Fuzzy Control of Morelia's Manufacturing Companies' Innovation Capabilities

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Abstract Innovation has considered organizations' competitive advantage. The purpose of this study is to visualize the effects of the behavior of innovation level at innovation capability change. This work presents a fuzzy controller design using logic tables and a generalized ordered weighted averaging (GOWA) index to model the internal innovation phenomenon of manufacturing enterprises in Morelia, Michoacán, Mexico. The linguistic rules were programmed using a fuzzy design module in MATLAB software, and the controller was simulated using the Simulink tool. The results show that the values of at least two inputs have to change in order for the innovation value to change, and two static input values are enough to restrict the minimum innovation value. This paper presents an original methodology for visualizing the behavior of the internal innovation of companies based on control and fuzzy set theory that allows us to capture the dynamics of the phenomenon.

Keywords Fuzzy control system · IGOWA operator · Fuzzy analysis · Innovation capabilities

1 Introduction

Throughout history, innovation has been defined in different ways. Schumpeter (1934) conceives innovation as a dynamic concept of economic development, while the Oslo manual (OECD 2005) defines innovation as the implementation of a new or significant product, good or service.

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Currently, evidence suggests that there is a dependency between enterprises' competitive success and innovation management processes. However, how to quantify and evaluate innovation and its impacts is too complex for many companies at present (Adams et al. 2006).

Worldwide, Mexico is ranked 56th out of 124 countries in the Global Innovation Index. With 72% efficiency, Mexico rose two places from its previous rating and has *"human capital and innovation"* as a strength and *"business sophistication"* as a weakness (Cornell University, INSEAD, and WIPO 2018). Michoacán, on the other hand, ranks 28th out of 32 states in the National Innovation Index with an efficiency of 0.90%. Morelia has an efficiency of 0.58% and is ranked 17th in the Medium City Innovation Index (Venture Institute, CONACYT, and Secretaría de Economía 2013).

This study presents a fuzzy control model that allows one to observe the innovation level behavior of companies in Morelia when there is a change in their innovation capabilities. The preliminaries section describes the roles of enterprises' innovation capabilities in generating internal innovation. In the methodology section, OWA's results were used to build a logic table, in order to acknowledge the change on innovation capabilities. The input and output ranges were defined, and the membership functions were constructed using the fuzzy module designer on MATLAB. Using the logic table as a baseline, a set of IF–THEN-type rules were established and programmed on the same module, which conclude the fuzzy control system design. To work with the controller designed, the inputs were settled at the medium possible value, to begin the analysis. The input values were changed synchrony incrementally, and the behavior of the output was observed. The results section of this paper presents the analysis of the innovation behavior when companies' innovation capabilities change. Finally, the concluding section summarizes the findings of the research and propose future research lines.

2 Preliminary

2.1 Innovation Capabilities

Innovation capabilities have taken an important place among enterprises' strategies. Knight and Cavusgil (2004) are positively linked to their development (Calantone 2002). Previous work shows that innovation allows enterprises to survive in a volatile environment (Calantone 2002).

An interesting approach to assess innovation management measurement is presented in Adams et al. (2006) here, the authors compare other authors' work on the subject, conciliated their opinions and design an enterprise innovation capability measurement model. Seven variables are included in this model: *inputs,* internal drivers which are the entry systems and tools for innovation process which provide a competitive advantage; *knowledge management which* includes the management of explicit and implicit knowledge within organizations and the process of collection and use of such information; *innovation strategy, which* helps to reduce processes inefficiencies and is linked to key business objectives, leadership and pro-activity in the commitment to innovation; *organization and culture,* which are used to know the intensity with which companies maintain their organizational structure aligned with their project management processes; *portfolio management* considered a determinant key of competitive advantage; *project management* is commonly measured in terms of cost, duration and return on investment; *and commercialization,* external drivers measure the intensity which company launches its products to the market (Alfaro-García et al. 2017).

Based on that new method, Alfaro-García et al. (2017) performed an assessment of the innovation capabilities of the enterprises in Morelia, Michoacan, Mexico. This study focused on the manufacturing enterprises of the region and was executed with fuzzy methods and an IGOWA operator. Alfaro's work presented a methodological structure for an innovation management measure using a fuzzy approach. The principal advantage of this operator is that the information aggregation considers the decision makers' highly complex attitudes, which is truly useful for innovation management and has been used as a baseline for the present work.

2.2 Fuzzy Control Systems

A system is *"a complex collection of highly related elements that accomplish a specific objective"* (Valdivia-Miranda 2012) with inputs that can be manipulated and outputs that can be observed. Those systems are generally affected by external and internal factors that cannot be manipulated, which are called *disturbances.* A control system manipulates the outputs using one rule or a set of rules, even the occurrence of disturbances (Valdivia-Miranda 2012).

Over time, fuzzy control has become quite an active area in the research and application of fuzzy set theory (Chuen Chien 1990). Mamdani, who was motivated by Zadeh's articles, is a pioneer of the discipline. Some applications of fuzzy set theory are qualitative phenomena modeling, pattern recognition, information processing, decision making, management, finance, among others. Particularly, fuzzy control has become one of the most successful applications due to its effectiveness in nonlinear complex system control (Feng 2006).

A characteristic of fuzzy control is that it incorporates a knowledge-based system (KBS), which allows for increased reliability, robustness and performance by incorporating knowledge of phenomena that cannot be included in an analytic model or an algorithm (Driankov et al. 1996).

Unlike a classic controller, a fuzzy control is built using a set of symbolic IF–THEN-type rules that are compiled using basic numeric objects and algorithms as true tables, interpolations, comparators and others, which are then used as the baselines to the controller's speed. Fuzzy control systems are thus heuristic forms that define nonlinear systems and are based on tables (Driankov et al. 1996).

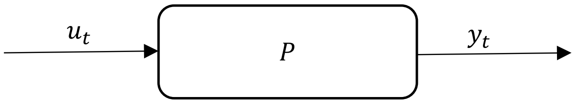

Fig. 1 Basic fuzzy control system diagram. Self-made figure

Identical to a conventional system, a fuzzy system is formed by a plant module (P) that contains the process or phenomenon that is to be represented. The inputs u_t are the independent variables that are required for the plant to operate, and the outputs y_t are the dependent variables that will be obtained once the inputs are processed by the plant (Hooda and Raich 2017) (Fig. 1).

In this controller, the algorithm is the linguistic rule set interpreter, and the decision will be based on fuzzy set theory (Mamdani et al. 1974).

3 Methodology

We base our methodology on Alfaro-García et al.'s results from their article *"On Ordered Weighted Logarithmic Averaging Operators and Distance Measures"* (Alfaro-Garcia et al. 2016), in which a function that generates and establishes the weight of each innovation capability is obtained. According to it, a fuzzy control model that allows the observation of the behavior of innovation based on the changes of enterprises' innovative capabilities is built.

3.1 Inputs and Outputs

These controller inputs are defined using Adam's innovation capability model as follows (Adams et al. 2006):

1. Innovation strategy,
2. Knowledge management,
3. Project management,
4. Portfolio management,
5. Inside factors,
6. Organization and structure, and
7. Outside factors.

Innovation is the only output.

Alfaro-García et al. at their article *"A Fuzzy Methodology for Innovation Management Measurement"* (Alfaro-García et al. 2017) defined the OWA index of innovation capabilities for Morelia's manufacturing companies as is shown in Fig. 2.

This index shows the weight of each capability to generate innovation in the company. With this index, a logic table was built. Each capability was placed in columns. Then, all combinations of the presence or absence of capabilities was set.

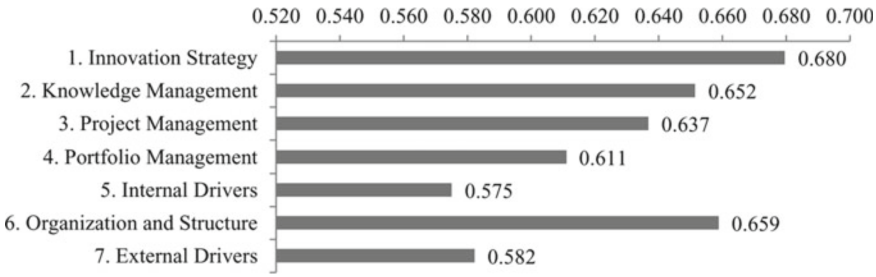

Fig. 2 IGOWA index for Morelia manufacturing companies (Alfaro-García et al. 2017)

A one was used to determine the presence of a capability and a zero to show the absence of it. To calculate the innovation value for each combination, the one or zero was multiplied by the weight of the correspondent capability and then added together, based on the way that innovation indexes are commonly calculated (Venture Institute, CONACYT, and Secretaría de Economía 2013). At the end, 128 combinations were set (Figs. 3 and 4).

After innovation values have been calculated, the rules get translated into linguistic labels. One becomes a "Hi", zero becomes a "Low", and the range of innovation gets divided into four intervals ("Null", "Low", "Medium" and "Hi"), between zero and 4.396, the minimum and maximum value obtained when all the innovation capabilities are absent or present, respectively (Fig. 5).

Once the linguistic rules have been settled, the plant of the fuzzy control is designed, using the fuzzy control module from MATLAB.

Following Mamdani's fuzzy controller design method (Mamdani et al. 1974), we characterize all variables as necessary because of fuzzy set theory. Hence, each one of the variables is going to be divided based on a linguistic form of the labeled levels. The number of levels will define the number of rules for the controller. Larger numbers of

P1	P2	P3	P4	P5	P6	P7
1	1	1	1	1	1	1
1	1	1	1	1	1	0
1	1	1	1	1	0	1
1	1	1	1	1	0	0

Fig. 3 Example of the logic table. Self-made table

P1	P2	P3	P4	P5	P6	P7	INNOVATION
0.68	0.652	0.637	0.611	0.575	0.659	0.582	4.396
0.68	0.652	0.637	0.611	0.575	0.659	0	3.814
0.68	0.652	0.637	0.611	0.575	0	0.582	3.737
0.68	0.652	0.637	0.611	0.575	0	0	3.155

Fig. 4 Example of the table set to calculate the innovation final values. Self-made figure

P2	P3	P4	P5	P6	P7	Innovation
Hi	Hi	Hi	Hi	Hi	Hi	Hi
Hi	Hi	Hi	Hi	Hi	Low	Hi
Hi	Hi	Hi	Hi	Low	Hi	Hi
Hi	Hi	Hi	Hi	Low	Low	Hi
Hi	Hi	Hi	Low	Hi	Hi	Hi

Fig. 5 Example of the logic table with linguistic labels. Self-made figure

rules imply a higher resolution, but the controller's robustness also increases, which will result in a slower controller that is useless for dynamic phenomena. Under these restrictions, each one of these variables was set to the levels of "Hi" and "Low". Each level was defined by a membership function with a 0–1 range (Fig. 6).

The output (innovation) is divided into four levels:

1. Null,
2. Low,
3. Medium, and
4. Hi.

The different levels are shown in Fig. 7.

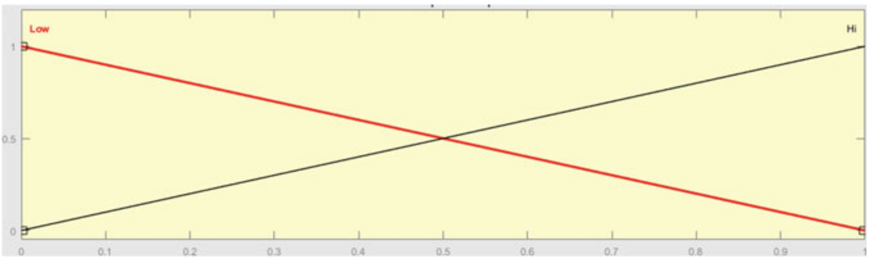

Fig. 6 Input structure. Self-made figure

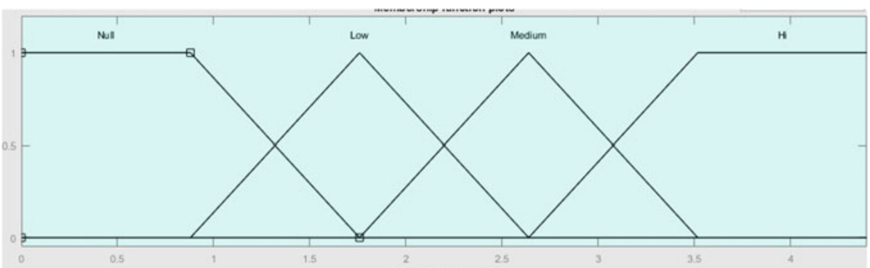

Fig. 7 Output structure. Self-made figure

Fig. 8 Example of the input area calculation. Figure from the MATLAB fuzzy control module

Fig. 9 Example of the output area calculation. Figure from MATLAB fuzzy control module

3.2 Range Definition

Once the linguistic labels have been settled, the plant of the fuzzy control is designed, using the fuzzy control module from MATLAB to set the rules of operation. These are IF–THEN-type rules that indicate to the controller which has to be the output, if one of the known conditions occurs. For example:

If (InnovationStrategy is Hi) and (KnowledgeManagement is Hi) and (ProjectManagement is Hi) and (PortafolioManagement is Hi) and (InternalDrivers is Hi) and (OrganizationAndStructure is Hi) and (ExternalDrivers is Hi), then (Innovation is Hi).

We use 128 total rules because of the number of combinations that define the innovation level. Then, for the unknown conditions according to Mamdani's method, the input value on each capability gives the area under the curve of the membership function, and as all the rules used were built with an AND operator, the resulting area for each rule is the intersection of the seven capabilities' areas. For the final result, OR operator has been applied to blend all the resulting areas and the center of area of the final figure has been calculated (Mamdani et al. 1974) (Fig. 8).

At the end, the control plant has been added at the simulation software "Simulink". The inputs have been set on 0.5 as a starting point, to give the output a chance to move above and under the set value (Fig. 9). The simulation allows us to observe the innovation-level changes that are caused by the observed capability changes over continuous time (Fig. 10).

4 Results

For this work, a large amount of testing was conducted that allowed us to observe the behavior of the innovation level due to the changes in the capabilities. In the first test, medium values were assigned to six variables, and an oscillatory value was assigned to one of the variables. Regardless of the variable which changes, the innovation level was a constant output value (Fig. 11).

In the second test, two inputs are altered, and five inputs maintain medium values. A fluctuation of the innovation value over a constant value is observed, and it is directly proportional to the change in the inputs. The minimum innovation value is

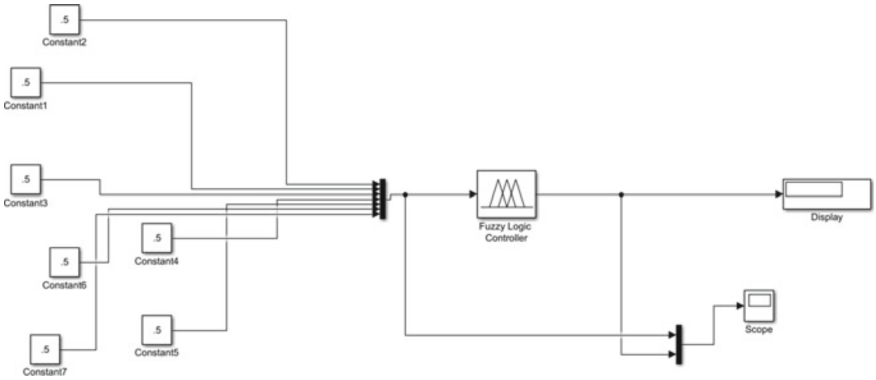

Fig. 10 Innovation capability fuzzy controller. Self-made figure

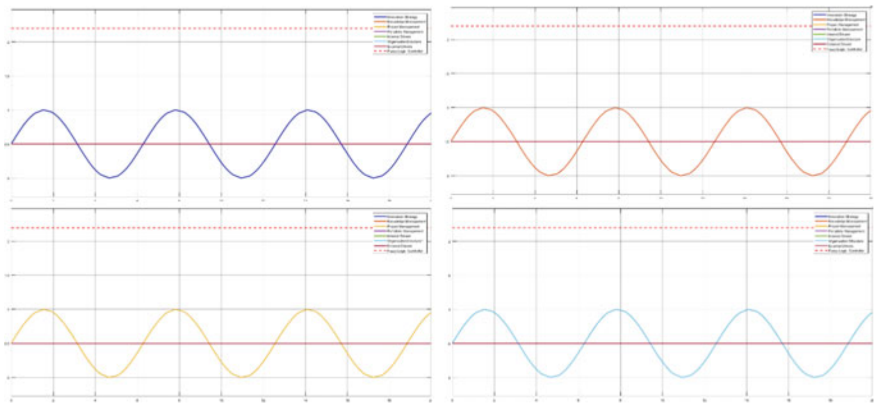

Fig. 11 Only one oscillating input. The innovation value is represented as a dotted line. Self-made figure

set by the constant input value, and when the input changes are lower, the innovation value is not affected. A change is only observed when the input values are higher than the static inputs (Fig. 12).

The next test was conducted using three oscillating inputs. In this case, innovation follows inputs and the lowest value is not set by the static variables. The results with four oscillating variables are similar (Fig. 13).

When five inputs are oscillating, the innovation value still behaves the same as the input values. However, a deformation in the output wave that is observed implies that the static input variables are influencing. The maximum innovation values that are reached are higher than those of the previous tests. When the six input variables are oscillating, we observe how the lowest value of innovation can be achieved. The restrictive static variable effect remains and increases as the number of static inputs increases (Fig. 14).

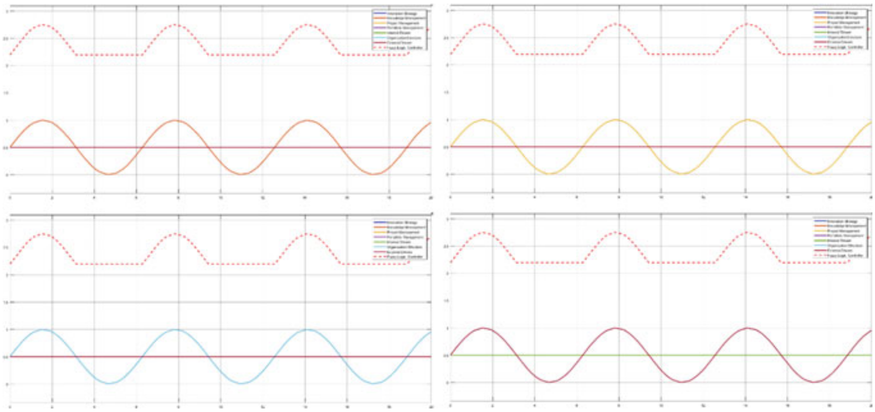

Fig. 12 Two oscillating inputs. The innovation value is shown as a dotted line. Self-made figure

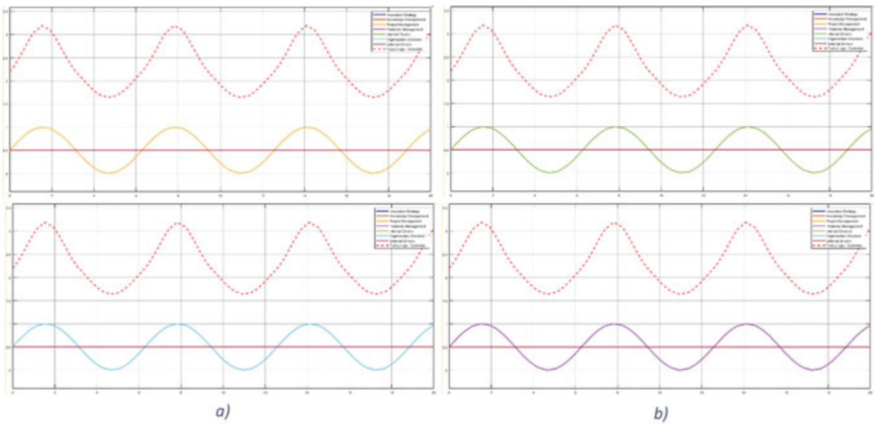

Fig. 13 **a** Three oscillating inputs. **b** Four oscillating inputs. The innovation value is shown as a dotted line. Self-made figure

Finally, the test is conducted with all input values changing. The innovation output value now completely follows the input values, and its fluctuation achieves the highest and lowest values that are originally established by the output design (Fig. 15).

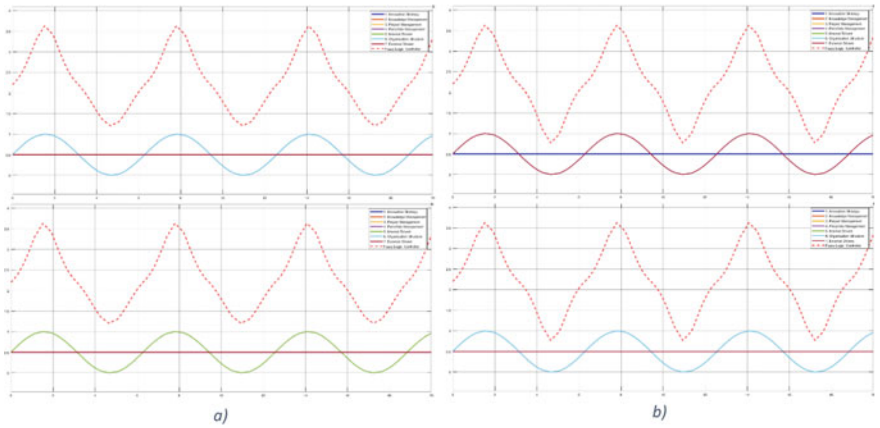

Fig. 14 **a** Five oscillating inputs. **b** Six oscillating inputs. The innovation value is shown as a dotted line. Self-made figure

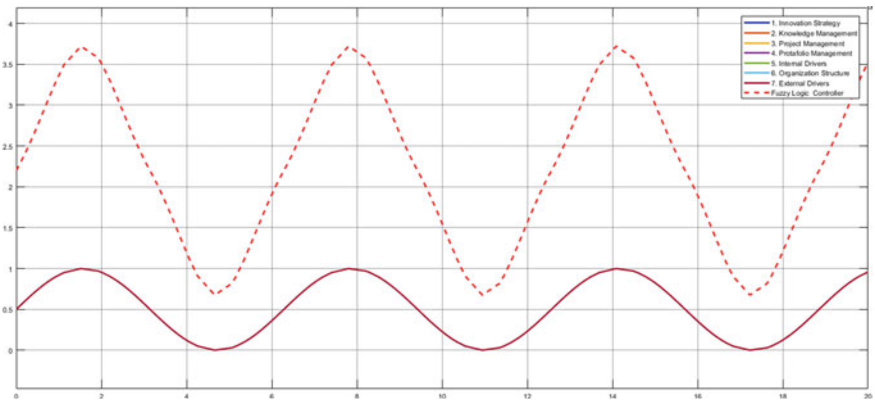

Fig. 15 Seven oscillating inputs. The innovation value is shown as a dotted line. Self-made figure

5 Conclusions

This investigation presents a fuzzy controller system for analyzing the innovation level inside enterprises according to the changes in the innovation capabilities. Using Alfaro's OWA index as a baseline, a logic table was constructed that defines the model's behavior.

An open-loop controller system was built that allowed the visualization of the changes in the internal innovation value of the enterprise according to the changes in their innovation capabilities. The innovation capabilities are synchronously and incrementally placed in order to observe the effect of enterprise innovation.

The results support the necessity of at least two capability changes in order to change the enterprises' innovation level. It is also shown that a minimum innovation level is defined by the values of two static variables inside the controller. Finally, it is observed that the maximum and minimum innovation values are only possible to achieve when all capabilities reach their maximum and minimum values, respectively.

The limitation of using a fuzzy control to study this phenomenon is that when the number of linguistic labels increases, also the number of rules, then it complicates the programming and slows the response of the controller, which makes it less useful for dynamic phenomena.

The union of the three themes, OWA's, control and innovation capabilities, has allowed to model innovation inside the companies with techniques that includes the opinion of the decision makers and visualized the possible behavior true time when a change in innovation has been made, different from the actual works where the model portrays only a moment in time.

Future investigation requires an analysis of the changes in the innovation level as innovation capabilities nonsynchronically change and even follow simultaneous inverse changes.

The fuzzy controller design was based on fuzzy logic because this tool allows one to model and describe phenomena with insufficient information to use a classic logic equation.

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