MODELING SUPPLY CHAIN QUALITY MANAGEMENT PERFORMANCE

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ABSTRACT
The body of knowledge of Supply Chain Management has evolved by integrating new approaches and concepts, such as Quality Management. Quality Management research in individual companies is usual, but there is a lack of research on how to incorporate quality requirements in supply chains design and planning. This paper describes the design of a rule-based model for measuring Supply Chain Quality Management performance. The proposed model integrates Triple Bottom Line (3BL) approach with the fuzzy set theory, considering environmental, economic and social performances and the imprecision in quantification of Supply Chain Quality Management performance. The application of the model allowed obtaining a crisp Sustainable Supply Chain Quality Management Index incorporating imprecision and vagueness on these calculations through a fuzzy rule-based system.

Keywords: Modeling, Supply Chain Quality Management, Triple Bottom Line, Fuzzy Logic.

1. INTRODUCTION

Quality Management approach has evolved from the traditional scenario focused on the company to complex systems of supply chains. This change in focus has led to a change in competitive priorities of many companies: from product quality to overall supply chain quality (Kuei and Madu 2001). Moreover, research in Supply Chain Management shifted from an operational and tactical level focused on cost, delivery and risk to a more complex and demanding strategic level (Melnyk *et al*. 2009).

A model is a simplified representation of a system and may be conceptual, verbal, diagrammatic, physical or formal (analytical or mathematical). Sayama (2015) highlights the following two approaches for the construction of scientific models:

- Descriptive modeling: it consists of describing the real state of a system at any time using quantitative methods (e.g., regression analysis and pattern recognition).
- Rule-based modeling: it consists of formulating dynamic rules that explain the behavior observed in a system. This type of modeling allows making predictions of possible states of the system, using dynamic equations, rules and principles, among other quantitative methods.

Both descriptive and rule-based approaches are widely applied in quantitative research in engineering and sciences. However, rule-based modeling plays a prominent role in the research of complex systems (Sayama 2015): the development of a rule-based model at microscopic scales and the study of its macroscopic behavior through computational simulation and/or mathematical analysis is almost a fundamental requirement for the analysis of complex systems, such as Supply Chain Quality Management.

Quality modeling is a little studied issue in Supply Chain Management (Batson and Mcgough 2007). Theory and practices about quality in individual companies are usual, but there is a lack of research on how to incorporate quality requirements in designing and planning global supply chains (Carmignani 2009; Dellana and Kros 2014; Mota et al. 2015), and how can be linked these practices and management systems with partners in the supply chain context (Bayo-Moriones et al. 2011; Gylling *et al*. 2015; Truong *et al*. 2016).

Although some researches have been carried about alignment between the type of product, strategy and network management systems quality (Mendes Dos Reis 2011) and models for designing and evaluating supply chains with focus on quality (Bayo-Moriones *et al*. 2011; Das and Sengupta 2010; Rashid and Aslam 2012; Truong *et al*. 2016), these ones have a descriptive approach and there is little use of rule-based modeling methods.

Therefore, it is necessary development and implementation of rule-based models for measuring Supply Chain Quality Management performance, considering environmental, economic and social performances and imprecision of data. In order to contribute to generation and dissemination of knowledge in this area, this paper describes a fuzzy rule-based model based on 3BL approach for measuring Supply Chain Quality Management performance.

This paper is structured as follows: first, there are backgrounds about Supply Chain Quality Management and Triple Bottom Line approach. Then, we describe the stages of proposed fuzzy rule-based model for measuring Sustainable Supply Chain Quality Management performance, its theoretical aspects and the application way. Lastly, we show the results obtained by applying the model and the analysis is made along with the conclusions.

2. SUPPLY CHAIN QUALITY MANAGEMENT

The theoretical foundation of Supply Chain Quality Management (SCQM) has been developed and its relevance in academic and industrial practice has been evaluated by comprehensively reviewing prior literature in major journals and inductively identifying the themes that emerge within it (Foster *et al*. 2011; Jraisat and Sawalha 2013; Kannan and Tan 2007).

The SCQM is the integration of Supply Chain Management (SCM) and Quality Management (QM) concepts. SCQM concept has been studied using different perspectives: systems approach, process approach, organizational learning, among others.

Kuei and Madu (2001) used a three-equations approach to outline a SCQM definition:

- SC = production-distribution network.
- Q = to meet market demands and to achieve customer satisfaction in a fast and cost-effective way, and
- M = to improve the conditions and the confidence for supply chain quality.

Robinson and Malhotra (2005) stated that "*SCQM is the formal coordination and integration of business processes involving all partner organizations in the supply chain to measure, analyze and continually improve products, services and processes in order to create value and achieve satisfaction of intermediate and final customers in the marketplace*".

Foster (2008) stated that SCQM is a system-based approach to improve performance, taking advantage of opportunities given by linkages between suppliers and customers. Mellat-Parasat (2013) stated that SCQM is the coordination and integration of inter-company processes involving all supply chain members through continuous improvement of inter-organizational processes in order to improve the performance and achieve customer satisfaction by emphasizing cooperative learning.

3. THE TRIPLE BOTTOM LINE

The Triple Bottom Line is a strategic issue and represents the three areas of sustainability: economic, environmental and social (Wilson 2015). Sustainability has become an important issue for most of the organizations and supply chains and it has created the need for developing non-financial measures of performance in addition to traditional measures (Agrawal *et al*. 2016; Hacking and Guthrie 2008).

Implementation of social responsibility policies and practices is not only the work of a company but of its supply chain, through the interrelation of partners to become a social responsible supply chain (Cruz-Trejos, Correa-Espinal and Cogollo-Flórez 2012).

Hubbard (2009) developed a Sustainable Balanced Scorecard conceptual framework and proposed an organizational sustainable performance index, calculated as the average performance in each of the six perspectives. This is a limitation of the model, since it assigns the same relative weight to each perspective.

Longo (2012) developed a simulation model for integrating sustainability aspects (technical, economic and environmental) in supply chain redesign and optimization. The implementation of metaheuristic techniques allowed to obtain positive impacts on the economic and environmental sustainability of the supply chain studied.

Montemanni *et al* (2013) designed a web-based software application for the sustainable design of a textile and apparel supply chain, in order to compute the environmental impact of the processes and material flows and to obtain alternative designs for the implementation of the supply chain, integrating cost and time performance indicators.

Rizzoli *et al* (2015) proposed a methodology for including the sustainability assessment in supply chain design and management. The tool is based in collection and organization of sustainability-related data of all stages of the product life cycle and then optimisation to choice in real time the better performing solution in sustainability.

Schulz and Flanigan (2016) developed a framework for a sustainability model in order to establishing a competitive advantage. The model integrates the concepts and roles of competitiveness with the 3BL theory and proposes some performance indicators for calculating Supply Chain Sustainability Index.

Fallahpour *et al* (2017) developed a model for supplier selection in sustainable supply chain management through a questionnaire-based survey. According to them, the economic aspect was the most essential, followed by environmental aspect and finally social aspect.

4. DEVELOPMENT OF A SUSTAINABLE SUPPLY CHAIN QUALITY MANAGEMENT INDEX

The development of the fuzzy rule-based model for measuring Supply Chain Quality Management performance was carried out through six stages: Development of performance indicators and setting fuzzy subsets parameters, Definition of fuzzy inference method, Elaboration of fuzzy rule-based system, Selection of defuzzification method and Calculation of Sustainable Supply Chain Quality Management Index.

4.1. Development of performance indicators and setting fuzzy subsets parameters

The first stage is the development of the indicators to measure performance in each one of the 3BL perspectives and thus to measure overall performance in SCQM. Table 1 shows the indicators in every 3BL perspective (Economic, Environmental and Social).

Table 1: Performance indicators and fuzzy subsets parameters of 3BL perspectives performance input variables

3BL	INDICATORS	FUZZY SUBSETS PARAMETERS		
		Low (trapezoidal)	Medium (triangular)	High (trapezoidal)
Economic	Percentage of logistics costs (%)	(0, 0, 6, 10)	(6, 10, 14)	(10, 14, 50, 50)
	Percentage of quality costs (%)	(0, 0, 15, 25)	(15, 25, 35)	(25, 35, 50, 50)
	Return on Assets (%)	(0, 0, 4, 7)	(4, 7, 10)	(7, 10, 50, 50)
Environ-mental	Average percentage of defective product (%)	(0, 0, 1, 2.5)	(1, 2.5, 4)	(2.5, 4, 20, 20)
	Emissions, effluent and waste as a percentage of total resources used (%)	(0, 0, 10, 20)	(10, 20, 30)	(20, 30, 40, 40)
	Average Percentage of Rejections and Returns (%)	(0, 0, 2, 5)	(2, 5, 8)	(5, 8, 30, 30)
Social	Customer Satisfaction measured as On Time In Full (OTIF) deliveries (%)	(0, 0, 70, 80)	(70, 80, 90)	(80, 90, 100, 100)
	Employee Satisfaction (%)	(0, 0, 40, 60)	(40, 60, 80)	(60, 80, 100, 100)
	Suppliers Development (%)	(0, 0, 30, 50)	(30, 50, 70)	(50, 70, 100, 100)

The parameters of input and output variables fuzzy sets for the calculations of performance by 3BL perspective and the SCQM Index were established by analyzing historical information (frequency histograms and segmentation into quartiles or quintiles according to the number of fuzzy sets established). The model was applied in the supply chain of a plastics sector company, whose name is kept in reserve due to commitments of confidentiality of the information supplied.

4.2. Definition of fuzzy inference method

A fuzzy inference method is used to obtain conclusions from "IF-THEN" rules and input values to the system by applying composition relations. Because of the outputs of system are continuous values, the Mandani type inference system was used in this model (Figures 1 and 2).

4.3. Elaboration of fuzzy rule-based system

The elaboration of rules is the most important stage in the design of fuzzy-rule based model inasmuch as it combines the expert opinion and the analysis of historical information. In this case, the Senior Management of the company used multiple comparison matrices for the elaboration of fuzzy rules, considering than the main objective of measuring Sustainable Supply Chain Quality Management is not financial or quality performance but jointly the environmental, economic and social performances.

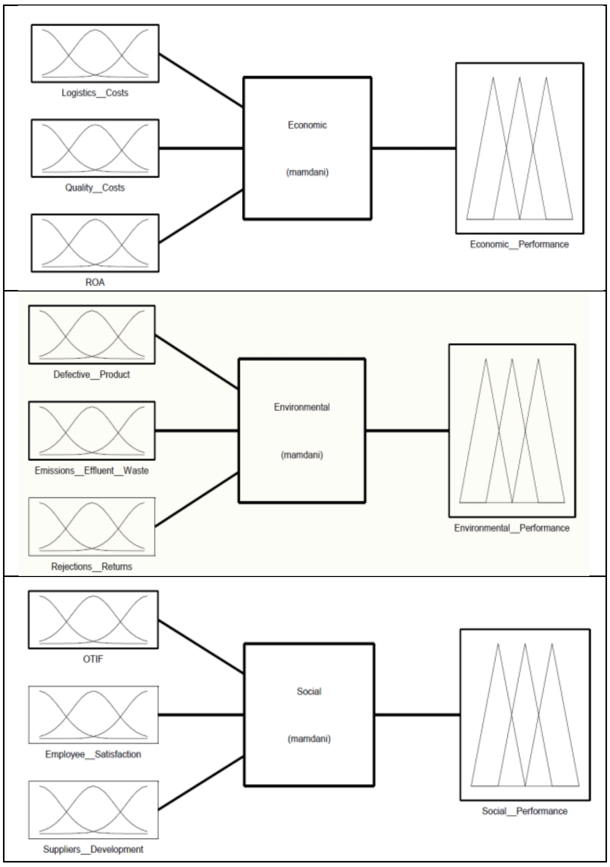

Figure 1: Fuzzy Inference Systems for Economic, Environmental and Social performance measurement.

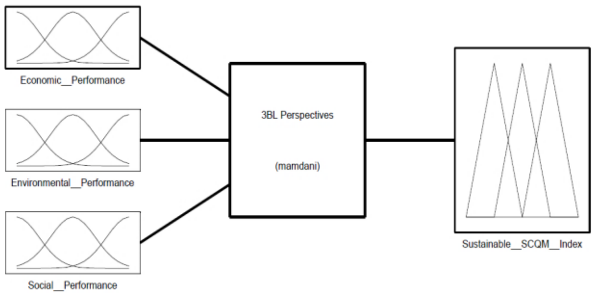

Figure 2: Fuzzy Inference System for measuring Sustainable Supply Chain Quality Management Index.

In this model are used "IF-THEN" rules, composed of the antecedent "IF" and the consequent "THEN", using connectors "AND" to develop necessary decision rules. This model contains three rules sets for 3BL perspectives and one rule set for Sustainable SCQM Index. The construction of fuzzy rule-based system was made by developing a conclusions matrix by considering all possible combinations of inputs and assigning a conclusion to each (Tables 2, 3, 4 and 5).

Table 2: Fuzzy rules matrix of Economic perspective

ROA	Logistics Costs	Quality Costs: Low	Quality Costs: Medium	Quality Costs: High
Low	Low	*M*	*L*	*L*
Low	Medium	*L*	*L*	*L*
Low	High	*L*	*L*	*L*
Medium	Low	*M*	*M*	*M*
Medium	Medium	*M*	*M*	*L*
Medium	High	*M*	*L*	*L*
High	Low	*H*	*M*	*M*
High	Medium	*M*	*M*	*M*
High	High	*M*	*L*	*L*

Table 3: Fuzzy rules matrix of Environmental perspective

Defective product	Emissions, Effluent & waste	Rejections & Returns: Low	Rejections & Returns: Medium	Rejections & Returns: High
Low	Low	*H*	*H*	*M*
Low	Medium	*H*	*M*	*M*
Low	High	*M*	*M*	*L*
Medium	Low	*H*	*M*	*M*
Medium	Medium	*M*	*M*	*M*
Medium	High	*L*	*L*	*L*
High	Low	*M*	*M*	*L*
High	Medium	*M*	*L*	*L*
High	High	*L*	*L*	*L*

Table 4: Fuzzy rules matrix of Social perspective

OTIF	Employee satisfaction	Suppliers development: Low	Suppliers development: Medium	Suppliers development: High
Low	Low	*L*	*L*	*L*
Low	Medium	*L*	*M*	*M*
Low	High	*L*	*M*	*M*
Medium	Low	*L*	*M*	*M*
Medium	Medium	*M*	*M*	*M*
Medium	High	*M*	*M*	*M*
High	Low	*M*	*M*	*M*
High	Medium	*M*	*M*	*H*
High	High	*M*	*H*	*H*

Table 5: Fuzzy rules matrix of Sustainable SCQM Index

Economic Performance	Environmental Performance	Social Performance: Low	Social Performance: Medium	Social Performance: High
Low	Low	*L*	*L*	*L*
Low	Medium	*L*	*L*	*M*
Low	High	*L*	*M*	*M*
Medium	Low	*L*	*M*	*M*
Medium	Medium	*M*	*M*	*M*
Medium	High	*M*	*M*	*M*
High	Low	*M*	*M*	*M*
High	Medium	*M*	*M*	*M*
High	High	*M*	*H*	*H*

Economic, Environmental and Social perspectives and Sustainable SCQM Index were evaluated on three input variables, which have three fuzzy categories (Table 1). Therefore, there are $3^3 = 27$ fuzzy rules in each of their systems.

Values in cells of Tables 2-5 represent the consequent describing each combination and correspond to linguistic labels of output variable fuzzy subsets, and "L" corresponds to low, "M" is medium and "H" is high. For example, in the Table 5, shaded cell corresponds to the following rule: IF “Economic performance” is High AND “Environmental performance” is Medium AND “Social Performance” is High THEN Sustainable SCQM Index is Medium.

The application of the Mandani type fuzzy inference system based on the rules systems previously described also allowed to obtain response surface 3D graphs for modeling the relation between the input and output variables in each 3BL perspective and in the Sustainable SCQM Index (Figures 3,4,5 and 6).

For example, Figure 6 shows that both Environmental and Economic performance contribute to the Sustainable SCQM Index, but the impact of Economic performance is greater at lower values than Environmental performance.

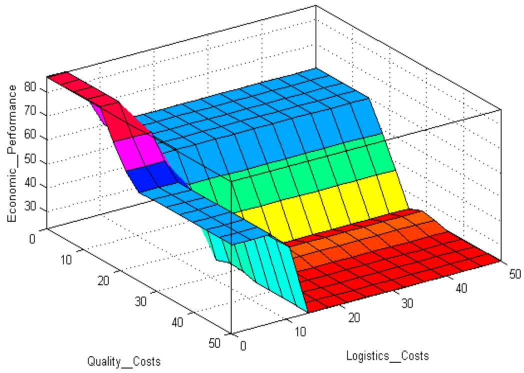

Figure 3: The 3D relation of input indicators (quality costs and logistics costs) and output variable (Economic Performance)

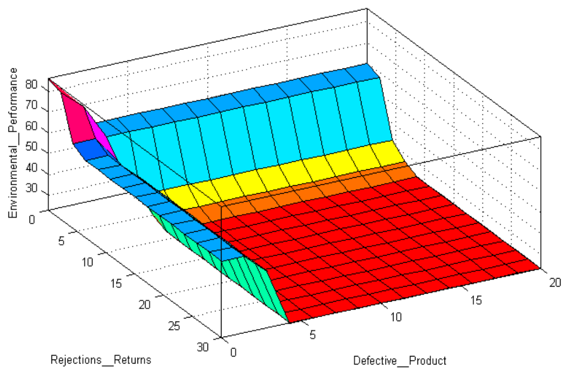

Figure 4: The 3D relation of input indicators (rejections and returns and defective product) and output variable (Environmental Performance)

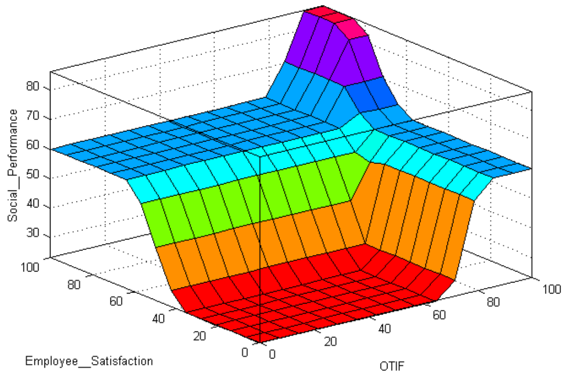

Figure 5: The 3D relation of input indicators (employee satisfaction and OTIF) and output variable (Social Performance)

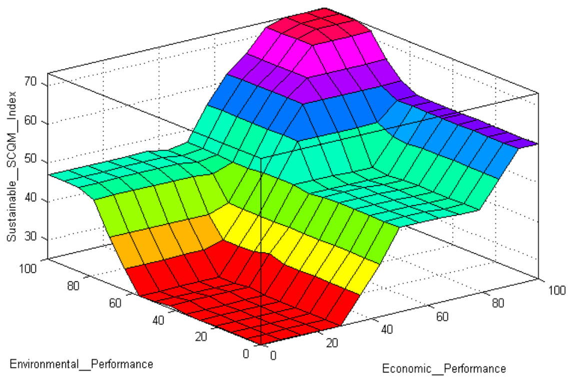

Figure 6: The 3D relation of input performance (Environmental and Economic) and output variable (Sustainable SCQM Index)

4.4. Selection of Defuzzification Method

Since the result of inference process is a set with a fuzzy distribution in response and for decision making it is necessary to use specific responses, the fuzziness must be removed and to obtain a crisp number.

The center of area method was used in this model for defuzzification, because of its continuity and that calculates the overlap area only once. The crisp value of the performance indicators for each 3BL perspective and the Sustainable SCQM Index were generated by the search of gravity center of the membership function of respective fuzzy outputs (Figures 7, 8, 9 and 10). The Fuzzy Logic Designer Application of Matlab© software was used as support for development of every stage of fuzzy rule-based model.

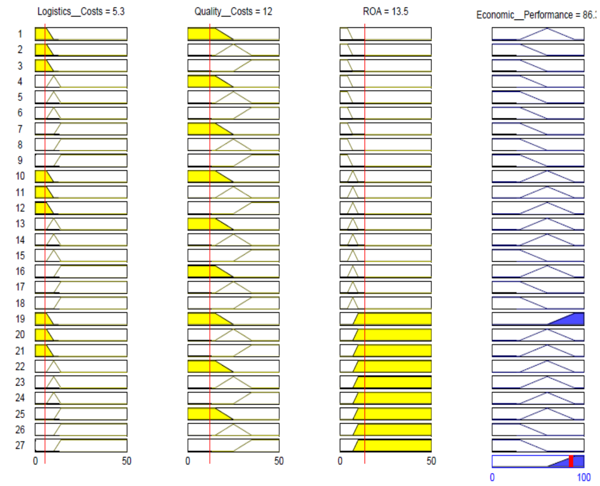

Figure 7: Scheme results of the fuzzy inference procedure to calculate Economic Performance

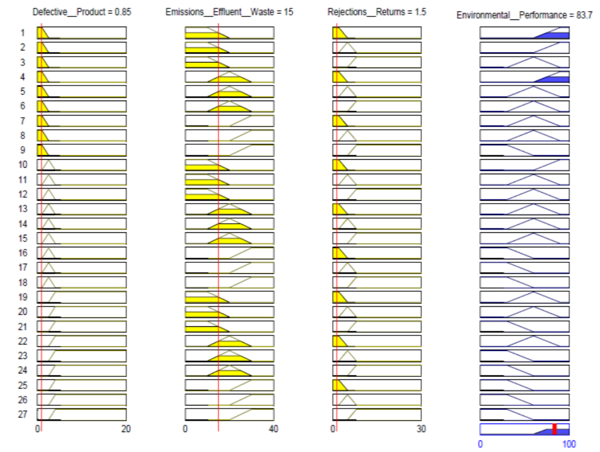

Figure 8: Scheme results of the fuzzy inference procedure to calculate Environmental Performance

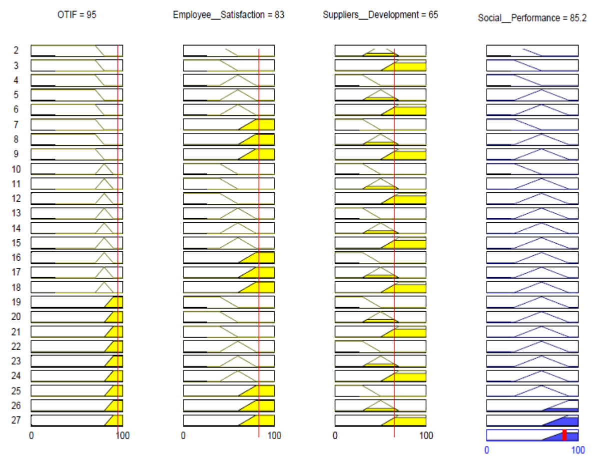

Figure 9: Scheme results of the fuzzy inference procedure to calculate Social Performance

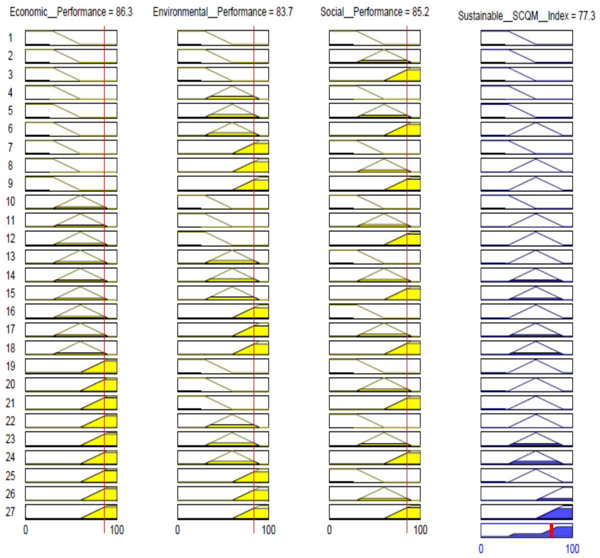

Figure 10: Scheme results of the fuzzy inference procedure to calculate Sustainable SCQM Index

4.5. Calculation of Sustainable Supply Chain Quality Management Index

The crisp numbers results of applying the fuzzy rule-based model for measuring Sustainable SCQM Index are shown in top of Figures 7 to 10. The results may be expressed in terms of the fuzzy rule-based systems, as follows:

- Economic Performance: IF Percentage of logistics costs is 5.3% AND Percentage of quality costs is 12% AND Return of Assets is 13.5% THEN Economic Performance is 86.3% (Figure 7).
- Environmental Performance: IF Percentage of defective product is 0.85% AND percentage of emissions, effluent and waste is 15% AND Percentage of rejections and returns is 1.5% THEN Environmental Performance is 83.7% (Figure 8).
- Social Performance: IF OTIF is 95% AND Employee satisfaction is 83% AND percentage of suppliers development is 65% THEN Social Performance is 85.2% (Figure 9).
- Sustainable SCQM Index: IF Economic Performance is 86.3% AND Environmental Performance is 83.7% AND Social Performance is 85.2% THEN Sustainable SCQM Index is 77.3% (Figure 10).

These numerical results may be interpreted as the compliance percentage of the goals and objectives of sustainability of the quality management practices in the supply chain context.

Moreover, it is important to highlight this model allows to make sensitivity analysis by varying the input variables values and then seeing the impact of the changes on the final performance. For example, if the company achieves to improve the performance of each 3BL perspective by 10% (thus, Economic Performance is 94.9%, Environmental Performance is 92.1% and Social Performance is 93.7%), the Sustainable SCQM Index would be 86.3% (Figure 11), which means that it would be improved by 11.6%, compared to the initial result of 77.3%.

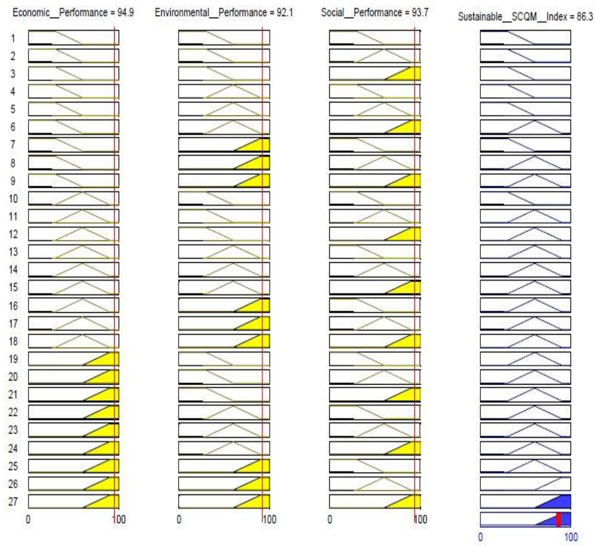

Figure 11: Results of the Sustainable SCQM Index obtained if the performance of each 3BL perspective would improve by 10%

5. CONCLUSIONS

The application of the fuzzy rule-based model allowed obtaining a crisp number as Sustainable SCQM Index that is important for decisions making. The model is based on a set of fuzzy rules easily interpretable and apprehended by the people involved in quality management in the supply chain.

The fuzzy rule-based model has a systematic structure that allows easy adaptation to others supply chains or other business management problems. The joint implementation of fuzzy logic and 3BL provides a new approach for modeling imprecision and interrelation of Economic, Environmental and Social variables in SCQM context.

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