Journal of Quality Engineering and Production Optimization

Vol. 6, No. 2, Summer & Autumn 2021

http://jqepo.shahed.ac.ir

Research Paper

DOI: 10.22070/JQEPO.2021.14946.1202

A Fuzzy Expert System to Select a Supply Chain Strategy: Lean, Agile or Leagile

Nima Esfandiari [1*], Mahmoud Moradi [2], Amir-Mohammad Golmohammadi [3]

[1] *Ph.D. Candidate in Industrial Management, University of Guilan, Rasht, Iran*

[2] *Associate Professor, Management Department, University of Guilan, Rasht, Iran*

[3] *Assistant Professor, Department of Industrial Engineering, Arak University, Arak, Iran*

**** Corresponding Author:** Nima Esfandiari (Email: Esfandiari.nima@gmail.com)*

Abstract *– Supply chain field has always been an aspiration for competitiveness in manufacturing organizations. Any organization's conditions can be judged based on several criteria, such as robustness, rapid reconfiguration, lead time compression, etc. These criteria effectively determine the kind of supply chain strategy; it should be noted that this strategy varies in different markets and industries. Therefore, considering an appropriate strategy for the supply chain is an essential issue for most managers. Hence, this study, using a fuzzy expert system, shows how to select the best supply chain strategy. Three popular strategies, i.e., lean, agile, and leagile, are the main elements in this research. In addition, five applicable criteria are applied for selecting a supply chain strategy. A fuzzy expert system based on if-then rules was designed to connect these criteria to three strategies and select an appropriate supply chain strategy. Hence, criteria and supply chain strategies are taken to be input and output of this expert system, respectively, which lead to faster decision-making in the selection of supply chain strategy.*

Keywords*– Supply Chain Strategy, Lean, Agile, Leagile, Fuzzy Expert System.*

I. INTRODUCTION

Nowadays, the business environment has to deal with global, dynamic, and cost-based competition (Udokporo et al., 2020). Besides, supply chain management has been proved as one of the main organizational capacities (Fadaki et al., 2020), as well as a proper mechanism for improvement of corporations' competitive advantage, as a vital factor for their sustainability (Malakouti et al., 2017). In fact, efficient supply chain planning must be considered as the main resource for competitive advantage. Proper supply chain strategies would assist the corporations in achieving competitive advantages through efficient use of supply chain potentials (Fadaki et al., 2020). It's a crucial task for any organization to satisfy customer requirements through properly designed supply chain strategies for the purpose of increased market competition and to cope with apparent evolutions in information technology (Galasso & Thierry, 2009; Rehman, 2017). Nowadays, the competition is not restricted to corporations themselves, but it is their supply chain hierarchy and management which determines either their success or failure (Childerhouse & Towill, 2000). Organizations compete with each other based on their own supply chain strategies which are suited to missions stated for any corporation. In order to achieve the best competition results, numerous exchanges (e.g., demand-based supply) are considered to be effective to be implemented in the decision-making process. Three contemporary supply chain paradigms applied by

Manuscript Received:31- August -2021 & Revised:5-Nov-2021 & Accepted: 28- Vov -2021
ISSN: 2423-3781

corporations worldwide include lean, agile, and leagile supply chains (Soni & Kodali, 2009).

Generally, lean production principles and actions are directed at the reduction of wastes, variability of the processes and procedures, creating value for customers, and improvement of operational efficiency. Therefore, a lean supply chain operates in a way to ensure the efficient downstream current of the values (Tortorella et al., 2018). Thus, we can argue that a lean supply chain includes a set of organizations that cooperate with directly cooperate and communicate with upstream and downstream currents of products, services, financial affairs, and informatics in order to reduce associated costs and wastes and fulfill customer requirements (Lamming, 1996; Vitasek et al., 2005; Reichhart & Holweg, 2007; Tortorella et al., 2017; Moyano-Fuentes et al., 2020).

Agility is defined as applying market knowledge and virtual corporations to exploit profitable opportunities in an unsustainable market (Mason-Jones et al., 2000a). Accordingly, an agile supply chain is suggested as a vital corporative strategy for management of supply network and development of flexible capabilities for fulfilling customers' ever-changing requirements (Zhang, 2011; Lim & Zhang, 2012; Gligor et al., 2016; Um, 2017; Centobelli et al., 2020).

While leanness and agility are respectively enumerated as two individual features of lean and agile supply chains, the leagile supply chain includes a combination of both (Silveira et al., 2001) and does his best to include elements of both lean and agile supply chain. Leagility is a combination of lean and agile paradigms within the general strategy of the supply chain, implemented through decoupling point locating to be fairly responsive against unsustainable demands from downstream and to assist upstream planning processes (Naylor et al., 1999). Therefore, supply chain strategies can be classified as strategies that emphasize both cost reduction (lean strategy), timely response (lean strategy), or a combination of both (leagile strategy) (Sharma & Kulkarni, 2016). Accordingly, it is necessary for corporations to comply with their own procedures and actions with customer requirements. Thus, it is necessary for the managers to gain a good understanding of the most suitable strategies (Bhamra et al., 2020). The purpose of this study is to study the concepts of lean, agile, and leagile concepts in the supply chain domain and the provision of a fuzzy expert system for the selection of the best supply chain strategies based on system characteristics. This study is planned like this: the second part attempts to review the literature; the third part, the recommended expert system, is presented, and the fourth part discusses a real-world case to illustrate both feasibility and application of the expert system. Finally, a conclusion and suggestions for future research are provided.

II. LITERATURE REVIEW

Lean and agile systems have been extensively researched in recent years as a result of the variations within the global market environment (Mason-Jones et al., 2000a). Accordingly, many corporations are seeking to implement agile and lean approaches in order to reduce their costs, improve customer services, and acquire of competitive advantage. On the one hand, lean thinking involves the elimination of wastes through any possible approach. The lean paradigm argues that actions that deplete resources but are not valuable from a customer point of view are considered as wastes to be eliminated (Villarreal et al., 2017). On the other hand, any agile organization is created to counteract the environmental changes to fulfill customers' variable requirements. Agility considers quality and service level improvement as the main success requirements in global markets and is inclined toward the provision of a timely and economic response to the market's unpredictable variations (Moradi et al., 2018).

A comparison between lean and agile paradigms has been undertaken by Naylor et al. (1999) for the first time in management literature. Besides attempting a comparison between lean and agile supply chains and emphasizing upon their similarities and differences, he does not reject any of them nor considers them favorable. Naylor considers four dimensions (e.g., quality, cost, lead time, and service level) as the most significant factors contributing to value definition in the supply chain from a customer perspective and correlates each paradigm's efficiency to intended supply chain features.

Mason-Jones et al. (2000b) have also explored leagility and claimed that the supply chain requires a type of strategy which would be compatible with particular products and their specific markets. They attempted an analysis of lean, agile, and leagile paradigms and their roles in counteracting different scenarios of market uncertainty.

Christopher and Towill (2000) have studied the correlation between the selection of agile and lean paradigms and market requirements, such that the market winner in lean and agile paradigms are cost and availability, respectively. Agile supply chains must be sensitive toward the market. Besides, they argue that the proper location of decoupling points for material and information flows may contribute to the development and engineering of a combined supply chain.

Huang et al. (2002) identified production supply chains and classified them into three classes, including lean, agile, and leagile. They enumerated the characteristics of each supply chain and attempted to select a proper kind of supply chain through a scoring model and to consider the product type supplied by each organization.

Bruce et al. (2004) studied lean, agile, and leagile (a hybrid version) in supply chain literature and conducted case studies in different textile manufacturing corporations. This study has provided us with a vast understanding of lean, agile, and leagile paradigms within a supply chain.

Agarwal et al. (2006) applied a hierarchical model for the selection of optimal strategy in consuming goods supply chain. They considered four domains, including cost, quality, lead time, and service level for the performance of the supply chain, and concepts such as market sensitivity, information driver, process integration, and flexibility have been defined as decision-making criteria. Each criterion has three sub-criteria. Then, an analytical network process (ANP) model has been presented for the selection of the best available strategies.

Vonderembse et al. (2006) presented a framework for the classification of different kinds of supply chains based on product descriptions, different types of standard, innovative and hybrid products and stages involved in product' life cycle. Accordingly, they classified supply chains into lean, agile, and leagile.

Qi et al. (2009) experimentally studied different supply chain strategies and tested the supply chain strategy model under different approaches of lean, agile and lean/agile, through gathering data from 604 manufacturing corporations located in China.

Razmi et al. (2011) attempted the selection of a proper supply chain strategy through a Fuzzy Multiple Attribute Decision-making Model (FMADM) approach. Their selected alternatives included a set of lean, agile, and leagile strategies. Their specific model has been implemented in a case study.

Zhang et al. (2012) developed a system dynamics model in the light of the system engineering concept for both traditional and leagile supply chains. The simulation results for these two supply chains illustrate the comparative advantage of the leagile supply chain.

Wieland (2013) presented a model for supply chain selection based on risk probability and risk impact. They considered four different supply chain strategies, including agility, robustness, resilience, and rigidity, and applied mathematical modeling to arrive at the optimal solution.

Vahdani (2016) suggests that the selection of the most appropriate robot for dangerous and repetitive tasks is such an important issue, and thus they used a new interval-valued hesitant fuzzy multi-attributes group decision method to solve the robot selection problem.

Raj et al. (2018) developed a conceptual model for leagile supply chain measures and have calculated the supply chain efficiency index for three lean, agile, and leagile paradigms using an analytical network process. The results illustrated that the leagile paradigm gained the highest score. Then, the leagile index has been calculated through a multi-grade fuzzy approach and recommended solutions for the improvement of weaker domains.

Gitinavard (2019) presented a hybrid group decision-making approach based on hesitant fuzzy sets theory for the selection of the best strategic project for Tehran municipality in order to analyze the practicality of the recommended framework.

Ghaderi et al. (2020) developed a Group Decision Making methodology based on a data envelopment analysis approach and while considering intuitionistic fuzzy information. They conducted a case study within a manufacturing company in order to evaluate the recommended approach.

Gitinavard et al. (2020) developed a new decision-making model based on a new version of the complex proportional assessment method with the last aggregation under a hesitant fuzzy environment. A real-time case study has been conducted in developing countries regarding the safety standards of the construction projects, which pinpoint the applicability of the new hesitant fuzzy decision model with the last aggregation approach. Besides, a clear example has been provided to validate the application of the recommended approach for larger safety problems.

Gitinavard et al. (2020) argue that the selection of the most suitable sustainable feedstock is considered as a key factor in the problem of optimal allocation of renewable products. To this end, they recommended a hybrid adaptive framework based on consensus evaluation approach, weighting and ranking procedure, and preferred demand assignment under dynamic hesitant fuzzy sets.

A review of the related literature suggests that a systematic argument for the analysis of supply chain strategies is missing. This study attempts to plan a framework to eliminate the limitations of the previous literature. To put it differently, the recommended expert system not only enables the analysis of verbal and quantified variables but also it makes us capable of considering the non-linear relations between criteria (inputs), and thus the selected choices shall be considered as well. Fuzzy Inference System can be mixed with expert opinion to provide us with interpretable results. Thus, expert systems are applied only when the gathered knowledge is based on the literature review or expert opinion regarding the correlation between input and output variables. Besides, the evaluation of supply chain strategies through fuzzy logic provides more opportunities for the selection of the most appropriate choice. Moreover, instead of paired comparison between multiple alternatives, the fuzzy expert system would directly compare them with organizational conditions and based on human's relative thought foundations. Thus, through this framework, the managers are capable of better analyzing their own business supply chains and acquiring recommendations for proper selection of supply chain. To achieve this aim and consider the complexity and ambiguity of decision-making conditions, a fuzzy expert system based on if-then rules has been proposed. As far as the literature review revealed, no previous research has been conducted for direct section and assessment of three supply chain strategies (e.g., lean, agile, and leagile) in the light of fuzzy expert system.

Generally, the properties and merits of the present study are as follows:

- Strategy selection through a comprehensive system based on the existing literature regarding the supply chain, without further need for paired comparison of alternatives among decision-makers;
- Reduction of error and bias in decisions resulting from default-based opinions or misunderstandings of system decision-makers;
- The fuzzy logic in the expert system provides the possibility of evaluation of alternative criterion conditions, such that choice selection would not be limited in case a choice within a criterion lacks sufficient compatibility with organizational circumstances;
- To the best of our knowledge, the application of fuzzy expert system has been evaluated for the first time for selection of supply chain strategy,

III. FUZZY EXPERT SYSTEM DESIGN

The study framework is illustrated in Fig. 1. Generally, the design of the Fuzzy Expert System in this study consists of the following stages: 1) primary design of the system; 2) fuzzification of both inputs and outputs; 3) Construction of fuzzy rules; 4) defuzzification; 5) model testing. MATLAB software has been applied to design the system. Besides, the required knowledge for the definition of system inputs and outputs as well as fuzzy rules has been acquired from a combination of the literature and expert opinions.

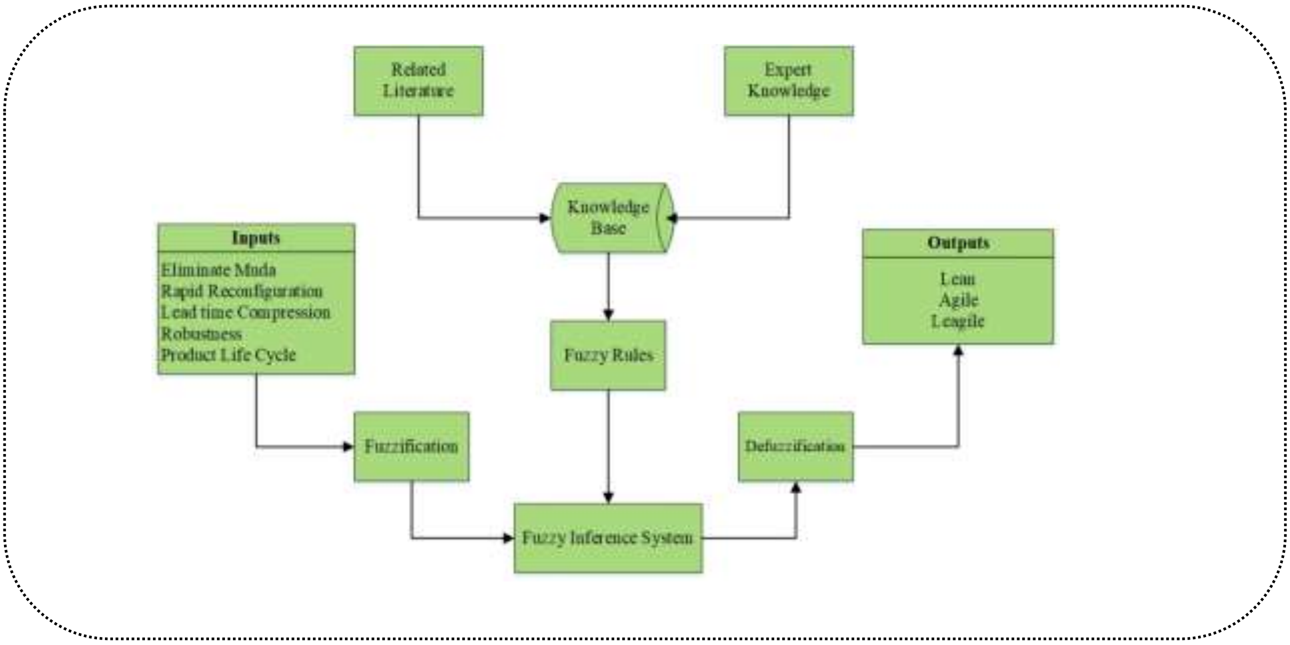

Fig. 1. Schematic design of study framework

A fuzzy expert system is a systematic reasoning methodology to describe system's complex behavior using of fuzzy set theory (Tang et al., 2012). In recent decades, these systems have been successfully implemented in different domains, including supply chain (Olugu & Wong, 2012), production scheduling (Kerr & Ebsary, 1988). Machine selection in manufacturing systems (Chtourou et al., 2005), product design (Zarandi et al., 2011), medicine (Khozeimeh et al., 2017), education (Hwang et al., 2020), Quality Systems (Khan, 1999), and Stock Exchange (fasanghari & montazer, 2010). These systems are data-oriented and relate the input and output variables through a set of IF-THEN rules. Equation (1) illustrates a sample fuzzy rule (Sari, 2017)

$$\text{IF } X \text{ is } A_i \text{ THEN } Y \text{ is } B_i,\ i=1, \dots, n \tag{1}$$

Where X and Y are input and output variables, respectively. Moreover, A_i and B_i resemble ambiguous linguistic terms (e.g., short, medium, long). In this study, more than one input and output variables exist which have been extracted through a review of the related literature.

For the selection of supply chain strategy, one must conduct a diligent assessment of organizational conditions. Since assessments regarding favorable organizational indices may be accompanied with error, the existence of error in the calculation of the optimal level of an index wouldn't incur any loss on decision-making process. Besides, considering the nature of fuzzy logic, the total of indices determines the organizational accepted level in any of the decicion-making criteria.

Another specification of the recommended expert fuzzy system is the lack of need for direct Paired comparison and comparison of each choice with favorable organizational conditions on the one hand. on the other hand, it provides a comprehensive system consisting of required knowledge for the supply chain for managers and decision-makers. This particularity of the decision-makers frees them up from the compulsion for Paired comparison and scoring a variety of evaluation criteria. That is because in case the decision-making objective would be different from what they bear in mind, pair comparison would be based on decision-makers; mental schemata and would be considered invalid as a result.

A. First Sep: primary design and system Assumptions

In this step, system's input and output variables are defined. Input variables include product's life cycle, lead time compression, eliminate Muda, rapid reconfiguration, and robustness which have been discussed in numerous studies as characteristics of lean, agile, and leagile supply chains (Naylor et al., 1999; Mason-Jones et al., 2000(a); Olhager et al., 2002; Bruce et al., 2004; Agarwal et al., 2006; Hilletofth, 2009). Besides, the output variables of this system include lean, agile, and leagile strategies of the supply chain, which have been studied extensively and are included in the literature review section of this paper. The input variables are as follows:

1. Lead time compression

In the agile manufacturing and supply chain domain, "Quick response" denotes product delivery within the lowest time possible. The same criterion has been known as "lead-time compression" in Naylor et al.'s (1999) pioneering work. This criterion has been included as one of the most significant leanness and agility features.

2. Eliminate muda

Waste elimination is highly significant in the lean manufacturing domain, and most scholars have used its Japanese equivalent. i.e. "muda" (Mason-Jones et al. (2000a). Eliminating muda is not much significant in the agile manufacturing domain. However, the descriptions provided by Naylor et al. (1999) attracted a significant deal of attention. Accordingly, eliminating muda is considered as an essential component of leanness; that's while the same feature is considered as desirable for agility. This contributes to a higher regard for "eliminate muda" as a significant criterion in supply chain efficiency.

3. Rapid reconfiguration

The main objective of the agile pattern is the provision of quick responses for market variations and customer demands. Besides, flexibility and speed are highly significant in the reconfiguration of the agile supply chain. However, in the lean model, reconfiguration is only significant as a non-value-added activity and must be reduced accordingly. Thus, speed is highly significant in an agile supply chain compared to a leagile supply chain (Naylor et al., 1999).

4. Robustness

An agile manufacturer must be highly tolerant of market variation and turbulence. Besides, he must be in a position to gain the highest profit from such variations. This characteristic, i.e. robustness is highly significant in agile model, but is not that much significant in lean model (Naylor et al., 1999).

5. Product Life Cycle

The product life cycle is defined as the sale of each product unit in time which is divided into four discrete stages, i.e., introduction, growth, maturity, and decline. For the lean supply chain, standard products must have a relatively longer life cycle (at least two years), and for the agile supply chain, innovative products with a short life cycle are favored. In addition, a leagile supply chain involves manufacturing products with an "assemble to order" strategy which stays longer in the maturity stage of the life cycle (Vonderembse et al., 2006).

Fig. 2 presents the definition of input and output variables of fuzzy expert system for selection of supply chain strategy. This system consists of five and three input and output variables respectively.

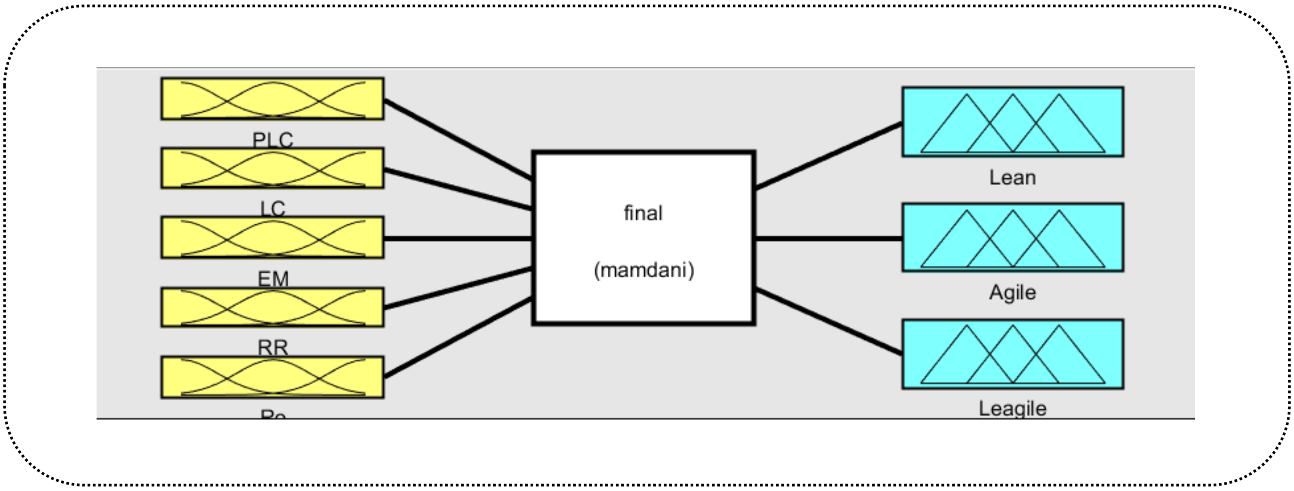

Fig. 2. Schematic design of Fuzzy Expert System

Thus, system assumptions are as follows:

- Supply chain strategy is limited to three lean, agile, and leagile strategies.
- Considering the uncertainty of real world, the indices are accompanied by some degrees of ambiguity.
- The criteria for the selection of supply chain strategy are limited to five key criteria which have been mentioned earlier in this report.

B. Second Step: fuzzification of input and output

The fuzzy logic approach is based on human logic and benefits from conceptual knowledge without any limitation being incurred. Some of the fuzzy logic concepts include fuzzy sets, verbal variables, probability distribution, and fuzzy if-then rules. Most of the qualitative literature are accompanied by some degree of ambiguity, such that it may happen that the data wouldn't be expressed in terms of accurate numbers. Thus, verbal evaluation is recommended as a substitute for quantified values. In these circumstances, verbal variables are highly significant, and expert's opinions must be quantified using fuzzy numbers and membership functions (Vinodh & Chintha, 2011)

According to Liang and Wang (1994), Triangular Fuzzy Numbers (TFNs) are the most common fuzzy numbers which have been applied for linguistic assessments. In this paper, the triangular membership function has been implemented for fuzzification of input variables, including lead time compression, eliminating Muda, rapid reconfiguration, and robustness. Besides, S and Z membership functions have been used for another input variable, i.e., product life cycle. Up to 12 months has been considered as a short life cycle. Moreover, higher than 24 months has been considered as a relatively long life cycle (Vonderembse et al., 2006). A Z-type fuzzy set is included in a maximum point of the range until membership is reduced to a minimal point. This type of fuzzy set is usually applied for modeling low, under, short, etc. furthermore, S-type fuzzy sets start from zero to reach their maximal value in a point or range. This particular type of fuzzy set are generally applied for modeling concepts including high, tall, over, etc. The triangular membership function has been used for fuzzification of output variables as well. For the purpose of fuzzifying inputs and outputs, any verbal variables have been extracted as illustrated in Table I, and II and fuzzy triangular numbers have been then implemented for them. Instances of implemented fuzzy numbers are illustrated in Fig. 3-5.

Table I. linguistic terms and fuzzy numbers used for definition of input variables

Variables	*Linguistic Term*		
	Arbitrary	*Desirable*	*Essential*
Eliminate Muda (EM)	(0 0 0.5)	(0 0.5 1)	(0.5 1 1)
Rapid Reconfiguration (RR)	(0 0 0.5)	(0 0.5 1)	(0.5 1 1)
Lead time Compression (LC)	(0 0 0.5)	(0 0.5 1)	(0.5 1 1)
Robustness (Ro)	(0 0 0.5)	(0 0.5 1)	(0.5 1 1)
Product Life Cycle (PLC)	Short	Long	
	(12 24)	(12 24)	

Table Ⅱ. linguistic terms and fuzzy numbers used for definition of output variables

Variables	*Linguistic Term*				
	Completely Inappropriate (CI)	*Inappropriate (I)*	*Medium (M)*	*Appropriate (A)*	*Completely Appropriate (CA)*
Lean	(0 0 0.25)	(0 0.25 0.5)	(0.25 0.5 0.75)	(0.5 0.75 1)	(0.75 1 1)
Agile	(0 0 0.25)	(0 0.25 0.5)	(0.25 0.5 0.75)	(0.5 0.75 1)	(0.75 1 1)
Leagile	(0 0 0.25)	(0 0.25 0.5)	(0.25 0.5 0.75)	(0.5 0.75 1)	(0.75 1 1)

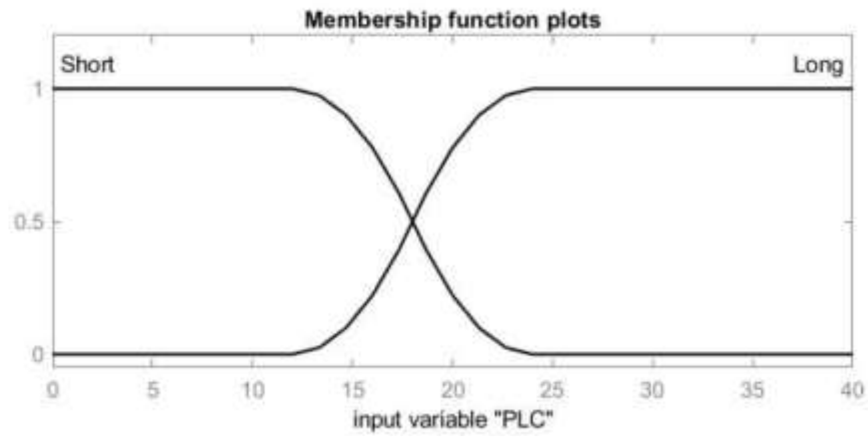

Fig. 3. membership function for product life cycle as an input variables

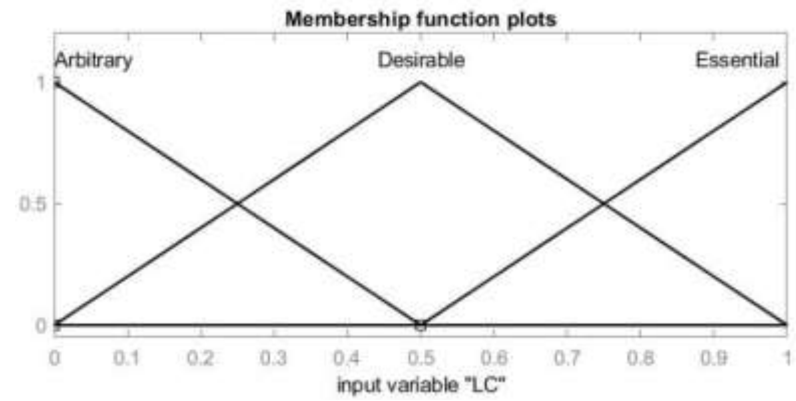

Fig. 4. membership function for lead time compression as an input variable

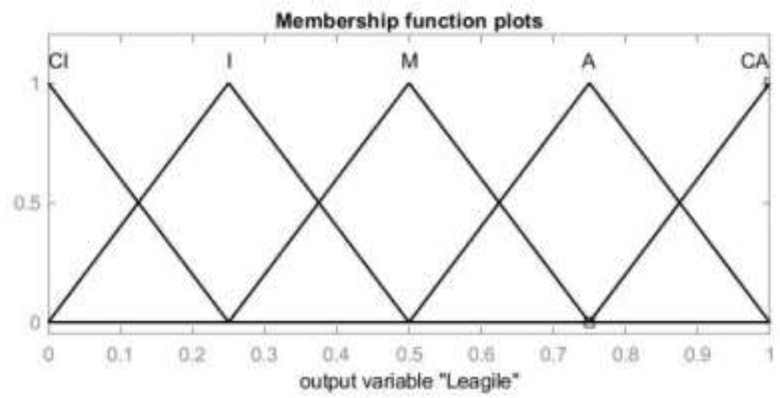

Figure. 5. membership function for leagile as an output variable

C. Third Step: Construction of fuzzy rules

Following the completion of the fuzzy inference system, attempts have been made to define fuzzy rules. Using these rules, the input data of the fuzzy inference system are transformed into output data. 162 rules can be defined for this system as a whole which have been mainly extracted from the theoretical underpinning and expert opinions. These rules have been presented to six university experts with at least ten years of direct academic instruction or being a player in manufacturing and operational domains. The result of this process would be the modification of the rules. In all these rules, the "and" operator has been used to define the similarities of the sets. Some of the rules alongside their references are included in Table Ⅲ.

D. Fourth Step: Defuzzification

The preliminary basis for expert systems have been provided so far, meaning that input and output variables as well as their membership functions have been prepared. In addition, the developed fuzzy rules define the relationship between input and output variables. Thus, the model can be verified and tested. Pre-test stages include insertion of the input variables, conducting fuzzy calculations and finally yielding the output variable; however, defuzzificaton means transforming the output fuzzy set into a precise and crisp value. The main purpose of this process is to simplify the analysis process. defuzzification is implemented through different approaches. Center of Gravity is a common defuzzification approach which has been applied in this study.

Table Ⅲ. Some representative fuzzy rules are useful for the selection of supply chain strategy

Fuzzy Rules	*Related Literature*
If (PLC is Long) and (PV is Low) and (LC is Essential) and (EM is Essential) and (RR is Desirable) and (Ro is Arbitrary), Then (Lean is CA)(Agile is I)(Leagile is CI)	(Naylor et al., 1999; Mason-Jones et al., 2000a; Olhager et al., 2002; Bruce et al., 2004; Agarwal et al., 2006; Hilletofth, 2009)
If (PLC is Short) and (PV is High) and (LC is Essential) and (EM is Desirable) and (RR is Desirable) and (Ro is Essential), Then (Lean is I)(Agile is CA)(Leagile is M)	(Naylor et al., 1999; Mason-Jones et al., 2000a; Olhager et al., 2002; Bruce et al., 2004; Agarwal et al., 2006; Hilletofth, 2009)
If (PLC is Short) and (PV is Medium) and (LC is Desirable) and (EM is Arbitrary) and (RR is Essential) and (Ro is Desirable), Then (Lean is CI)(Agile is M)(Leagile is CA)	(Naylor et al., 1999; Mason-Jones et al., 2000a; Olhager et al., 2002; Bruce et al., 2004; Agarwal et al., 2006; Hilletofth, 2009)

E. Fourth Step: Defuzzification

The preliminary basis for expert systems have been provided so far, meaning that input and output variables, as well as their membership functions, have been prepared. In addition, the developed fuzzy rules define the relationship between input and output variables. Thus, the model can be verified and tested. Pre-test stages include insertion of the input variables, conducting fuzzy calculations and finally yielding the output variable; however, defuzzification means transforming the fuzzy output set into a precise and crisp value. The main purpose of this process is to simplify the analysis process. Defuzzification is implemented through different approaches. Center of Gravity is a common defuzzification approach that has been applied in this study.

F. Fifth Stage: Model testing and verification

Generally, the transformation of any concept into a software product is accompanied by some degree of error. If the error is within an acceptable range, the model would be valid as well. Otherwise, the model must be verified. Output behavior analysis and the whole rule testing have been applied for model testing.

1. Output behavior testing (sensitivity analysis)

In this approach, the value for two input variables has been considered as constant. Then, the value of the other two variables would be increased (decreased). For any increase or reduction within inputs, the value of each output is to be computed using an expert system. Behavior should be developed for any output by putting all these values together. This behavior would be analyzed, and in case the outputs' behavior for the constant input and two variable inputs would be validated through a review of the related literature or expert opinions, the fuzzy expert system would be validated as well; otherwise, the fuzzy expert system is to be verified. This procedure has been repeated for each input cluster. The outputs have been generated using MATLAB software. Then, they have been analyzed and compared based on the related literature and expert opinions. The analysis results confirmed the accuracy of the outputs.

For instance, Fig 6-8 display three instances of these behaviors for agile, lean, and leagile strategies.

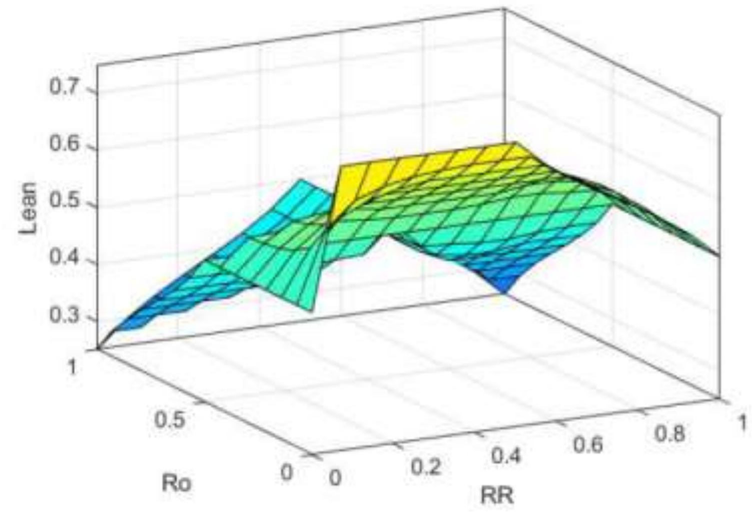

Fig. 6. Lean Strategy's output variable behavior in terms of two variables, i.e. robustness and rapid reconfiguration

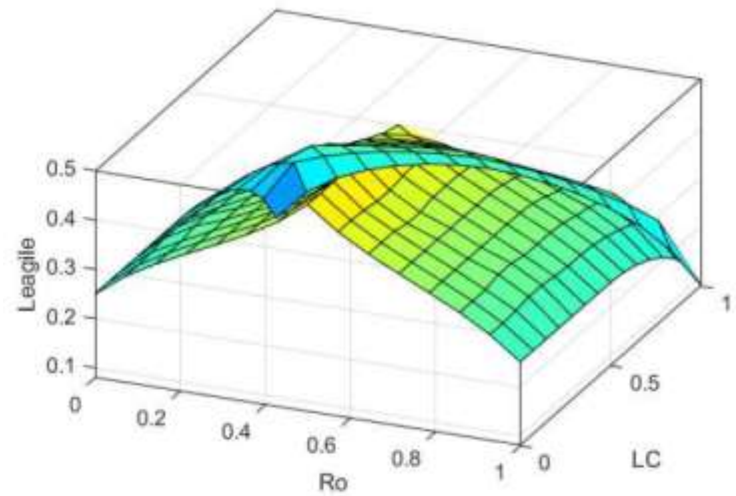

Fig. 7. leagile strategy's output variable behavior based on two variables, i.e. robustness and lead time compression

2. Testing the whole set of rules

At first, the inputs of the inference engine (the precedent side of any rule) have been inserted into an expert system. The inference engine was able to generate the corresponding output for all inputs of the same rule the output obtained from the rule has been compared with the expected output. By expected output, we mean the kind of output which is to be derived based on the codified rules. The accuracy of all the rules has been validated after testing all the rules.

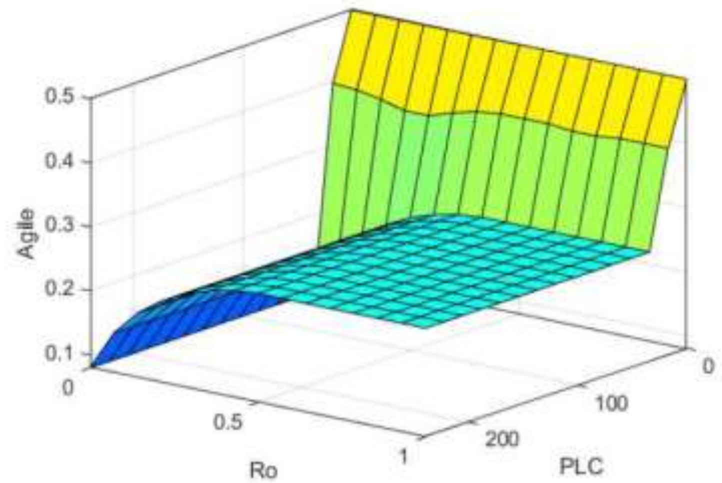

Fig. 8. agile strategy's output variable behavior based on two variables, i.e. robustness and product life cycle

IV. CASE STUDY

To better illustrate the topic at hand, a real case study is used. This study has been conducted in one of the national manufacturing companies, which showed some degree of inclination for the selection of supply chain strategy. The main problem involved in this factory is a strategic direction in company's manufacturing and supply chain. In recent years, various actions have been taken, including Total Quality Management (TQM), Just in Time production, automation, etc. Some of these actions were congruent with one or more lean, agile, or leagile strategies on the one hand. On the other hand, development and maintaining a relation between all new and old initiatives is considered as one of the most challenging issues. That is because consistency in actions is a permanent requirement. This relationship is not that much tough at the beginning and requires further maintenance.

Table Ⅳ. summary results for Robustness criteria measurement, speedy Rapid Reconfiguration and Leadtime Compression

participant	*Lead time Compression*	*Eliminate muda*	*Rapid Reconfiguration*	*Robustness*
1	(0.5 1 1)	(0.5 1 1)	(0 0.5 1)	(0 0 0.5)
2	(0.5 1 1)	(0.5 1 1)	(0 0.5 1)	(0 0 0.5)
⋮	⋮	⋮	⋮	⋮
8	(0 0.5 1)	(0 0.5 1)	(0 0 0.5)	(0 0.5 1)
9	(0 0.5 1)	(0 0.5 1)	(0 0 0.5)	(0 0.5 1)
Fuzzy mean	(0.333 0.833 1)	(0.388 0.888 1)	(0 0.277 0.777)	(0 0.222 0.722)
X_{max}^{1}	0.722	0.759	0.351	0.314
X_{max}^{2}	0.777	0.824	0.314	0.268
X_{max}^{3}	0.750	0.791	0.33	0.291
crisp number = z*	0.777	0.824	0.351	0.314

Thus, the main objective of this study is to define a strategic direction for company's supply chain. Then, the company may be able to use various initiatives and practices in line with the particular strategy at hand.

In this part of the study, the results of company's supply chain strategy are provided in the light of recommended fuzzy expert system. Nine of company's managers and specialists cooperated in the development and selection of a particular strategy. The size of organizational inputs (except for product life cycle) has been calculated by obtaining participants' opinions. The responses provided by each of the participants have been transformed to fuzzy numbers through the relevant membership functions. The fuzzy mean of the responses has been calculated according to Table Ⅳ and equation (2), except for the product life cycle variable. The obtained mean was fuzzy; thus, equation (3) has been followed for defuzzification purposes (Wang & Luoh, 2000). Besides, the summary results of input variables defuzzification, as well as output values, are included in Table Ⅳ.

$$(m_{\alpha}^{1}.m_{\mathrm{m}}^{1}.m_{\beta}^{1})$$
$$(m_{\alpha}^{2}.m_{\mathrm{m}}^{2}.m_{\beta}^{2})$$
$$\vdots \qquad \text{fuzzy average} = \left(\frac{m_{\alpha}^{1}+m_{\alpha}^{2}+\cdots+m_{\alpha}^{n}}{n}\,.\,\frac{m_{\mathrm{m}}^{1}+m_{\mathrm{m}}^{2}+\cdots+m_{\mathrm{m}}^{n}}{n}\,.\,\frac{m_{\beta}^{1}+m_{\beta}^{2}+\cdots+m_{\beta}^{n}}{n}\right) \tag{2}$$
$$(m_{\alpha}^{n}.m_{\mathrm{m}}^{n}.m_{\beta}^{n})$$

$$X_{max}^{1} = \frac{m_{\alpha}+m_{\mathrm{m}}+m_{\beta}}{3}$$
$$X_{max}^{2} = \frac{m_{\alpha}+4m_{\mathrm{m}}+m_{\beta}}{6} \quad \text{crisp number} = z^{*} = \max\{X_{max}^{1}, X_{max}^{2}, X_{max}^{3}\} \tag{3}$$
$$X_{max}^{3} = \frac{m_{\alpha}+2m_{\mathrm{m}}+m_{\beta}}{4}$$

Then, this process was completed using Mamdani Model in the fuzzy toolbox of MATLAB software. In addition, the min method has been used for implication, and the max method has been used for aggregation of fuzzy rules. The centroid approach has been used for the defuzzification of fuzzy outputs. Finally, after insertion of the inputs into an expert system, the value of the outputs has been determined as displayed in Table Ⅴ and Fig. 9.

Table Ⅴ. The value of input variables and membership degree of output variables

Inputs	***Value***	***outputs***	***Value***
Eliminate Muda	0.825	Lean	**0.52**
Rapid Reconfiguration	0.352	Agile	**0.324**
Lead time Compression	0.778	Leagile	**0.344**
Robustness	0.315		
Product Life Cycle	120		

Lean strategy with membership degrees of 0.08 and 0.92 are appropriate and medium, respectively. Agile strategy with membership degrees of 0.296 and 0.704 are medium and inappropriate, respectively. And leagile strategy with membership degrees of 0.624 and 0.376 are inappropriate and medium, respectively.

The membership degree of any supply chain strategy clarifies its favorability for the organization under study. As it can be seen from Table V, lean strategy has the highest favorability, and agile strategy has the lowest. In other words, the characteristics of lean strategy must be given higher priority in designing the supply chain. In addition, the proper strategy must include strategies' characteristics as their membership degrees.

Fig. 9. the value of each supply chain strategy within the case study

V. DISCUSSION AND CONCLUSION

In this study, an expert system has been designed for the definition of the proper supply chain strategy. This study contributes to filling the gap within the supply chain management field, such that attempts have been made to provide a model in the form of a fuzzy expert system to reduce the ambiguity. Contrary to binary logic in which a component is either member of a set or not, it has been made possible through the application of fuzzy logic to provide a model to discuss the membership degree of one type of supply chain strategy compared to the organization's appropriate strategy. Significant variables in the selection of supply chain strategy have been extracted from the literature. Then, the system was completed through the development of fuzzy rules, and finally, the model's feasibility was verified after being tested in the form of a case study. Generally, the steps involved in the primary design of the system, fuzzification of both inputs and outputs, Construction of fuzzy rules, defuzzification, model testing, and application in a real-world instance have been followed.

The definition of proper organizational strategies is considered as one of the success factors. Some organizations apply a particular type of strategy since it is favorable. This action is not a favorable decision because of two main underlying reasons. First, designing the supply chain is a strategic decision and is accompanied by long-term consequences, and any wrong decision may lead to unfavorable and irreparable impacts in the long run. Second, any organization is included in its own specific supply chain. Therefore, it is logical to apply a different approach for designing its supply chain according to its particular status and features. Thus, the recommended expert system in this study may help organizational managers and experts in making the right decisions regarding the proper supply chain, such that they would apply any design action or instrument as they would require that.

Moreover, it assists the managers and decision-makers to select the strategies more accurately and with lower error. Such that the output of the recommended system would define the degree of requirement for agile, lean, and leagile strategies for the supply chain and would redeem the managers from the inherent ambiguities in strategy definition. To put it differently, a good framework has been provided for modeling the performance of the supply chain based on dependent input variables. The performance of the supply chain is defined as the degree of supply chain preparation to respond market needs. The present study's framework helps the decision-makers in the analysis of variables contributing to supply chain improvement through the selection of the most appropriate supply chain

In addition, the results of this study contributed to the higher application of the expert fuzzy system in finding out the most suitable supply chain strategy through the application of the expert system and fuzzy inference.

It has been suggested that the application of a fuzzy expert system would reduce the bias and error in decisions based on applying the assumptions or decision makers' misunderstandings. Doing so, the strategy selection is implemented through a comprehensive system consisting of the available knowledge in supply chain strategy, without further need for paired comparison by the decision-makers.

In the present case study, lean strategy has been considered as the most suitable strategy for a corporation's supply chain among all other strategies. Thus, lean strategies are preferred over other strategies in supply chain management. Besides, considering the assigned membership degrees, there is the possibility of application of agile and leagile strategies, such that lean strategy would be the dominant one. This means that eliminating muda must be the main focus of lean thinking throughout the system. Further, cost reduction must be considered as the market winner (Mason-Jones et al., 2000(a)) as well as the main agent in offering value from the customer viewpoint within the lean supply chain.

It is noteworthy that the recommended expert system is by no means comprehensive at all and entails some limitations to be improved. First, five important criteria regarding the performance of the supply chain have been applied in this study; meanwhile, considering the importance of matching the supply chain strategy with the product), other variables including product variety, type, and other product-related criteria must be included within input variables. Second, three lean, agile, and leagile strategies have been the focus of this study; however, other types of the supply chain, including Rigid and Resilient, are applicable within the fuzzy expert system. Besides, various other strategies, including Quick Response Manufacturing (QRM), flexible manufacturing, etc., can be applied as well. Third, fuzzy rules are of equal importance. Thus, combined with decision-making methods for criteria and rules, different weights can be considered for the development of this study. Moreover, other cases in different industries can be studied as well.

REFERENCES

Agarwal, A., Shankar, R., & Tiwari, M. K. (2006). Modeling the metrics of lean, agile and leagile supply chain: An ANP-based approach. *European journal of operational research*, *173*(1), 211-225.

Bhamra, R., Nand, A., Yang, L., Albregard, P., Azevedo, G., Corraini, D., & Emiliasiq, M. (2020). Is leagile still relevant? A review and research opportunities. *Total Quality Management & Business Excellence*, 1-25. DOI: 10.1080/14783363.2020.1750360

Bruce, M., Daly, L., & Towers, N. (2004). Lean or agile: a solution for supply chain management in the textiles and clothing industry?. *International journal of operations & production management*, *24*(2), 151-170.

Centobelli, P., Cerchione, R., & Ertz, M. (2020). Agile supply chain management: where did it come from and where will it go in the era of digital transformation?. *Industrial Marketing Management, 90,* 324-345.

Childerhouse, P., & Towill, D. (2000). Engineering supply chains to match customer requirements. *Logistics information management*, *13*(6), 337-345.

Christopher, M. and Towill, D.R. (2000), "Supply chain migration from lean and functional to agile and customized." *International Journal of Supply Chain Management*, *5*(4), 206-213.

Chtourou, H., Masmoudi, W., & Maalej, A. (2005). An expert system for manufacturing systems machine selection. Expert Systems with Applications, *28*(3), 461-467

Fadaki, M., Rahman, S., & Chan, C. (2020). Leagile supply chain: design drivers and business performance implications. *International Journal of Production Research*, *58*(18), 5601-5623.

Fasanghari, M., & Montazer, G. A. (2010). Design and implementation of fuzzy expert system for Tehran Stock Exchange portfolio recommendation. *Expert Systems with Applications*, *37*(9),

Galasso, F., & Thierry, C. (2009). Design of cooperative processes in a customer–supplier relationship: An approach based on simulation and decision theory. *Engineering Applications of Artificial Intelligence*, *22*(6), 865-881.

Ghaderi, H., Gitinavard, H., & Mehralizadeh, M. (2020). An Intuitionistic Fuzzy DEA Cross-Efficiency Methodology with an Application to Production Group Decision-Making Problems. *Journal of Quality Engineering and Production Optimization*, *5*(2), 69-86.

Gitinavard, H. (2019). Strategic Evaluation of Sustainable Projects based on Hybrid Group Decision Analysis with Incomplete Information. *Journal of Quality Engineering and Production Optimization*, *4*(2), 17-30.

Gitinavard, H., Mousavi, S. M., Vahdani, B., & Siadat, A. (2020). Project safety evaluation by a new soft computing approach-based last aggregation hesitant fuzzy complex proportional assessment in construction industry. *Scientia Iranica*, *27*(2), 983-1000.

Gitinavard, H., Shirazi, M. A., & Zarandi, M. H. F. (2020). Sustainable feedstocks selection and renewable products allocation: A new hybrid adaptive utility-based consensus model. *Journal of environmental management*, *264*, 110428.

Gligor, D. M., Holcomb, M. C., & Feizabadi, J. (2016). An exploration of the strategic antecedents of firm supply chain agility: The role of a firm's orientations. *International Journal of Production Economics*, *179*, 24-34.

Hilletofth, P. (2009). How to develop a differentiated supply chain strategy. *Industrial Management & Data Systems*, 109(1), 16-33.

Huang, S. H., Uppal, M., & Shi, J. (2002). A product driven approach to manufacturing supply chain selection. *Supply Chain Management: An International Journal*, *7*(4), 189-199.

Hwang, G. J., Sung, H. Y., Chang, S. C., & Huang, X. C. (2020). A fuzzy expert system-based adaptive learning approach to improving students' learning performances by considering affective and cognitive factors. *Computers and Education: Artificial Intelligence*, *1*, 100003.

Kerr, R. M., & Ebsary, R. V. (1988). Implementation of an expert system for production scheduling. European Journal of Operational Research, *33*(1), 17-29.

Khan, M. K. (1999). Development of an expert system for implementation of ISO 9000 quality systems. *Total Quality Management*, *10*(1), 47-59.

Khozeimeh, F., Alizadehsani, R., Roshanzamir, M., Khosravi, A., Layegh, P., & Nahavandi, S. (2017). An expert system for selecting wart treatment method. *Computers in biology and medicine*, *81*, 167-175.

Lamming, R. (1996). Squaring lean supply with supply chain management. *International Journal of Operations & Production Management*, *16*(2), 183-196.

Liang, G. S., & Wang, M. J. J. (1994). Personnel selection using fuzzy MCDM algorithm. *European journal of operational research*, *78*(1), 22-33.

Lim, M. K., & Zhang, Z. (2012). A multi-agent system using iterative bidding mechanism to enhance manufacturing agility. *Expert systems with applications*, *39*(9), 8259-8273.

Malakouti, M., Rezaei, S., & Shahijan, M. K. (2017). Agile supply chain management (ASCM): a management decision-making approach. *Asia Pacific Journal of Marketing and Logistics*, 29(1), 171-182.

Mason-Jones, R., Naylor, B., & Towill, D. R. (2000a). Engineering the leagile supply chain. *International journal of agile management systems*, *2*(1), 54-61.

Mason-Jones, R., Naylor, B., & Towill, D. R. (2000b). Lean, agile or leagile? Matching your supply chain to the marketplace. *International Journal of Production Research, 38*(17), 4061-4070.

Moradi, M., Esfandiari, N., & Moghaddam, M. K. (2018). An integrated FLinPreRa-FQFD approach to leagility assessment:(case study of four industries). *International Journal of Lean Six Sigma*, *11*(2), 331-358.

Moyano-Fuentes, J., Maqueira-Marín, J. M., Martínez-Jurado, P. J., & Sacristán-Díaz, M. (2020). Extending lean management along the supply chain: impact on efficiency. *Journal of Manufacturing Technology Management*, *32*(1), 63-84.

Naylor, J. B., Naim, M. M., & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of production economics*, *62*(1-2), 107-118.

Olhager, J., Persson, F., Parborg, B., & Linkoping, S. R. (2002). Supply Chain impacts at Ericsson-from production units to demand-driven supply units. *International Journal of Technology Management*, *23*(1-3), 40-59.

Olugu, E. U., & Wong, K. Y. (2012). An expert fuzzy rule-based system for closed-loop supply chain performance assessment in the automotive industry. *Expert Systems with Applications*, *39*(1), 375-384.

Qi, Y., Boyer, K. K., & Zhao, X. (2009). Supply chain strategy, product characteristics, and performance impact: evidence from Chinese manufacturers. *Decision Sciences*, *40*(4), 667-695.

Raj, S. A., Jayakrishna, K., & Vimal, K. E. K. (2018). Modelling the metrics of leagile supply chain and leagility evaluation. *International Journal of Agile Systems and Management*, *11*(2), 179-202.

Razmi, J., Seifoory, M., & Pishvaee, M. S. (2011). A fuzzy multi-attribute decision making model for selecting the best supply chain strategy: Lean, agile or leagile. *Advances in Industrial Engineering*, *45*(Special Issue), 127-142.

Rehman, M.A. (2017). Determination of relative importance of agility enablers for agile manufacturing companies by analytical hierarchy process. *International Journal of Agile Systems and Management*, *10*(1), 49-72.

Reichhart, A., & Holweg, M. (2007). Lean distribution: concepts, contributions, conflicts. *International journal of production research*, *45*(16), 3699-3722.

Sari, K. (2017). Modeling of a fuzzy expert system for choosing an appropriate supply chain collaboration strategy. *Intelligent Automation & Soft Computing*, 1-8.

Sharma, P., & Kulkarni, M. S. (2016). Framework for a dynamic and responsive. *International Journal of Productivity and Performance Management*, 65(2), 207-222.

Silveira, G.D, Borenstein, D., & Fogliatto, F. S. (2001). Mass customization: Literature review and research directions. *International journal of production economics*, *72*(1), 1-13.

Soni, G., & Kodali, R. (2009). Performance value analysis for the justification of the leagile supply chain. *International Journal of Business Performance Management*, *11*(1-2), 96-133.

Tang, M., Chen, X., Hu, W., & Yu, W. (2012). Generation of a probabilistic fuzzy rule base by learning from examples. *Information Sciences*, *217*, 21-30.

Tortorella, G. L., Miorando, R., & Tlapa, D. (2017). Implementation of lean supply chain: an empirical research on the effect of context. *The TQM Journal*, *29*(4), 610-623.

Tortorella, G., Giglio, R., Fettermmann, D. C., & Tlapa, D. (2018). Lean supply chain practices: an exploratory study on their relationship. *The International Journal of Logistics Management*, 29(3), 1049-1076.

Udokporo, C., Anosike, A., & Lim, M. (2020). A decision-support framework for Lean, Agile and Green practices in product life cycle stages*.* *Production Planning & Control*, 1-22.

Um, J. (2017). Improving supply chain flexibility and agility through variety management. *The International Journal of Logistics Management*, *28*(2), 464-487.

Vahdani, B. (2016). Solving robot selection problem by a new interval-valued hesitant fuzzy multi-attributes group decision method. *International Journal of Industrial Mathematics*, *8*(3), 231-240.

Villarreal, B., Garza-Reyes, J. A., Kumar, V., & Lim, M. K. (2017). Improving road transport operations through lean thinking: A case study. *International Journal of Logistics Research and Applications*, *20*(2), 163-180.

Vinodh, S., & Chintha, S. K. (2011). Leanness assessment using multi-grade fuzzy approach. *International Journal of Production Research*, *49*(2), 431-445.

Vitasek, K. L., Manrodt, K. B., & Abbott, J. (2005). What makes a lean supply chain?. *Supply chain management review*, *9*(7), 39-45.

Vonderembse, M. A., Uppal, M., Huang, S. H., & Dismukes, J. P. (2006). Designing supply chains: Towards theory development. *International Journal of production economics*, *100*(2), 223-238.

Wang, W. J., & Luoh, L. (2000). Simple computation for the defuzzifications of center of sum and center of gravity. *Journal of Intelligent & Fuzzy Systems*, *9*(1, 2), 53-59.

Wieland, A. (2013). Selecting the right supply chain based on risks. *Journal of Manufacturing Technology Management*, *24*(5), 652-668.

Zarandi, M. H. F., Mansour, S., Hosseinijou, S. A., & Avazbeigi, M. (2011). A material selection methodology and expert system for sustainable product design. *The International Journal of Advanced Manufacturing Technology*,*57*(9-12), 885-903.

Zhang, D. Z. (2011). Towards theory building in agile manufacturing strategies—Case studies of an agility taxonomy. *International Journal of Production Economics*, *131*(1), 303-312.

Zhang, Y., Wang, Y., & Wu, L. (2012). Research on demand-driven leagile supply chain operation model: a simulation based on anylogic in system engineering. *Systems Engineering Procedia*, *3*, 249-258.