Statistical analysis of manufacturing system complexity

Germán Herrera Vidal1,2 · Jairo R. Coronado Hernández3 · Claudia Minnaard4 · Gustavo Gatica5 · Pablo Schwarzenberg5

Received: 19 July 2021 / Accepted: 23 February 2022 / Published online: 4 March 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Given the dynamism of the markets and the economic growth, nowadays companies must look for mechanisms that allow them to develop new strategies and compete successfully. The objective of this work is to develop a statistical analysis of the complexity of a manufacturing system. The methodological approach starts with the analysis of the data obtained through the Likert technique, identifying characteristics associated with high complexity, consequently, an inquiry is made on the factors that influence significantly from an experimental analysis, then a factor analysis is made to determine the correlations between the variables raised, and finally the association between the complexity of the manufacturing characteristics and the complexity of the elements of a system is evaluated. The study is based on a sample of 71 small- and medium-sized companies in the city of Cartagena, Colombia. The results obtained show a dominance of complexity in manufacturing systems, confirming the level of significance between subsectors, type of operation, and type of process; determining that there are high correlations between the variables; and corroborating the relationship between the variables and the characteristics of the manufacturing system.

Keywords Complexity · Manufacturing · Statistical · Characteristics

1 Introduction
A country’s economy is strengthened by the development of the manufacturing industry, thanks to the creation of value from raw materials and the generation of sources of employment. In Latin American countries, there is a large proportion of companies in the industrial sector belonging to micro, small, and medium enterprises (PyMes), given the amount of gross sales, the number of employees, total assets, tax rates, or other economic mechanisms or formulas [1]. It is worth considering that PyMes managers face great challenges, since they must not only have skill, agility, and quality, but also be competitive and strategic in business [2, 3].

According to Pine and Hull and Michalos et al. [4, 5], this is reflected in the wide variety of products and services they offer. Therefore, a research interest is generated by the search for measures that provide a productive and competitive strengthening, focused on cost reduction, quality improvement, delivery times, flexibility, speed of response, and customization. A previous study by Vidal and Hernández [6] shows the result in the manufacturing sector in the city of Cartagena, Colombia. Derived from a research project and initiative of the Cartagena Chamber of Commerce to strengthen the development of
productive, managerial and associative capacities of Colombian PyMes belonging to the city’s clusters (see Table 1). Consequently, Papakostas et al. [7] state that increased flexibility in manufacturing processes and product variety lead to greater complexity in the system. A complex system is understood as one that is composed of a large number of parts that interact in a non-simple way [8]. According to Flynn and Flynn [9], it is also necessary to take into account the number of parts, the types of processes, the type of operation, and the stability of the production schedule. According to Calinescu et al. [10], there are determining factors in manufacturing complexity such as (i) the product structure; (ii) the plant structure; (iii) the planning and scheduling functions; (iv) the flow of information during the process; (v) the dynamism, variability, and uncertainty of the environment; and (vi) other functions within the organization such as training and information.

From here is where it is established that there are different types of complexity in manufacturing systems. According to their classification, according to their origin, for Isik [11] they can be internal, external, and total. Internal complexity, associated with the manufacturer, external complexity with respect to the supply chain, and total complexity that covers the combination of both. According to Gaio et al. [12], complexity in manufacturing systems can be static or dynamic, depending on the time and its behavior. Static complexity refers to a characteristic associated to the systems, and dynamic complexity refers to the analysis of the system over a time horizon.

An uncontrolled complexity generates an increase in expenses and operational costs. According to Bick and Drexl-Wittbecker [13], research shows that in manufacturing companies, costs related to product and process complexity represent 25% of total costs. This is why several authors have ventured in the search for manufacturing systems to be more simplified, for this some have taken classical comparison parameters such as manufacturing time [14], routes or distance between stations [15], material handling costs [16], product quality [17], and others from the measurement of complexity such as Wu et al., Jacobs, and Efthymiou et al. [18–20].

Given the above, the purpose of this research is the development of a statistical analysis of the complexity in manufacturing system. This allows to study and analyze the data obtained from the Likert technique, identifying the characteristics associated with high complexity, as well as to inquire about the factors that influence significantly from an experimental analysis, then a factor analysis is performed to determine the correlations between the variables raised, and finally the association between the complexity of the manufacturing characteristics and the complexity of the elements of a system is evaluated. The work is divided into three sections, first the method is developed, followed by the results and finally the conclusions.

2 Method

Methodologically, six stages are needed to carry out the research: (i) type and method of research; (ii) source and technique of information collection; (iii) population, sample, and treatment of information; (iv) proposed technical sheet; (v) applied study technique; and (vi) statistical analysis (as depicted in Fig. 1).

2.1 Type and method of investigation

In order to be able to practice research, it was necessary to resort to a descriptive explanatory study according to Hernández et al. [21], which suggested the relationship of variables, interpreted through the analysis of information [22].

2.2 Source and data collection technique

In the collection of data and information, a structured survey was used, applied to managers and administrators of the production area. In addition, studies related to the subject were reviewed.

2.3 Population, sample, and treatment of information

From the study developed by Vidal and Hernández [6] and the results obtained in Table 1, it is evident that until the end of 2019 the manufacturing industry in the city of Cartagena, Colombia, is represented by a total

| Table 1 Participation of manufacturing companies |
|-----------------------------------------------|
| Size               | Total companies | Share in total | Manufacturing sector | Participation in the sector |
|---------------------|----------------|----------------|----------------------|---------------------------|
| Microenterprise     | 29,576         | 90.9%          | 3669                 | 92.1%                     |
| Small and medium    | 2792           | 8.6%           | 278                  | 7.0%                      |
| Large               | 167            | 0.5%           | 35                   | 0.9%                      |
| Total               | 32,535         | 100%           | 3982                 | 100%                      |

Source: Vidal and Hernández [6]
of 3982 companies; the number of microenterprises is 3669, PyMes 278, and in the case of large companies a number of 35. In terms of percentages, 92% is equivalent to microenterprises, 7% to PyMes, and 1% to large industries.

The instrument applied was aimed at PyMes in the manufacturing sector. For the selection of the companies, the most representative subsectors were taken into account, taking as a criterion the number of each one. Among these are (i) manufacture of food products with 38 companies; (ii) manufacture of fabricated metal products, except machinery and equipment with 36 companies; (iii) manufacture of chemical substances and products with 15 companies; (iv) processing of wood and manufacture of wood and cork products, except furniture with 14 companies; (v) manufacture of rubber and plastic products with 13 companies; and (vi) printing activities and production of copies from original recordings with 12 companies. Given the above, the companies in each economic subsector (population) were identified, and those representing 70% of accumulated participation were chosen as a sampling criterion. In number, they are equivalent to 71 companies out of a total of 128 [6].

2.4 Proposed technical sheet

The data sheet is composed of items such as application sector, economic subsectors, population size, and collection process. Table 2 lists the relevant elements of the sample design.

2.5 Applied study technique

The technique used to measure and study complexity is the use of questionnaires using Likert scales; the results obtained are analyzed statistically or by techniques of grounded theory. This technique has been of interest to researchers; in Guimaraes et al. [23], a questionnaire was applied to 500 plant managers to test the impact of complexity on the performance of manufacturing systems.

In Bozarth et al. [24], questionnaires are used at 209 manufacturing plants in various industries in seven countries in

| Table 2 Technical sheet |
|--------------------------|
| Items                    | Description                                                                 |
| Field of application     | Manufacturing PyMes                                                        |
| Economic subsectors      | Food manufacturing companies (38), metalworking (36), chemical (15), wood (14), plastic (13), and lithographic (12) |
| Population size          | 128                                                                         |
| Collection process       | Sample                                                                      |
| Distribution of the sample | Food (13), metalworking (20), chemical (11), wood (10), plastic (9), and lithographic (8) |
| Analysis unit            | Production area managers and administrators                                 |
| Processing system        | Microsoft Excel-Statgraphics v18 and Jupyter                                |
different geographical regions of the world to study which sources add complexity and have an impact on business performance. Consequently, Garbie and Shikdar [25] used this technique to study complexity in exactly seven (7) organizations in the industrial estate of Rusail (Muscat), concluding the lack of clarity and lack of attention from manufacturers and academics. Eckstein et al. [26] using questionnaires in 143 German companies investigates the effects of product complexity on the agility and adaptability of the supply chain as a function of cost and operational performance.

More recently, Kohr et al. [27] through a survey of 136 companies investigated the degree of implementation of complexity management methods and the impact of complexity factors in various industries, identifying how the industry is lagging behind in the field of complexity management. In Alshammari et al. [28] through questionnaires distributed to 150 companies in Kuwait, working on projects collected quantitative data, aiming to study complexity in the industry. Given the above and according to previous research, it is evident that studies and analysis of complexity in Latin American countries associated with business environments present a high degree of scarcity, and therefore, is a weak aspect in manufacturing systems.

2.6 Statistical analysis

The first statistical analysis that is developed is the reliability and consistency of the instrument applied. According to Saraph et al. [29], this is valid if it measures what it is supposed to measure and for Sekaran and Bougie [30] it must be able to measure consistently over time despite the conditions of the test or the status of the respondents. In this sense, taking into account the result of the sample of 71 surveys, from the Cronbach’s alpha consistency analysis, for the 31 variables chosen the statistic is equivalent to 0.950281, being reliable and consistent (greater than 0.7).

As a complement, a group of university academics, PyMees managers, and experts or advisors from the industrial sector were interviewed to validate the correct development of the instrument. The second analysis corresponds to the treatment of data or information, which allows obtaining the frequency table of the different economic subsectors, types of operation, and type of processes. From this, the technical study of Likert scale, experimental design, factorial analysis, and associativity analysis are applied.

3 Results

This section presents the results obtained, separated by sections, (i) manufacturing characteristics, (ii) Likert scale technique, (iii) experimental statistical analysis, (iv) factorial analysis, and (v) associative analysis of complexity.

### 3.1 Manufacturing characteristics

For the analysis of manufacturing characteristics, the different economic subsectors, operations types, and processes types were taken into account.

Table 3 shows that 28.2% of the subsectors are represented by (M), followed by companies (F) with 18.3%, then companies that manufacture (C) with 15.5%, and finally companies dedicated to the transformation of (W), manufacture of (P), and companies (L), with 14.1%, 12.7%, and 11.3%, respectively. Regarding the type of operation, 60.6% are (MTO) companies, 38% are (MTS), and 1.4% are (H). Considering the type of process, (FS) represented 80.3%, (JS) 8.5%, and (PR) 11.3%.

### 3.2 Likert scale technique

For the application of the Likert scale technique, the elements belonging to the manufacturing sector were initially defined, such as (i) product, (ii) process, (iii) plant, (iv) persons, and (v) planning. Thirty-one variables to be evaluated were structured. As a result, the Likert scale from 1 to 5 was used, where 1 represents the simple score while 5 represents the absolutely complex. For a more detailed analysis, the mean value above neutral or moderate complexity was considered. Taking into account the global mean value, Table 4 shows absolute complexity in manufacturing systems.

By means of a graphical analysis using Statgraphics software v18, it was possible to show that within the criteria with a very high complexity are (i) controlling the quality of the product with 15.49%, (ii) equipment maintenance management with 15.49%, and (iii) material requirement planning with 11.27%. Among the criteria with high complexity,

| Table 3 Manufacturing characteristics |
|--------------------------------------|
| Subsector type                       | Frequency | Percentage |
| Food (F)                             | 13        | 18.3%      |
| Metalworking (M)                     | 20        | 28.2%      |
| Chemical (C)                         | 11        | 15.5%      |
| Wood (W)                             | 10        | 14.1%      |
| Plastic (P)                          | 9         | 12.7%      |
| Lithographic (L)                     | 8         | 11.3%      |

| Operation type                       | Frequency | Percentage |
| Make to order (MTO)                  | 43        | 60.6%      |
| Make to stock (MTS)                  | 27        | 38.0%      |
| Hybrid (H)                           | 1         | 1.4%       |

| Process type                         | Frequency | Percentage |
| Flow shop (FS)                       | 57        | 80.3%      |
| Job shop (JS)                        | 6         | 8.5%       |
| Project (PR)                         | 8         | 11.3%      |
the following stand out: (i) process cost control with 35.21%, (ii) product design and development with 32.39%, and (iii) management of demand forecasts with 32.39% (see Fig. 2).

### 3.3 Experimental statistical analysis

In this phase, the factors that significantly influence the characteristics associated with the response variable “high complexity” are identified, taking the results of those surveyed above 4. The factors correspond to (i) economic subsector of manufacturing, (ii) operation type, and (iii) process type. Initially, the hypotheses are raised:

- **Hypothesis A (H0):** The effect of the subsector factor is the same when economic subsectors are compared.
- **Hypothesis A (H1):** The effect of the subsector factor is different when economic subsectors are compared.
- **Hypothesis B (H0):** The effect of the transaction type factor is the same when comparing the transaction types.
- **Hypothesis B (H1):** The effect of the subsector operation type factor is different when comparing operation types.
- **Hypothesis C (H0):** The effect of the process type factor is the same when comparing process types.
- **Hypothesis C (H1):** The effect of the process type factor is different when comparing process types.

The experimental design technique was then used to determine the level of significance of the factors by means of an analysis of variances or ANOVA table. Table 5 shows that the factors operation type and process type have a p value lower than 0.05, both in the main effects and in the interactions; therefore, the null hypothesis is rejected; given the above, it can be inferred that these two factors significantly influence the high complexity in the manufacturing technology.

| Group      | Items                          | Mean  |
|------------|--------------------------------|-------|
| Product    | Product design and development | 4,577 |
|            | Check the quantity of the product | 4,661 |
|            | Controlling the quality of the product | 4,535 |
|            | Product distribution management | 4,845 |
|            | Define product lot sizes        | 4,873 |
|            | Packing and packaging the product | 4,859 |
| Process    | Process design                  | 4,521 |
|            | Process control                 | 4,535 |
|            | Material handling management    | 4,478 |
|            | Management of internal transport | 4,676 |
|            | Operational standardization     | 4,605 |
|            | Measurement of work centers     | 4,647 |
|            | Selection of equipment and technology | 4,563 |
|            | Equipment maintenance management | 4,704 |
|            | Inventory management             | 4,591 |
|            | Process cost control            | 4,338 |
| Plant      | Physical capacity and distribution | 4,591 |
|            | Working environment              | 4,605 |
|            | Industrial safety management    | 4,408 |
|            | Environmental management         | 4,563 |
|            | Occupational health management   | 4,591 |
| Persons    | Training management             | 4,704 |
|            | Ergonomics in the working environment | 4,591 |
|            | Ethics and the working environment | 4,732 |
|            | Motivation and incentive system  | 4,746 |
|            | Work climate management          | 4,718 |
| Planning   | Management of demand forecasts   | 4,408 |
|            | Capacity planning                | 4,422 |
|            | Production planning              | 4,352 |
|            | Material requirement planning    | 4,478 |
|            | Resource requirement planning    | 4,478 |
systems of small and medium enterprises (PyMes) in the city of Cartagena, Colombia.

From this, an analysis of graphs is made by means of the software Statgraphics Centurion v18, to compare the different levels of the factors with respect to the high complexity variable that is being analyzed. The results obtained indicate that there is no significant difference when comparing the economic subsectors; however, the (F), (L), (W), and (M) subsectors generate a greater complexity than the (P) and (C) subsectors. In the same way, the analysis was made taking into account the process type factor; the results obtained indicate that there is no significant difference when comparing the (JS) and (PR). However, the (FS) is different from all others and with a greater impact on the high complexity variable (see Fig. 3).

In terms of the operation type of factor, the results obtained indicate that there is no significant difference when the (MTO) and (MTS) types are compared, as these generate the greatest complexity. Making an analysis of the relationship between the process type and the operation type, the results indicate that the relationship is significant; therefore, high levels of complexity are reached when the operation type is (MTO) and (MTS) and when the process type is (FS) (see Fig. 4).

Finally, the assumptions of the model were verified, taking into account tests of normality, homogeneity of variances, and independence of data, which they leave between seeing those compliments.

3.4 Factorial analysis

This section allows the development of a statistical technique to find groupings of variables correlated with others, allowing to make a debugging with respect to the number of uncorrelated variables. Given the above, the hypotheses are proposed:

Hypothesis D (H0): The variables of the different manufacturing factors are not correlated.
Hypothesis D (H1): The variables of the different manufacturing factors are correlated.

The correlations between all the variables considered are located on the basis of a matrix (see Fig. 5). The Kaiser–Meyer–Olkin index (KMO) indicates how appropriate it is to apply the factor analysis, which specifies that it corresponds to a value of 0.79 being adequate, since from 0.8 onwards it is considered a good result. Similarly, Bartlett’s sphericity test, which allows corroborating the hypotheses, where the p value is less than 0.05, therefore the null hypothesis is rejected and the analysis is continued.

Consequently, the main factors that meet the requirement (eigenvalues > 1) are extracted, resulting in six (6) relevant factors to summarize the original variables of the study. Table 6 specifies the high degrees of correspondence between the variable and the factor (Eta).

Table 5 Analysis of variance for high complexity

| Source    | Sum of squares | G | Middle square | F-ratio | p value |
|-----------|----------------|---|--------------|---------|---------|
| Main effects |                |   |              |         |         |
| A: Subsector | 0.044          | 5 | 0.008        | 1.15    | 0.3696  |
| B: Operation type | 0.183          | 2 | 0.091        | 11.96   | 0.0004  |
| C: Process type | 0.324          | 2 | 0.162        | 21.10   | 0.0000  |
| Interactions |                |   |              |         |         |
| AB        | 0.162          | 10| 0.0162       | 2.11    | 0.0743  |
| AC        | 0.141          | 10| 0.014        | 1.84    | 0.1177  |
| BC        | 0.176          | 4 | 0.044        | 5.75    | 0.0030  |
| Residue   | 0.153          | 20| 0.007        |         |         |
| Total (corrected) | 1.186          | 53|              |         |         |

Fig. 3 Mean plot for the economic subsector factor and mean plot for process type factor
Figure 6 shows the paired matrix of the different principal components (Eta); each component has its respective variables grouped together. This allows corroborating the alternative hypothesis, since there are high correlations between the factors.

3.5 Associative complexity analysis

This section covers the interest of assessing the association between the complexity of the manufacturing characteristics shaped by (i) economic subsectors, (ii) operation types, and (iii) processes type and the complexity of the elements such as (i) product, (ii) process, (iii) plant, (iv) persons, and (v) planning. On the basis of the sample taken previously, the hypotheses are put forward:

Hypothesis E (H0): The complexity of manufacturing characteristics are independent of the complexity of the elements of a system.
Hypothesis E (H1): The complexity of manufacturing characteristics depends on the complexity of the elements of a system.

Fig. 4 Mean plot for operation type factor and interaction plot

Fig. 5 Correlation matrix of variables
Table 6  Principal component extraction analysis

| Variables                                 | Items        | Eta 1 | Eta 2  | Eta 3  | Eta 4  | Eta 5  | Eta 6  |
|-------------------------------------------|--------------|-------|--------|--------|--------|--------|--------|
| Product design and development            | Product1     | 0.518 | -0.464 | 0.010  | 0.074  | 0.114  | 0.304  |
| Check the quality of the product          | Product2     | 0.633 | 0.070  | -0.096 | -0.053 | -0.108 | -0.263 |
| Controlling the quality of the product    | Product3     | 0.746 | 0.047  | -0.075 | -0.054 | -0.090 | 0.095  |
| Product distribution management           | Product4     | 0.807 | 0.169  | -0.132 | -0.084 | 0.106  | -0.137 |
| Define product lot sizes                   | Product5     | 0.620 | 0.122  | 0.179  | -0.034 | -0.116 | -0.148 |
| Packing and packaging the product         | Product6     | 0.633 | 0.101  | 0.099  | -0.017 | -0.105 | 0.042  |
| Process design                            | Process1     | 0.694 | -0.158 | -0.110 | 0.085  | 0.336  | 0.043  |
| Process control                           | Process2     | 0.624 | -0.091 | 0.106  | 0.187  | 0.127  | -0.117 |
| Material handling management              | Process3     | 0.050 | 0.282  | 0.266  | 0.201  | -0.182 | 0.400  |
| Management of internal transport          | Process4     | 0.494 | 0.040  | 0.140  | 0.047  | -0.131 | 0.112  |
| Operational standardization               | Process5     | 0.521 | 0.355  | 0.008  | 0.021  | 0.065  | -0.057 |
| Measurement of work centers               | Process6     | 0.109 | 0.210  | 0.233  | 0.000  | 0.302  | 0.063  |
| Selection of equipment and technology     | Process7     | 0.052 | 0.759  | -0.138 | 0.063  | 0.204  | 0.072  |
| Equipment maintenance management          | Process8     | 0.133 | 0.652  | -0.172 | -0.098 | 0.268  | 0.183  |
| Inventory management                      | Process9     | -0.036 | -0.055 | 0.117  | 0.602  | 0.010  | -0.159 |
| Process cost control                      | Process10    | 0.173 | -0.039 | 0.009  | 0.481  | 0.324  | -0.303 |
| Physical capacity and distribution        | Plant1       | 0.125 | 0.384  | 0.032  | 0.111  | 0.137  | 0.121  |
| Working environment                       | Plant2       | 0.023 | 0.622  | 0.159  | 0.178  | 0.018  | -0.146 |
| Industrial safety management              | Plant3       | -0.021 | -0.202 | 0.903  | 0.003  | 0.090  | 0.296  |
| Environmental management                  | Plant4       | -0.030 | -0.053 | 0.932  | 0.214  | -0.157 | -0.031 |
| Occupational health management            | Plant5       | 0.037 | 0.070  | 0.720  | -0.179 | 0.219  | 0.054  |
| Training management                       | People1      | 0.047 | -0.039 | 0.094  | 0.042  | 0.517  | 0.340  |
| Ergonomics in the working                 | People2      | -0.109 | 0.156  | 0.298  | -0.231 | 0.789  | 0.056  |
| Ethics and the working environment        | People3      | 0.045 | 0.082  | 0.091  | -0.123 | 0.316  | 0.750  |
| Motivation and incentive system           | People4      | -0.036 | 0.132  | -0.113 | 0.099  | 0.613  | 0.121  |
| Work climate management                   | People5      | -0.031 | 0.154  | -0.063 | -0.087 | 0.757  | 0.136  |
| Management of demand forecasts            | Planning1    | -0.211 | 0.012  | -0.043 | 0.503  | 0.550  | -0.094 |
| Capacity planning                         | Planning2    | -0.082 | -0.012 | -0.002 | 0.485  | 0.222  | 0.313  |
| Production planning                       | Planning3    | 0.022 | 0.085  | -0.057 | 0.712  | -0.080 | 0.295  |
| Material requirement planning             | Planning4    | 0.044 | 0.176  | -0.041 | 0.816  | -0.198 | 0.063  |
| Resource requirement planning             | Planning5    | 0.004 | 0.160  | -0.056 | 0.692  | -0.007 | 0.279  |

Fig. 6  Correlational factor extraction correlation matrix
The application of the chi-square test and the results of the $p$ value with a significance level of 0.05 can be seen in Table 7. It is clear that the complexity of product quality control depends on the operation type, inventory management and industrial safety depend on the process type, and environmental management depends on the type of subsector. This is because the $p$ value result is less than the level of significance, so the null hypothesis is rejected and the alternative hypothesis is accepted. Likewise, it is established that the other associations between the various characteristics and elements are independent.

### 4 Conclusion

This research was based on the development of a statistical analysis of complexity in manufacturing systems. The study was applied in the manufacturing sector of the city of Cartagena, Colombia, taking as a sample the small and medium enterprises (PyMes) in the industry. Initially the analysis of the results obtained from the Likert technique allowed the identification of the characteristics linked to high complexity, then the application of an experimental study determined that the effect of the subsector factor is the same when the economic subsectors are contrasted and that the effect of the type of operation and type of processes are different when a comparison is made. The results show a dominant evidence of complexity in manufacturing systems, corroborating statistically that there is no significant difference when comparing the economic subsectors and the types of operations (MTO) and (MTS); however, when comparing the types of processes the type (FS) has a greater impact on complexity. By means of a factor analysis it was possible to establish that there are high correlations between the factors and by means of an associativity analysis the relationship between the study variables and the characteristics of

| Items                                | Subsector type | Operation type | Process type |
|--------------------------------------|---------------|----------------|--------------|
| Product design and development       | 0.2123        | 0.8339         | 0.5584       |
| Check the quantity of the product    | 0.1500        | 0.8339         | 0.0533       |
| Controlling the quality of the product| 0.2612        | 0.0409         | 0.1160       |
| Product distribution management      | 0.0563        | 0.4381         | 0.6605       |
| Define product lot sizes             | 0.4864        | 0.8728         | 0.0710       |
| Packing and packaging the product    | 0.9104        | 0.4791         | 0.6064       |
| Process design                       | 0.0787        | 0.6265         | 0.1614       |
| Process control                      | 0.2177        | 0.3418         | 0.5199       |
| Material handling management         | 0.8226        | 0.2683         | 0.8298       |
| Management of internal transport     | 0.4223        | 0.9716         | 0.6237       |
| Operational standardization          | 0.9480        | 0.5266         | 0.5815       |
| Measurement of work centers          | 0.1078        | 0.3195         | 0.9091       |
| Selection of equipment and technology| 0.7253        | 0.8792         | 0.9703       |
| Equipment maintenance management     | 0.8539        | 0.5973         | 0.0882       |
| Inventory management                 | 0.3597        | 0.2086         | 0.0375       |
| Process cost control                 | 0.2571        | 0.2405         | 0.0788       |
| Physical capacity and distribution   | 0.5432        | 0.8431         | 0.2971       |
| Working environment                  | 0.0545        | 0.3571         | 0.1881       |
| Industrial safety management         | 0.1570        | 0.5452         | 0.0412       |
| Environmental management             | 0.0473        | 0.5452         | 0.4615       |
| Occupational health management       | 0.1404        | 0.7487         | 0.4672       |
| Training management                  | 0.7621        | 0.4397         | 0.1864       |
| Ergonomics in the working            | 0.5946        | 0.6949         | 0.3469       |
| Ethics and the working environment   | 0.3023        | 0.1716         | 0.4653       |
| Motivation and incentive system      | 0.4368        | 0.7725         | 0.0794       |
| Work climate management              | 0.3561        | 0.4649         | 0.3802       |
| Management of demand forecasts       | 0.8509        | 0.4361         | 0.7077       |
| Capacity planning                    | 0.6615        | 0.9102         | 0.9276       |
| Production planning                  | 0.7810        | 0.9507         | 0.9638       |
| Material requirement planning        | 0.0724        | 0.2833         | 0.2747       |
| Resource requirement planning        | 0.3343        | 0.8424         | 0.7878       |
the manufacturing system. For future research, it would be useful to consider this result and develop measurements of total complexity in different scenarios, allowing a statistical analysis with respect to performance indicators.

Acknowledgements Thanks are due to the 71 small- and medium-sized enterprises in the manufacturing sector of the city of Cartagena, Colombia, for their access to technical visits, compilation of information, and support for the implementation of the instrument. Likewise to the Fundación Universitaria Tecnológico Comfenalco (FUTC), Investigation Group Ciptec, Universidad de la Costa (CUC)—Colombia and to the Universidad Nacional Lomas de Zamora (UNLZ)—Argentina, for the support of its academic and scientific group.

Declarations

Ethics approval The authors hereby state that the present work is in compliance with the ethical standards.

Consent to participate Not applicable.

Consent for publication The manuscript has not been published before and is not being considered for publication elsewhere.

Conflict of interest The authors declare no competing interests.

References

1. Salom G, Shulterbrandt S (2012) Microenterprises, SMEs and Latin America. In Inter Forum Magazine. Retrieved on (pp. 10–12)
2. Wolf J, Pett T (2006) Small-firm performance: modeling the role of product and process improvements. J Small Bus Manag 44(2):268–284. https://doi.org/10.1111/j.1540-627X.2006.00167.x
3. Escobar A, Velandia G, Hernández P (2017) Gestión del conocimiento e innovación en las PYME exportadoras del sector industrial en Colombia
4. Pine II B, Hull R (1995) Mass customization: the new frontier in business competition. R and D Manag 25(2):254
5. Michalos G, Makris S, Papakostas N, Mourtzis D, Chryssoulouris G (2010) Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J Manuf Sci Technol 2(2):81–91. https://doi.org/10.1016/j.cirp.2009.12.001
6. Vidal GH, Hernández JRC (2021) Study of the effects of complexity on the manufacturing sector. Prod Eng Res Devel. https://doi.org/10.1007/s11140-020-01014-2
7. Papakostas N, Papachatzakis P, Xanthakis V, Mourtzis D, Chryssoulouris G (2010) An approach to operational aircraft maintenance planning. Decis Support Syst 48(4):604–612. https://doi.org/10.1016/j.dss.2009.11.010
8. Herbert S (1962) The architecture of complexity. Proc Am Philos Soc 106(6):467–482. https://doi.org/10.2307/985254
9. Flynn B, Flynn E (1999) Information-processing alternatives for coping with manufacturing environment complexity. Decis Sci 30(4):1021–1052. https://doi.org/10.1111/1540-5915.1999.tb00917.x
10. Calinescu A, Efstratiou J, Bermejo J, Schirn J (1997) Assessing decision-making and process complexity in a manufacturer through simulation. IFAC Proceedings Volumes 30(24):149–152
11. Isik F (2010) An entropy-based approach for measuring complexity in supply chains. Int J Prod Res 48(12):3681–3696. https://doi.org/10.1080/00207540902810593
12. Gaiola L, Gino F, Zaninotto E (2002) I sistemi di produzione: manuale per la gestione operativa dell’impresa. Carocci
13. Bick W, Drexel-Wittbecker S (2008) Komplexität reduzieren: Konzept. Methoden. Praxis. LOG.X, Stuttgart
14. Salum L (2000) The cellular manufacturing layout problem. Int J Prod Res 38(5):1053–1069. https://doi.org/10.1080/002075400189013
15. Heragu S, Kusiak A (1988) Machine layout problem in flexible manufacturing systems. Oper Res 36(2):258–268
16. Meller R, Gau K (1996) The facility layout problem: recent and emerging trends and perspectives. J Manuf Syst 15(5):351–366. https://doi.org/10.1287/opre.36.2.258
17. Li S, Rao S, Ragu-Nathan T, Ragu-Nathan B (2005) Development and validation of a measurement instrument for studying supply chain management practices. J Oper Manag 23(6):618–641. https://doi.org/10.1016/j.jom.2005.01.002
18. Wu Y, Frizelle G, Ayral Y, Marsein J, Van der Merwe E, Zhou D (2002) A simulation study on supply chain complexity in manufacturing industry. En Proceedings of the conference of the manufacturing complexity network. University of Cambridge. https://doi.org/10.1016/j.cirpj.2019.02.001
19. Jacobs M (2007) Product complexity: a definition and impacts on operations. Decision Line 38(5):6–12. https://doi.org/10.1016/j.cirpj.2019.02.001
20. Ethymiou K, Mourtzis D, Pagaropoulos A, Papakostas N, Chryssoulouris G (2016) Manufacturing systems complexity analysis methods review. Int J Comput Integr Manuf 29(9):1025–1044. https://doi.org/10.1080/09519922.2015.1130245
21. Hernández S, Fernández C, Baptista L (2014) Metodología de la investigación. Investigación cuantitativa (p.5)
22. Tamayo M (2004) El proceso de la investigación científica. Editorial Limusa
23. Guimaraes T, Martensson N, Stahre J, Ighoria M (1999) Empirically testing the impact of manufacturing system complexity on performance. Int J Oper Prod Manag. https://doi.org/10.1108/01443579910294228
24. Bozarth C, Wasing D, Flynn B, Flynn E (2009) The impact of supply chain complexity on manufacturing plant performance. J Oper Manag 27(1):78–93. https://doi.org/10.1016/j.ijom.2008.07
25. Garbee L, Shikdar A (2010) Complexity level in industrial firms: case studies and implementation. En Proceedings of the 2010 international conference on industrial engineering and operations management (IEOM 2010). Dhaka, Bangladesh: International University of Bangladesh, p9–10
26. Eckstein D, Goullner M, Blome C, Henke M (2015) The performance impact of supply chain agility and supply chain adaptability: the moderating effect of product complexity. Int J Prod Res 53(10):3028–3046. https://doi.org/10.1080/00207543.2014.970707
27. Kooro D, Budde L, Friedli T (2017) Identifying complexity drivers in discrete manufacturing and process industry. Procedia CIRP 63:52–57
28. Alshammar F, Yahya K, Haron Z (2020) A conceptual approach in developing a project manager’s skills framework (PMSF) for improving the performance of complex projects in Kuwait construction industry. En IOP Conference Series: Materials Science and Engineering. IOP Publishing, p 012007
29. Saraph J, Benson PG, Schroeder RG (1989) An instrument for measuring the critical factors of quality management. Decis Sci 20(4):810–829. https://doi.org/10.1111/j.1540-5915.1989.tb01421.x
30. Sekaran U, Bougie R (2016) Research methods for business: a skill building approach. John Wiley & Sons

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.