter-relationships. The method can be described as follows [54,55]:

The total-influence matrix for factors $\boldsymbol{T_C} = [t_{ij}]_{n\times n}$ obtained from DEMATEL is considered as shown in Eq. (14).

$$\boldsymbol{T}_c = \begin{array}{cc} & \begin{array}{ccccc} D_1 & & D_j & & D_n \\ c_{11}\ldots c_{1m_1} & \ldots & c_{j1}\ldots c_{jm_j} & \ldots & c_{n1}\ldots c_{nm_n} \end{array} \\ \begin{array}{c} D_1 \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ \vdots\ \vdots \\ D_i \begin{array}{c} c_{i1} \\ c_{i2} \\ \vdots \\ c_{im_i} \end{array} \\ \vdots\ \vdots \\ D_n \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} & \begin{bmatrix} \boldsymbol{T}_c^{11} & \ldots & \boldsymbol{T}_c^{1j} & \ldots & \boldsymbol{T}_c^{1n} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{i1} & \ldots & \boldsymbol{T}_c^{ij} & \ldots & \boldsymbol{T}_c^{in} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{n1} & \ldots & \boldsymbol{T}_c^{nj} & \ldots & \boldsymbol{T}_c^{nn} \end{bmatrix} \end{array} \tag{14}$$

where D_i and c_{ij} represent the dimensions and the factors within each dimension, respectively. Then, we normalize $\boldsymbol{T_C}$ by each dimension and obtain a new matrix $\boldsymbol{T_C^\alpha}$ as given in Eq. (15).

$$\boldsymbol{T}_c^\alpha = \begin{array}{c} \\ \\ D_1 \\ \vdots \\ D_i \\ \vdots \\ D_n \end{array} \begin{array}{c} \\ \\ c_{11}\; c_{12} \cdots c_{1m_1} \\ \vdots \\ c_{i1}\; c_{i2} \cdots c_{im_i} \\ \vdots \\ c_{n1}\; c_{n2} \cdots c_{nm_n} \end{array} \overset{\begin{array}{ccccc} D_1 & & D_j & & D_n \\ c_{11}\dots c_{1m_1} & \cdots & c_{j1}\dots c_{jm_j} & \cdots & c_{n1}\dots c_{nm_n} \end{array}}{\begin{bmatrix} \boldsymbol{T}_c^{\alpha 11} & \cdots & \boldsymbol{T}_c^{\alpha 1j} & \cdots & \boldsymbol{T}_c^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{\alpha i1} & \cdots & \boldsymbol{T}_c^{\alpha ij} & \cdots & \boldsymbol{T}_c^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{\alpha n1} & \cdots & \boldsymbol{T}_c^{\alpha nj} & \cdots & \boldsymbol{T}_c^{\alpha nn} \end{bmatrix}} \tag{15}$$

Let the total-influence matrix match and fill into the inter-dependence clusters. It yields an unweighted supermatrix $\boldsymbol{W}$ which is based on transposing the normalized total-influence matrix $\boldsymbol{T_C^\alpha}$ as shown in Eq. (16).

$$\boldsymbol{W} = (\boldsymbol{T}_c^\alpha)' = \begin{array}{c} D_1 \\ \vdots \\ D_j \\ \vdots \\ D_n \end{array} \begin{array}{c} c_{11}\; c_{12} \cdots c_{1m_1} \\ \vdots \\ c_{j1}\; c_{j2} \cdots c_{jm_j} \\ \vdots \\ c_{n1}\; c_{n2} \cdots c_{nm_n} \end{array} \overset{\begin{array}{ccccc} D_1 & & D_i & & D_n \\ c_{11}\dots c_{1m_1} & \cdots & c_{i1}\dots c_{im_i} & \cdots & c_{n1}\dots c_{nm_n} \end{array}}{\begin{bmatrix} \boldsymbol{W}^{11} & \cdots & \boldsymbol{W}^{i1} & \cdots & \boldsymbol{W}^{n1} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{W}^{1j} & \cdots & \boldsymbol{W}^{ij} & \cdots & \boldsymbol{W}^{nj} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{W}^{1n} & \cdots & \boldsymbol{W}^{in} & \cdots & \boldsymbol{W}^{nn} \end{bmatrix}} \tag{16}$$

We consider the total-influence matrix for dimensions $\boldsymbol{T_D} = [t_{ij}^D]$ obtained from $\boldsymbol{T_C}$ as shown in Eq. (17). The normalized total-influence matrix $\boldsymbol{T_D^\alpha}$ is obtained using Eq. (18) where $d_i = \sum_{j=1}^n t_D^{ij}$.

$$\boldsymbol{T_D} = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & & \vdots & & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix} \tag{17}$$

$$\boldsymbol{T_D^\alpha} = \begin{bmatrix} t_D^{11}/d_1 & \cdots & t_D^{1j}/d_1 & \cdots & t_D^{1n}/d_1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/d_i & \cdots & t_D^{ij}/d_i & \cdots & t_D^{in}/d_i \\ \vdots & & \vdots & & \vdots \\ t_D^{n1}/d_n & \cdots & t_D^{nj}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} = \begin{bmatrix} t_D^{\alpha 11} & \cdots & t_D^{\alpha 1j} & \cdots & t_D^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha i1} & \cdots & t_D^{\alpha ij} & \cdots & t_D^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha n1} & \cdots & t_D^{\alpha nj} & \cdots & t_D^{\alpha nn} \end{bmatrix} \tag{18}$$

The weighted supermatrix $\boldsymbol{W^\alpha}$ is then calculated by multiplying the normalized total-influence matrix $\boldsymbol{T_D^\alpha}$ with the unweighted supermatrix $\boldsymbol{W}$ as represented in Eq. (19).

$$\boldsymbol{W^\alpha} = \boldsymbol{T_D^\alpha W} = \begin{bmatrix} t_D^{\alpha 11} \times \boldsymbol{W^{11}} & \cdots & t_D^{\alpha i1} \times \boldsymbol{W^{i1}} & \cdots & t_D^{\alpha n1} \times \boldsymbol{W^{n1}} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1j} \times \boldsymbol{W^{1j}} & \cdots & t_D^{\alpha ij} \times \boldsymbol{W^{ij}} & \cdots & t_D^{\alpha nj} \times \boldsymbol{W^{nj}} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1n} \times \boldsymbol{W^{1n}} & \cdots & t_D^{\alpha in} \times \boldsymbol{W^{in}} & \cdots & t_D^{\alpha nn} \times \boldsymbol{W^{nn}} \end{bmatrix} \tag{19}$$

We limit the weighted supermatrix $\boldsymbol{W^\alpha}$ by raising it to a sufficiently large power g until it converges and becomes a long-term stable supermatrix, i.e. $\lim_{g\to\infty}(\boldsymbol{W^\alpha})^g$. Therefore, the global weights of the factors can be obtained.

3.4. The evaluation process

Based on the proposed fuzzy-DEMATEL-ANP method, the evaluation process is described as follows:

Step 1: Organizing an evaluation committee. The committee is formed of a group of individuals in the company who have adequate information concerning the inter-relationships among the factors that contribute to achieving supply chain agility and the current status of the overall supply chain with respect to each factor.

Step 2: Designing the fuzzy linguistic scales. We design two linguistic scales: one for estimating the degree of influence between each pair of factors and another for judging the current state of each factor. Table 2 gives the linguistic variables and their corresponding TFNs.

Step 3: Obtaining assessments of the evaluators. Based upon the factors identified in the reference framework, a two-part questionnaire is developed and sent to the evaluators to acquire their assessments. The first part of the questionnaire contains 110 assessments concerning the influential relationships between the factors and the second part contains 11 assessments pertaining to current status of the supply chain with respect to each factor. The linguistics variables given in Table 2 are used in making the assessments.

Step 4: Aggregating the evaluators' assessments. The linguistic assessments given by the evaluators are converted into their corresponding TFNs and then defuzzified and aggregated using the CFCS method described in Section 3.3.

Step 5: Establishing the causal relationships between the factors. The initial direct-influence matrix is established using the aggregated crisp values obtained in Step 4. The causal relationships between the factors and their influential effects are then analyzed following the procedure of the DEMATEL method described in Section 3.1.

Step 6: Determining the weights of the factors. Based on the total-influence matrix obtained in Step 5, the relative weights of the factors are determined by following the steps of the proposed hybrid DEMATEL-ANP method described in Section 3.2.

Step 7: Ranking the factors. The factors are ranked on the basis of their total priority index. Assuming w_i denotes

Table 2
Linguistic scales used in the assessments.

Variables describing the influences between the factors	Variables describing the current state of the factors	Corresponding triangular fuzzy numbers
No influence	Very poor	(0, 0, 0.25)
Very low influence	Poor	(0, 0.25, 0.5)
Low influence	Fair	(0.25, 0.5, 0.75)
High influence	Good	(0.5, 0.75, 1)
Very high influence	Very good	(0.75, 1, 1)

the weight of the ith factor calculated in Step 6 and s_i denotes the corresponding crisp score obtained in Step 4, then the total priority index for the ith factor, denoted by TPI_i, is defined as in Eq. (20). The factors with the highest TPI_i values identify the critical factors for achieving supply chain agility.

$$TPI_i = \frac{w_i(\max_i s_i - s_i)}{\max_i s_i - \min_i s_i} \quad (20)$$

4. Case study

The evaluation framework presented in this research was applied to a case study of an automotive company in Iran. The auto industry is one of the most competitive sectors in which innovation and change play a crucial role [56]. Due to significant and unprecedented changes in general economic conditions, the case company has recently faced the challenges of increased market and business volatility and unpredictability. It has also suffered from higher competition in the market and increasing pressures arising from government policies. These concerns have prompted the top management to seek to improve the agility of the company's supply chain. It is a nationwide network currently comprising more than 400 suppliers, four main manufacturing plants, and around 800 dealers.

The company has incorporated some aspects of supply chain agility into its supply chain strategies; however, as recognized by the top management, the agile performance of the supply chain is not satisfactory and the required flexibility and speed to efficiently identify and respond to changes is still largely lacking. Therefore, it is of great value to the top management to determine the critical factors for achieving supply chain agility and the practical initiatives needed to enhance agile capabilities within the overall supply chain.

Following the proposed evaluation process, a committee of 12 evaluators was formed. All of the evaluators were working in supply chain-related positions with at least ten years of experience in supply chain management and more than eight years of working within the case supply chain. The evaluators' assessments were obtained using questionnaire and defuzzified and aggregated using Eqs. (1)–(8).

The consensus among the evaluators was tested by calculating the inconsistency rate of $\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{|\bar{t}_{ij}^{p}-\bar{t}_{ij}^{p-1}|}{\bar{t}_{ij}^{p}} \times 100\%$, where $n = 11$ denotes the number of factors, $p = 12$ is the number of evaluators, and $\bar{t}_{ij}^{p}$ is the average influence of the ith factor on the jth factor based on p evaluations. For the evaluators' judgments on the influential relationships, the inconsistency rate of 3.50% was obtained. It was less than the recommended threshold of 5% [54,55], implying that additional questionnaires would not influence the results. Therefore, the credibility of the questionnaires was 96.50% (credibility = 1 − inconsistency rate). Similarly, the inconsistency rate of 4.49% and the credibility of 95.51% were obtained for the evaluators' judgments on the current status of the factors in the supply chain.

Table 3 gives the total-influence matrix for factors and Table 4 shows the total-influence matrix for dimensions as well as the sum of influences given and received by each dimension. Also, Table 5 gives the sum of influences for the factors. These results were used to construct the NRM as shown in Fig. 1. In order to decrease the complexity of the NRM, we filtered the minor effects and included only those elements of the total-influence matrix that were higher than the threshold value of 0.155.

The results given in Table 5 shows that management commitment and support, management competence, well-recognized need for agility, and integration of agility into the strategic context of the supply chain were identified as the most affecting factors in achieving supply chain agility. Similarly, continuous monitoring of the supply chain and business environment, information flow within the supply chain, and creation of a culture of learning and change were characterized as the most influenced factors. The results also show that creation of a culture of learning and change, integration of agility into the strategic context, and collaboration between supply chain partners were the factors with the highest total influences within the system.

The NRM given in Fig. 1 depicts the causal relationships among the factors. Based on the NRM, the strategic commitment and human/cultural competence are classified into the cause group while the effect group is composed of the infrastructures and mechanisms. This implies that the strategic commitment to supply chain agility is the driver for developing and retaining the supply chain mechanisms and infrastructures that are required for creating an agile supply chain. In addition, effective development and operation of these infrastructures and mechanisms is highly dependent on the human/cultural competence throughout the supply chain.

The strategic commitment to supply chain agility is also the driver for the development of agile-enabling human/cultural competencies. Moreover, the development of strategic commitment to agility in the supply chain and effective implementation of the formulated agile-enabling strategies require competent management and employees. Thus, there is a mutual relationship between the human/cultural competence and the strategic commitment dimensions in the NRM.

Fig. 1 also shows that the degree to which supply chain agility is incorporated into strategic vision and objectives as well as the supply chain operation strategies is influenced by recognizing the need for agility as well as commitment and support from management. It also indicates that the recognized need to agility and management commitment and support are affected by each other.

Table 3
The total-influence matrix for factors.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	0.117	0.232	0.200	0.216	0.249	0.208	0.227	0.240	0.146	0.191	0.295
C_2	0.147	0.127	0.128	0.256	0.287	0.266	0.236	0.242	0.176	0.234	0.325
C_3	0.198	0.245	0.092	0.257	0.296	0.253	0.237	0.249	0.169	0.225	0.348
C_4	0.104	0.098	0.068	0.086	0.146	0.189	0.125	0.104	0.076	0.115	0.201
C_5	0.142	0.142	0.096	0.152	0.131	0.234	0.161	0.132	0.123	0.162	0.263
C_6	0.147	0.145	0.072	0.129	0.152	0.101	0.175	0.103	0.087	0.112	0.224
C_7	0.154	0.093	0.072	0.095	0.110	0.105	0.073	0.085	0.076	0.103	0.154
C_8	0.108	0.107	0.068	0.180	0.218	0.226	0.188	0.094	0.148	0.176	0.212
C_9	0.213	0.235	0.147	0.265	0.298	0.268	0.222	0.220	0.118	0.225	0.333
C_{10}	0.160	0.168	0.107	0.232	0.248	0.232	0.189	0.216	0.143	0.126	0.286
C_{11}	0.134	0.144	0.100	0.231	0.251	0.200	0.186	0.180	0.174	0.207	0.179

Table 4
The total-influence matrix for dimensions and the influences given and received by each dimension.

Dimensions		D_1	D_2	D_3	r	c	$r+c$	$r-c$
Strategic commitment	D_1	0.165	0.248	0.234	0.647	0.429	1.077	0.218
Infrastructures and mechanisms	D_2	0.108	0.140	0.149	0.396	0.617	1.013	−0.221
Human/cultural competence	D_3	0.156	0.229	0.199	0.585	0.582	1.167	0.003

Table 5
The influences given and received by each factor.

	r	c	$r+c$	$r-c$
C_1	2.321	1.624	3.945	0.697
C_2	2.424	1.736	4.160	0.688
C_3	2.569	1.150	3.719	1.419
C_4	1.312	2.099	3.411	−0.787
C_5	1.738	2.386	4.124	−0.648
C_6	1.447	2.282	3.729	−0.835
C_7	1.120	2.019	3.139	−0.899
C_8	1.725	1.865	3.590	−0.140
C_9	2.544	1.436	3.980	1.108
C_{10}	2.107	1.876	3.983	0.231
C_{11}	1.986	2.820	4.806	−0.834

Within the second dimension, the results imply that all information and collaboration infrastructures and mechanisms are enhanced by effective use of appropriate technologies. In addition, effectiveness of monitoring of the supply chain and business environment is influenced by collaboration between supply chain partners and the quality of information flow throughout the supply chain. Moreover, the development of an efficient flow of information is influenced by the degree of supply chain collaborations.

The NRM also confirms the influential role of management and employees in creating a culture of learning and change across the supply chain. Such a culture, in turn, provides a basis for upgrading human competencies and capabilities that are important to the agility of the supply chain. Furthermore, the evaluators believe that the competence of employees is influenced by management competence.

After determining the relationship structure between the factors, we used the ANP to obtain the weights of the factors. Table 6 shows the unweighted supermatrix calculated based on the total-influence matrix for factors. The global weights of the factors obtained from the stable supermatrix are given in the third column of Table 7.

The global weights indicate that the creation of a culture of learning and change is, relatively, the most important determinant of achieving agility in the case supply chain. This corresponds to the fact that an effective learning and change culture enables continuous review and re-evaluation of supply chain strategies and enhancing and strengthening competencies, infrastructures, and mechanisms that are required for achieving supply chain agility. The second important factor is competence of employees that implies the critical role of competent and skilled employees in effectively responding to changes and the development and implementation of agile business practices. After that, integration of agility into the strategic context of the supply chain is identified as the third important factor. This can be an indication of the fact that all supply chain processes and the required capabilities are shaped by supply chain strategies.

Based on the global weights obtained from the proposed evaluation method and the aggregated data on current status of the factors in the supply chain, we calculated the total priority index (*TPI*) for each factor using Eq. (20). The factors were then ranked in descending order of *TPI* (Table 7). The obtained results show that the creation of a culture of learning and change, collaboration between supply chain partners, management commitment and support, and integration of agility into the strategic context of the supply chain are the critical factors for achieving agility in the case supply chain. Based on the constituting elements of these factors described in Table 1, the authors conducted interviews with the evaluators and identified that a relatively high level of resistance to change, lack of commitment and openness to learning within the supply

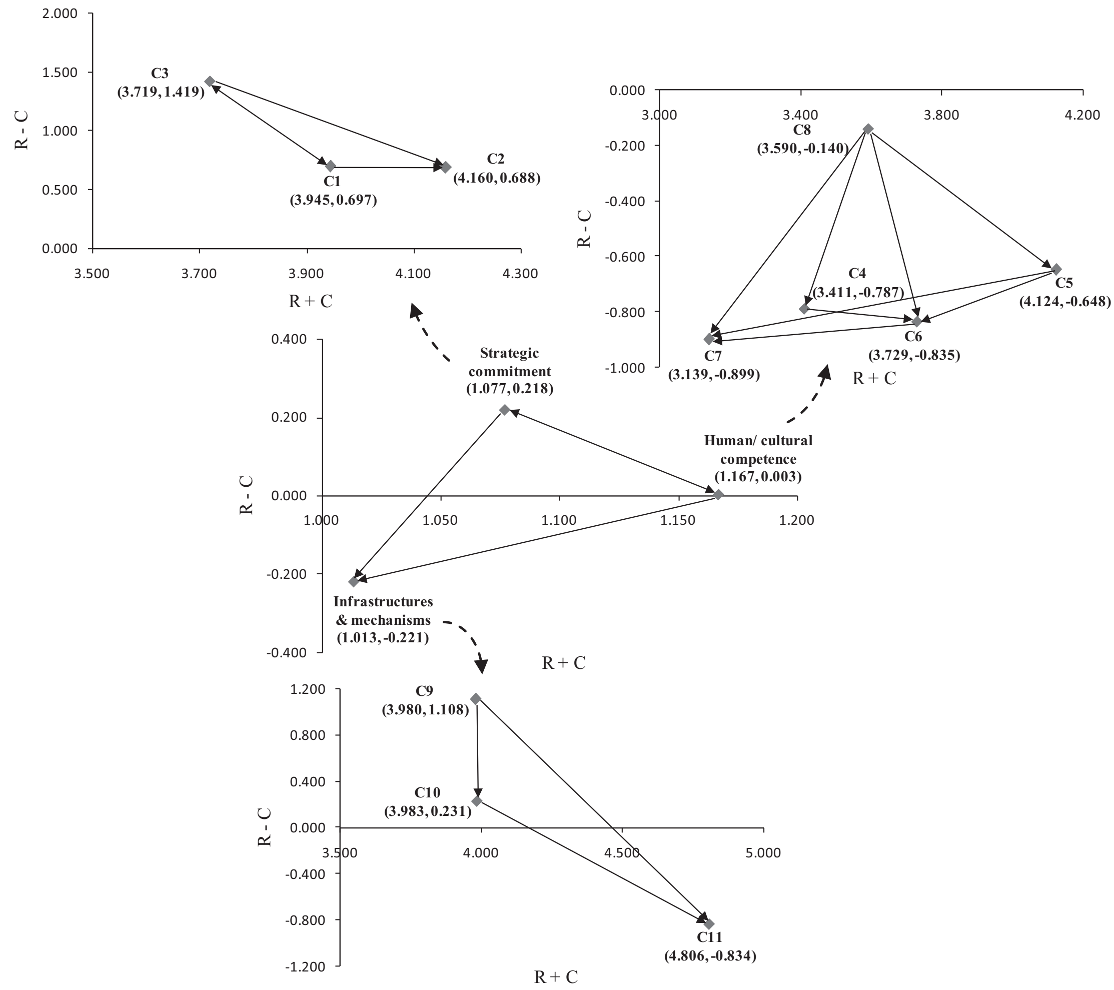

Fig. 1. The NRM of the factors that contribute to achieving supply chain agility.

Table 6
The unweighted supermatrix.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
C_1	0.213	0.366	0.370	0.385	0.374	0.404	0.483	0.382	0.358	0.368	0.354
C_2	0.423	0.316	0.458	0.363	0.374	0.398	0.292	0.378	0.395	0.386	0.381
C_3	0.364	0.318	0.172	0.252	0.253	0.198	0.226	0.240	0.247	0.246	0.265
C_4	0.189	0.199	0.199	0.132	0.188	0.195	0.203	0.199	0.208	0.208	0.220
C_5	0.218	0.223	0.229	0.225	0.162	0.230	0.235	0.241	0.234	0.222	0.240
C_6	0.182	0.207	0.196	0.291	0.289	0.153	0.224	0.249	0.211	0.208	0.191
C_7	0.199	0.183	0.183	0.192	0.199	0.265	0.156	0.208	0.174	0.169	0.177
C_8	0.211	0.188	0.193	0.160	0.163	0.156	0.182	0.104	0.173	0.193	0.172
C_9	0.231	0.239	0.228	0.194	0.224	0.206	0.228	0.276	0.175	0.258	0.311
C_{10}	0.302	0.318	0.303	0.293	0.296	0.265	0.309	0.328	0.333	0.227	0.370
C_{11}	0.467	0.442	0.469	0.513	0.480	0.530	0.462	0.396	0.493	0.515	0.320

chain, lack of inter-organizational trust, and lack of a shared belief in the value of supply chain agility among the supply chain partners were the main barriers that should be overcome to enhance agility of the case supply chain. In addition, most evaluators reported that the supply chain operation strategies needed to be further revisited to provide the basis for achieving supply chain agility. They also reported that the agility-related issues should be adequately considered in decisions around supplier selection and relationships.

Table 7
Final ranking of the critical factors.

	Critical factors	Global weight	Current score	TPI	Rank
C_1	Well-recognized need for agility	0.097	0.597	0.014	9
C_2	Integration of agility into the strategic context of the supply chain	0.101	0.481	0.058	4
C_3	Management commitment and support	0.069	0.403	0.059	3
C_4	Intra-organizational collaboration	0.074	0.519	0.032	7
C_5	Collaboration between supply chain partners	0.084	0.364	0.084	2
C_6	Information flow within the supply chain	0.080	0.461	0.051	5
C_7	Continuous monitoring of the supply chain and business environment	0.071	0.636	0.000	11
C_8	Use of agile-enabling technologies	0.066	0.442	0.047	6
C_9	Management competence	0.086	0.597	0.012	10
C_{10}	Competence of employees	0.110	0.578	0.024	8
C_{11}	Creation of a culture of learning and change	0.163	0.442	0.116	1

5. Conclusions

In this paper, a practical evaluation framework was developed to identify critical factors for achieving supply chain agility. First, a reference framework of the factors that contribute to achieving supply chain agility was constructed. These factors embrace a wide variety of supply chain aspects, ranging from supply chain strategies, infrastructures, and mechanisms, to competencies and cultural characteristics of the supply chain. The identified factors are inter-related implying that achieving supply chain agility requires a holistic approach that addresses all agility-related issues in a unified, integrative way.

Then, a hybrid fuzzy-DEMATEL-ANP method was proposed to evaluate the identified factors. The proposed method uses the DEMATEL as a systematic approach to explore and analyze the influential relationships between the factors and combines it with the ANP to assign a weight to each factor that represents its relative importance. It also uses fuzzy logic to capture the ambiguities, uncertainties, and vagueness inherent in evaluating the factors and their relationships and provides an efficient mechanism for group evaluation. The proposed evaluation framework was then applied to an automotive supply chain and a ranking of the identified factors was developed. The top-ranked factors identified by the framework highlight the most important issues that should be addressed and characterize the initiatives that should be taken in order to achieve agility in the case supply chain.

The proposed evaluation framework serves as a self-assessment tool that can be used by supply chain managers and practitioners to develop a ranking of the factors that contribute to achieving agility in a specific supply chain. Such ranking highlights the areas that need to be improved and help address the main barriers that should be overcome in order to achieve higher levels of supply chain agility. For future research, the proposed framework can be expanded by incorporating the assessment of agile performance of the supply chain and linking the identified agile-enabling factors to performance-related attributes. Also, instead of relying on qualitative judgments, more objective, quantitative measures can be defined and used for evaluating the mentioned factors in order to obtain more accurate results.

Through systematic review and analysis of the related literature and identification and integration of the factors emerging from earlier studies using GT, this paper presents the most comprehensive framework of the factors that contribute to achieving supply chain agility to date. It identifies a comprehensive set of the fundamental agile-enabling elements in the supply chain and organizes them into an integrative reference framework which is adequate for the purpose of the current research. However, it is not yet possible to guarantee that there is not any other potentially critical agile-enabling factor because there may be other factors that have not been addressed in the currently available published literature, and thus, remained unexplored. Investigation of such factors can be the subject of further studies.

For future research, industry-specific rankings of the identified agile-enabling factors can be established based on survey of truly-agile supply chains working in the same industry. Such rankings provide insight into the main issues that should be addressed in order to enhance supply chain agility in a specific industry, and thus, will be of value for supply chain managers and practitioners.

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