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IMPROVING STATIC COMPLEXITY IN MANUFACTURING SYSTEMS: UNDER THE ECONOMIC LOT SIZING PROBLEM (ELSP) AND SINGLE MINUTE EXCHANGE DIE (SMED) APPROACH

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ABSTRACT
The application of modern methodologies focused on lean manufacturing such as Single Minute Exchange Die (SMED) generates benefits for companies, aimed at reducing setup times, reducing operational costs and increasing productivity. Its implementation requires the management of indicators that allow the evaluation and analysis of the system, in this case the entropic measurement of static complexity. This paper develops an experimental case based on the improvement of static complexity using the SMED methodology, a modern method that is not widely used in practice. The methodological proposal presents two scenarios, one where the Economic Lot Sizing Problem (ELSP) model is developed and the other where SMED is used. In both scenarios, static complexity is studied and calculated, and a comparative analysis is carried out. The results show that with the implementation of the technique the setup time is reduced by approximately 50%, the static complexity is reduced by 3.3% and the operational costs are reduced by 29.3%, constituting an important economic saving for the company that will be tangible in the medium and long term.

KEYWORDS: Static complexity, Manufacturing systems, SMED, ELSP.

MSC: 90B22 90B25

RESUMEN
La aplicación de metodologías modernas enfocadas en lean manufacturing como el Single Minute Exchange Die (SMED) genera beneficios para las empresas, orientados a reducir los tiempos de preparación, reducir los costos operativos y aumentar la productividad. Su implementación requiere el manejo de indicadores que permitan la evaluación y análisis del sistema, en este caso la medición entrópica de la complejidad estática. En este trabajo se desarrolla un caso experimental basado en la mejora de la complejidad estática utilizando la metodología SMED, un método moderno que no se utiliza ampliamente en la práctica. La propuesta metodológica presenta dos escenarios, uno donde se desarrolla el modelo de Problema Económico de Dimensionamiento de Lotes (ELSP) y otro donde se utiliza SMED. En ambos escenarios, se estudia y calcula la complejidad estática, y se realiza un análisis comparativo. Los resultados muestran que con la implementación de la técnica el tiempo de preparación se reduce en aproximadamente un 50%, la complejidad estática se reduce en un 3,3% y la complejidad estática se reduce en un 3,3% y los costes operativos se reducen en un 29,3%, constituyendo un importante ahorro económico para la empresa que será tangible a medio y largo plazo.

PALABRAS CLAVE: Complejidad estática, Sistemas de fabricación, SMED, ELSP.

1. INTRODUCTION

Since the beginning of this century, the competitiveness of markets has increased, characterized by products with short life cycles, uncertain demand, increased customization and rapid response to the customer by Chen et al. [14]. This situation leads to an increase in the complexity of production systems to respond quickly to these changes. According to Probst [52], complexity is defined as a characteristic of the system, which depends on the elements that conform or interrelate it. According to Sivadasan et al. [59], it is related to the variability between the actual and the planned. Similarly, Kochan et al. [43] state that it has a direct impact on the company's production indicators. From another perspective, Jensen and Heckling [37] state that a company tends to be less complex when the specific information relevant to decision making is at hand, regardless of the number of assets, organizational units or people in the organization. Studies on complexity in modern times tend to be indispensable and fundamental for modern organizations by Bozarth et al. [11], which is why it is important to manage it. According to Modrak and Soltysova [49], this has begun to be considered as a new form of evaluation of industrial companies, being one of the tools for improvement analysis and business restructuring. Complexity can be divided into static and dynamic, according to Gaio et al. [22], static complexity is one in which the variables do not change over time and dynamic complexity is when the variables evolve with respect to time.
In the literature, different approaches and methods for measuring complexity are distinguished, with nonlinear dynamics, information theory (Shannon's Entropy) being the most widely used, which are based on analytical equations and show a

positive trend in mathematical models, hybrid methods and enumeration by Vidal et al. [64]. Regardless of the type of method used, the measurement of complexity in manufacturing systems will allow managers to study, evaluate and analyze the system and facilitate decision making. According to Modrak and Marton [48] this metric serves as a parameter to establish improvement plans based on actions and methodologies that guarantee an optimal performance of the operations. These methodologies are part of the Lean philosophy that has its beginnings since the era of the first concepts of scientific management in the field of operations by Herrera et al.[31], whose purpose is to eliminate the "Muda" which is a Japanese term, meaning "elimination of waste" by Sarai [56]. It consists of a continuous improvement that brings together different methods: (i) Value Stream Mapping - VSM. (ii) Five Eses - 5S's. (iii) Total Productive Maintenance - TPM. (iv) Single Minute Exchange of Die - SMED. (v) Six Sigma. (vi) Kaizen, among others.
According to Bajpai [8] the SMED methodology was developed in Japan by Shiegeo Shino in the 1950s, which can be applied to any process without the need for high volumes of investment. According to Garcia et al. [23] it aims to reduce the setup time of a machine or equipment. Considering this time as the time needed to set up the production line from the end of the last product to obtain a new good product by Ulutas [62]. Optimizing this variable to one digit and in units of minutes by Arai and Sekine [4]. The benefits are the reduction of waste and scrap by Hasabe et al. [28]; flexibility in the production line Garcia et al. [23]; reduction of batch sizes Hasabe et al. [28] and higher productivity Lozano et al. [46].
The start-up or implementation involves the development of so me external and internal activities. According to Shingo [58] external configuration activities are those that can be executed while the system is running and internal can only be performed when the system is stopped. According to Dillon and Shingo [18] five steps should be addressed (i) Observing and recording, (ii) Separation between internal and external tasks, (iii) Converting the maximum number of internal tasks to external tasks, (iv) Streamlining all possible tasks and (v) Documentation of internal and external procedures.
This paper develops an experimental case based on the improvement of static complexity using the SMED methodology. It is divided into four sections, first the work related to the subject is developed, followed by the methodology, then the results are presented and finally the conclusions.

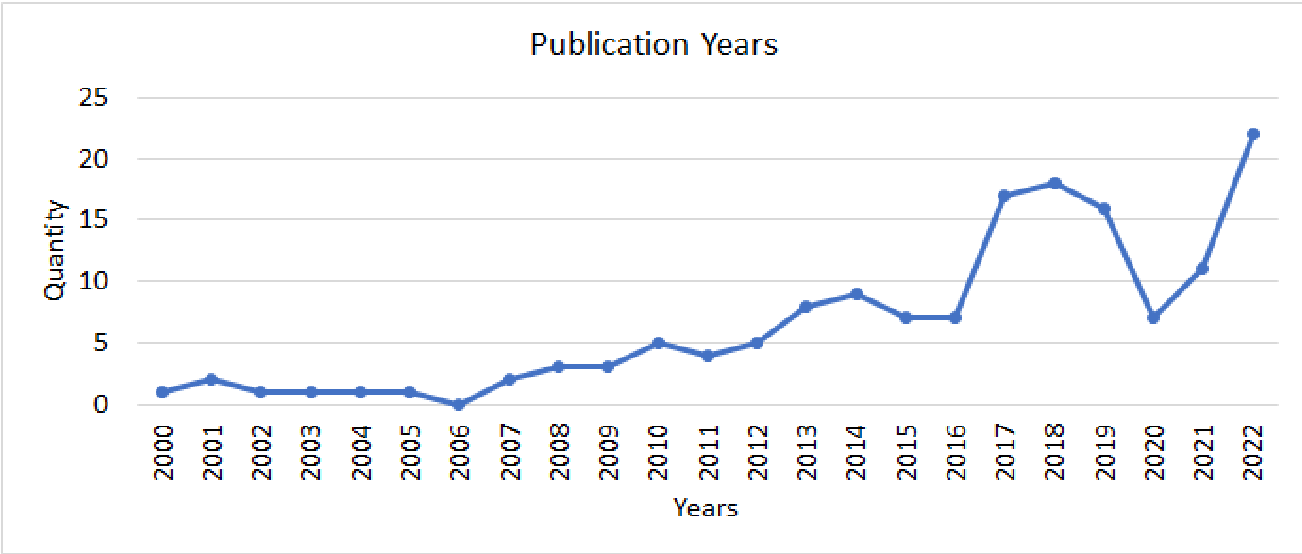
2. RELATED WORK

The theoretical foundation for the research is carried out on the basis of related works: (i) Single Minute Exchange of Die – SMED, and (ii) Static complexity.

2.1 Single Minute Exchange Die (SMED)

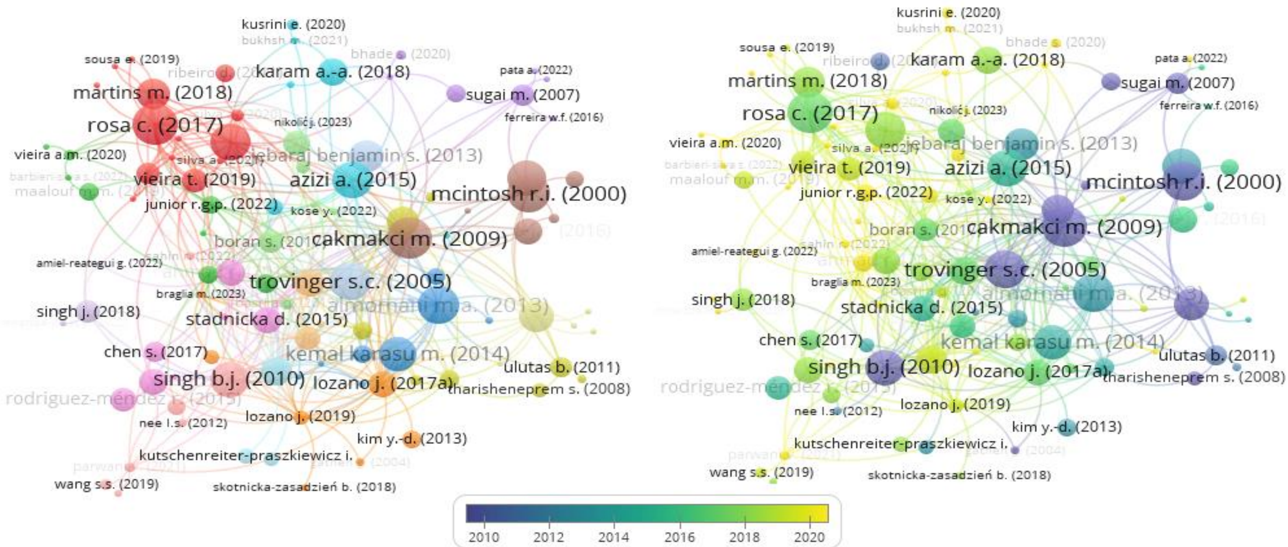
The Single Minute Exchange Die (SMED) system was born as a set of concepts and techniques that aim to reduce set-up or changeover times from one product to another by Ahmad and Soberi [2]. According to Shingo [58] it is translated as the rapid change of tooling in less than ten minutes. Its creation is attributed to the Japanese Shigeo Shingo in the automotive industrial sector by Godina et al. [24]. Its application began in 1950 at Mazda, Hiroshima, then in 1957, at Mitsubishi, Hiroshima, and subsequently at Toyota, Nagoya in 1969 by Shingo [58]. Starting from the need for frequent interruptions due to unproductive time lost in the process by Alves andTenera [3]. This proved to be an obstacle if better levels of efficiency and effectiveness were to be achieved Dillon and Shingo [18]. Rapid tooling change is the core of the SMED methodology and finds a solution to the above described, in search of higher productivity by Henry [29]. This is made possible by reducing the time spent on set-up activities while the machine is running and simplifying the remaining steps to keep production flowing smoothly by Jebaraj et al. [36]. Tool changeover time being the time elapsed between the last manufactured compliant product of the previous series, to the first produced compliant product of the next series by Dillon and Shingo [18]. Methodologically, SMED has been divided into internal and external operations by Kurniawan et al. [45]. Turning internal operations into external operations, making tooling changeover a flexible process with the necessary resources and giving rise to the concept of economic batch quantity and decreased product manufacturing times by Azizi and Manoharan [7]. According to Patel et al. [50] internal setup is only performed when the machine is off and external setup when the machine is running. This is where improvements arise that provide significant savings in operation times and costs, comparing the current and proposed method by Dillon and Shingo [18].
A review of the literature, based on the production of scientific articles published in the Scopus databases associated with the "SMED" theme, between 2000 and 2022, shows a total of 151 documents. Figure 1 shows a trend of growth in the number of total records. It should be noted that during the first decade, 20 papers were published, representing 13% of the publications, this being a less productive period; in contrast to the last 12 years, which reflects 87% represented by 131 papers, showing a period of greater production. The trend clearly highlights the interest of the scientific and academic community in this area of knowledge.

Figure-1. Production and trend in the Smed field



A data analysis was carried out using VosViewer software. Figure 2 shows the most cited articles in the field of "SMED" in Scopus databases, with the works developed by Petersen, C., (2008) standing out with 274 citations, followed by Rosa, C., (2017) with 69 citations; then appears Cakmakci, M., (2009) with 68 citations; followed by Mcintosh, R., (2000) with 60 citations and Trovinger, S., (2005) with 56 citations.

Figure-2. Most cited articles in Scopus database



In addition to this, recent research carried out by Braglia et al. [12] who present a new Lean tool called Setup Saving Deployment (SSD), which improves the efficiency of setup by classifying, analyzing and eliminating setup losses within a change process, and supports decision making for SMED implementation. Next is the work developed by Junior et al. [38] who addressed a case study, based on the implementation of a new single minute exchange of dies (SMED) framework in an oil and gas company, the results showed a decrease in setup times and increase in the level of efficiency. Next comes the article developed by Kose et al. [44] which evaluates the ergonomic part of the configuration process by integrating multi-criteria decision making in SMED, the proposed model was validated by applying it to a real manufacturing system in the household appliance supplier industry, showing a reduction in set-up time and ergonomic improvement. Similarly, the study developed by Afonso et al. [1], which integrates the principles of Lean Manufacturing and Ergonomics in organizations to increase productivity and improve working conditions simultaneously, allowing the integrated application of SMED and ergonomic analysis in a metallurgical factory, stands out. Another one that stands out is the article by Şahin and Kologlu [55], who conduct a case study in a bearing manufacturing company to reduce machine setup time in the turning line using SMED, the main results indicate that machine setup times were reduced by more than 45% in the turning line and machine capacities increase satisfactorily.

2.2 Static Complexity

Complexity in a manufacturing system is the interaction of the various elements that make up the system, such as plant, products, process, parts and planning by Herrera and Coronado [30], which depends on the volume and variety of the elements by Elmaraghy et al. [20]. According to Herrera and Coronado[30] the first definitions of complexity appear in 1963 with the theory of Ashby [6], only complexity absorbs complexity, suggesting that the greater the complexity, the more control is needed in the system. Consistent with this, De Rosnay [15] establishes that complex systems are those with greater heterogeneity in each of their elements. Another pioneer who stands out is Yates [68] who identifies that complexity depends on the size of the system, randomness and asymmetry. Then Klir [42] in his research specifies that the greater the volume of information, the greater the complexity.

According to Wiendahl and Scholtissek [67] complexity in industrial manufacturing can be divided into complexity of the products themselves and complexity of production. Production can be further subdivided into production structures (structural complexity) and production processes (dynamic complexity). According to Deshmukh et al. [17] the static complexity of manufacturing systems depends on the structure of the system, the variety of subsystems and the strength of interactions. For Bronner [13] the dynamic type comprises the variation of system behaviour over time. In a review of the literature developed by Herrera and Coronado[30] they establish that in static complexity there are sources that generate complexity such as the quantity and variety of products, the number of parts, the structure of the product, the number of machines and work centers and the distribution in the plant. In contrast, in dynamic complexity, the sources are production volume, planning and scheduling, and uncertainty in the system.

A review of the literature, based on the production of scientific articles published in the Scopus databases associated with the subject "Complexity in manufacturing", between 2000 and 2022, shows a total of 304 documents. Figure 3 shows a trend of growth in the number of total records, showing a progressive growth in research interest and relevance of the subject in modern times.

Figure-3. Production and trend in the field of Complexity in manufacturing

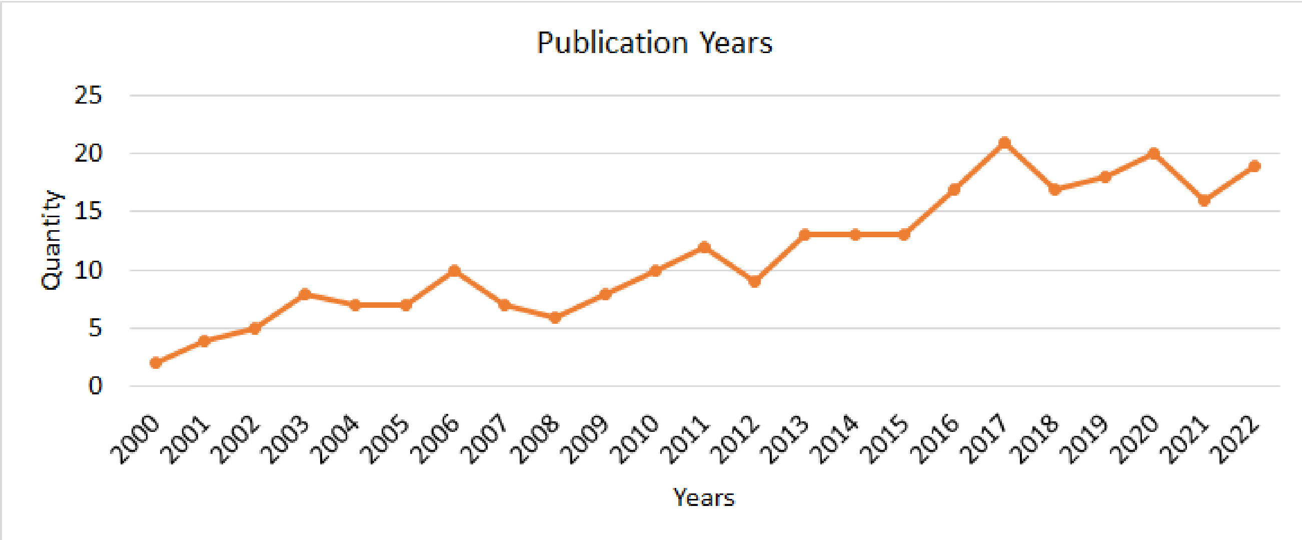
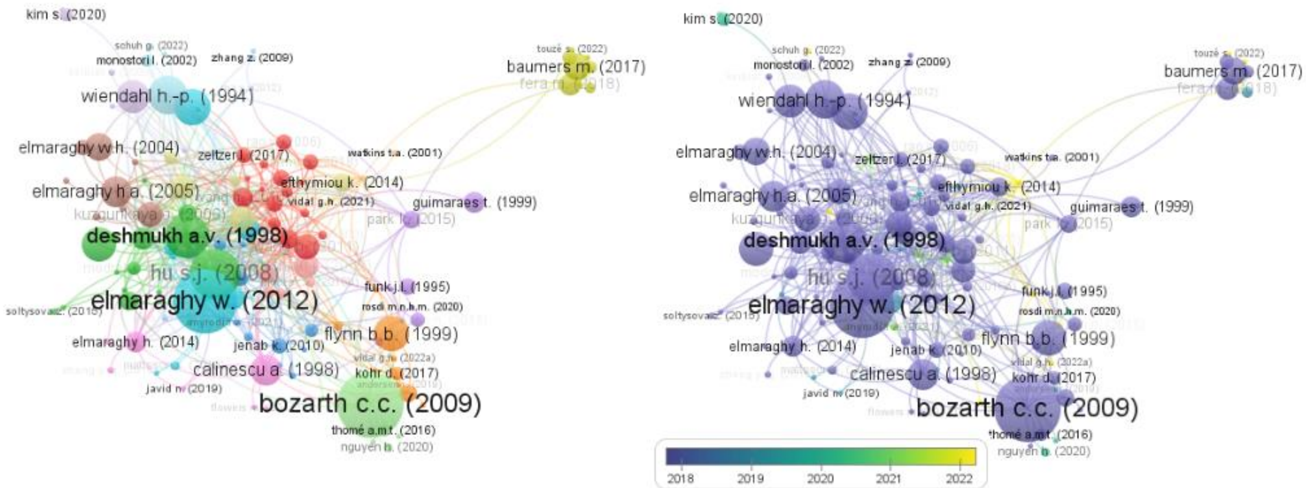


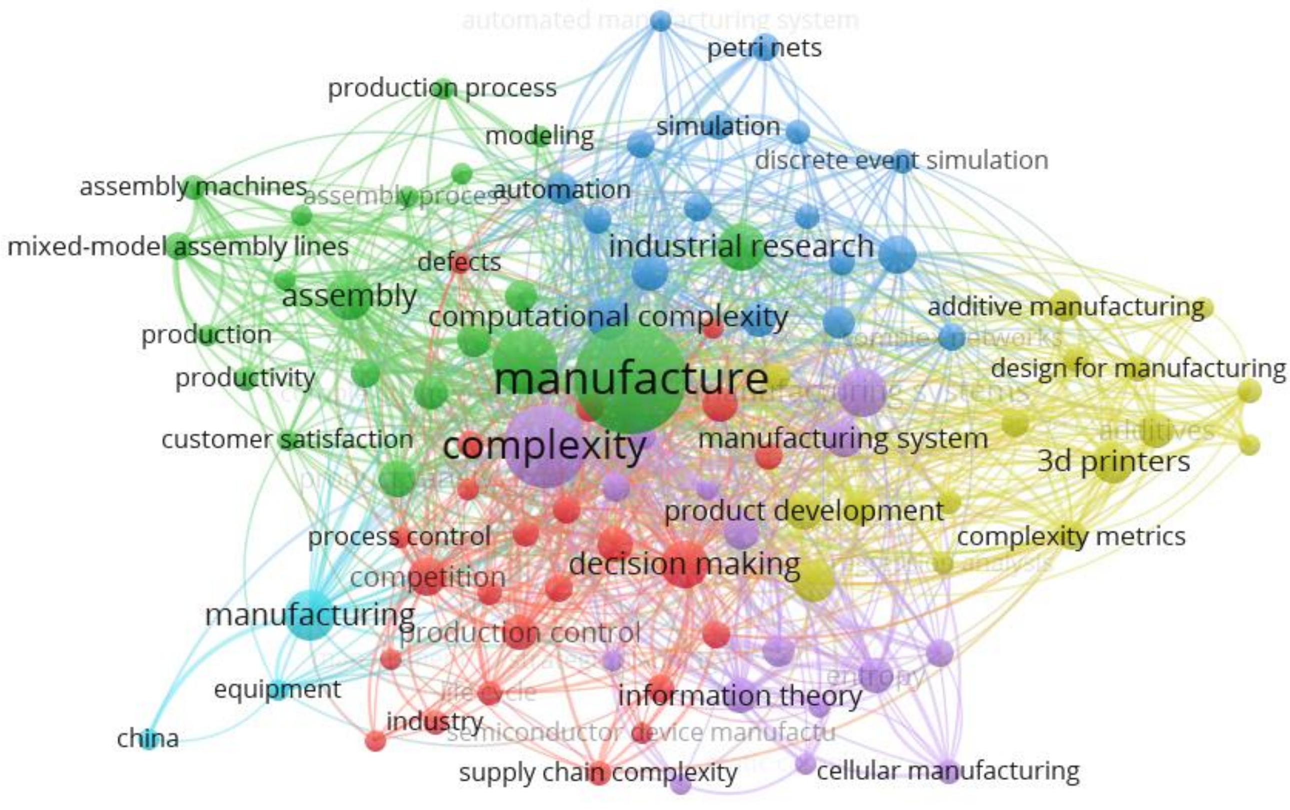
Figure 4 shows the most cited articles in the field of "Complexity in manufacturing" in the Scopus databases, with the works developed by Bozarth, C. (2009) with a total of 502 citations, followed by Elmaraghy, W. (2012) with 471 citations, then appears Hu, S. (2008) with 292 citations, followed by Deshmukh, A, (1998) with 221 citations and Plotkin, S. (2017) with 201 citations.

Figure-4. Most cited articles in Scopus database



In a review of the literature, considering the most recent and highly interactive articles, Jayapal et al. [35] propose a complexity metric based on view similarity to guide part selection in additive manufacturing, the metric helps to improve the selection process by objectively screening a large number of parts and identifying the most suitable parts. In the same year, Peralta [51] make a process of complexity management proposing a framework to guide the design and development of sustainable and fractal manufacturing systems, this management is developed through its configuration, as occurs with natural ecosystems, providing the opportunity to adapt production systems to the new complex contexts of industry 4.0. This is followed by the article developed by Hanif et al. [26] where they order the elements of internal complexity of manufacturing in terms of priority over the period of improving sustainability, these elements were grouped into organizational, operational and productivity complexity, applying the fuzzy analytical hierarchical process as a method of decision making with multiple criteria in management.

Figure-5. Most related key words in Scopus database



This is followed by the work developed by Schuh et al. [57] who present a data-driven approach to create transparency and derive recommendations for complexity reduction measures by applying cluster analysis methods to production data. The results are validated using the case of a German parts manufacturer, using a process similarity index. This is followed by the article by Vidal et al. [66] who develop a statistical analysis of the complexity of a manufacturing system, identifying characteristics associated with high complexity, investigating the factors that have a significant

influence based on an experimental analysis and finally evaluating the association between the complexity of the manufacturing characteristics and the complexity of the elements of a system. Similarly, the study developed by Kim et al. [41] characterizes a measure of complexity and identifies the impact of complexity on operational performance in a manufacturing system. To do so, they define design complexity by considering both the volume ratio and the area ratio of a part design. The results show that design complexity negatively affects the average lead time of the system. In the same year, the authors Touzé et al. [61] present a methodology, together with their software implementation called "Design 2 Cost", to evaluate the manufacturing cost and complexity of a part. In parallel, Tlija and Al-Tamimi [60] in their research propose a decision-making system that takes into account emerging manufacturing processes, such as additive manufacturing and hybrid manufacturing, and tracks product changes. Based on manufacturing complexity and cost. Vidal et al. [65] also stand out, developing a modelling and statistical analysis of complexity in manufacturing systems under flow shop and hybrid environments, the results obtained corroborate the proposed hypotheses, where statistically the structural design factors and the variation of production time per stage significantly influence the response variable associated with the total complexity, likewise, they show that there is a correlation between the performance indicators and the studied variable, highlighting the incidence with production costs. In the same year, Vidal and Hernández [63] identify the effects and factors that generate complexity in an economic sector, based on the instrument developed by the University of Bayreuth, which makes it possible to identify effects, factors, methods and management indicators.
From the information obtained from the Scopus database, the keywords were taken, using VosViewer software. The analysis identified a total of 1928 keywords, with a minimum co-occurrence threshold of 1 times per word (see figure 5). It is worth noting that the size of the nodes and the letters provide higher frequency. Six clusters identified with different colours were identified. The words that stand out are those that frame a network associated with complexity in production systems, in aspects associated with product and process design, product variety, production control and the application of lean or flexible manufacturing systems. This can be corroborated by recent research work developed by Vidal et al. [64] who emphasize that complexity management is oriented towards mass customization and lean strategies, low cost, agile, flexible and efficient designs. Another study in Vidal and Hernández [63] identify the improvement methods that can be applied for an adequate management of complexity and distinguish the methodologies of the lean manufacturing philosophy, especially the optimization in the configuration of set-up times by means of SMED. Herein lies the innovative element of this research, given the little relation in the applicability of modern methods of agile manufacturing operations with respect to the measurement of complexity in systems, being a new indicator that serves as a parameter in decision-making.

3. METHOD

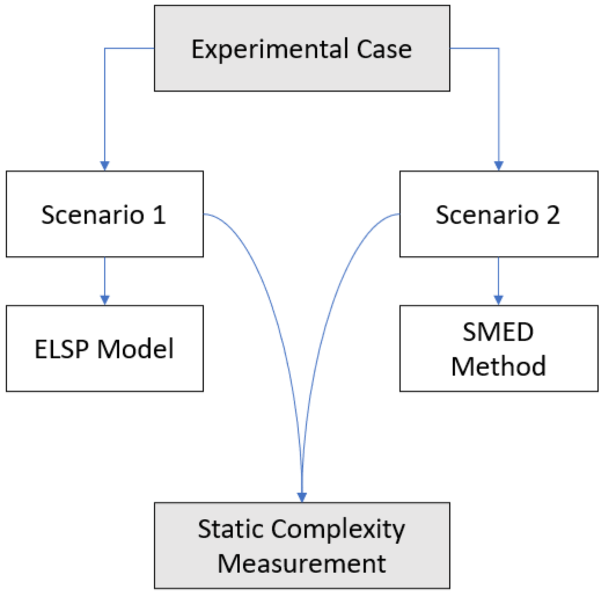
Methodologically, in order to carry out the research, an experimental case is needed, composed of two scenarios, a first scenario where the ELSP model is developed and a second where the SMED methodology is addressed, in both of which the static complexity is studied and calculated, and a comparative analysis is developed (see figure 6).

3.1 Experimental Case

For the experimental case, a private company in the lithographic sector in the city of Cartagena - Colombia was used as a reference. Within the process, priority was given to the machine with the highest volume of work flow and high frequency of reference changes. It should be noted that the set-up and set-up times depend on the mechanical configuration, die changes and cleaning of the components. Given the above, a controlled experiment was conducted with n-products on a single machine with a finite production capacity. One of the assumptions is that the demand for the products is stationary and known. The experiment is carried out by means of two scenarios that will serve as a comparative basis. The first scenario consists of an installation in which n products are processed in a machine; the planning of this system will be carried out based on the Economic Lot Sizing Problem (ELSP) model and the static complexity of the system is calculated from the entropy. The second scenario is performed using the same data, but applying the Single Minute Exchange Die (SMED).
In this phase, the hypotheses are formulated:

H0: The application of the SMED method does not reduce the static complexity of the system.
H1: The application of the SMED method does reduce the static complexity of the system.

Figure-6. Methodological proposal



3.2 Scenario 1 - ELSP model

One of the first formal approaches to the problem can be found in Rogers [54]. Since then, a multitude of approaches have been addressed in the literature, and multiple variants of the problem have been defined. The traditional and most widespread definition assumes the following assumptions by Bomberger [10]: (i) The machine produces a single item at each instant, (ii) Production capacity is limited, but sufficient to satisfy demand, (iii) Production rates are deterministic and constant, (iv) There is a setup cost and time associated with the release of batches of items, (v) Setup times and costs are sequence independent, (vi) Demand rates are deterministic and constant, and (vii) Inventory costs are directly proportional to inventory levels.
Most of the mathematical models used for production planning are based on models for determining lot sizes by Rizk and Martel [53]. Lot sizing is the quantity of units to produce of a set of items over a planned time horizon. When demand is constant, decision makers are interested in determining the production cycle for multiple items over an infinite time horizon, seeking to minimize machine set-up costs and inventory and/or shortage costs by Hsu [32]. The ELSP model is an Np-Hard model by Khouja [40]. The ELSP planning problem is shown in equation 1. It is evident that the model seeks the minimization of the total annual costs; and it is composed of the setup costs and the storage costs. The model is subject to the capacity constraint within the production cycle (see equation 2 and 3).
Several approaches have been found to find good solutions in the ESLP model by Khouja [40]. In this research work, the common cycle (CC) approach introduced by Hansmann [27] will be used.

$$\min TC = \sum_{J=1}^{n} \left(\frac{k_j}{Q_j} + \frac{h'_j Q_j}{2} \right) \quad (1)$$

Subject to:

$$Q_j = \lambda_j T((\quad (1)$$

$$\sum_{j=1}^{n} \left(s_j + \frac{\lambda_j T}{p_j} \right) \leq T \quad (2)$$

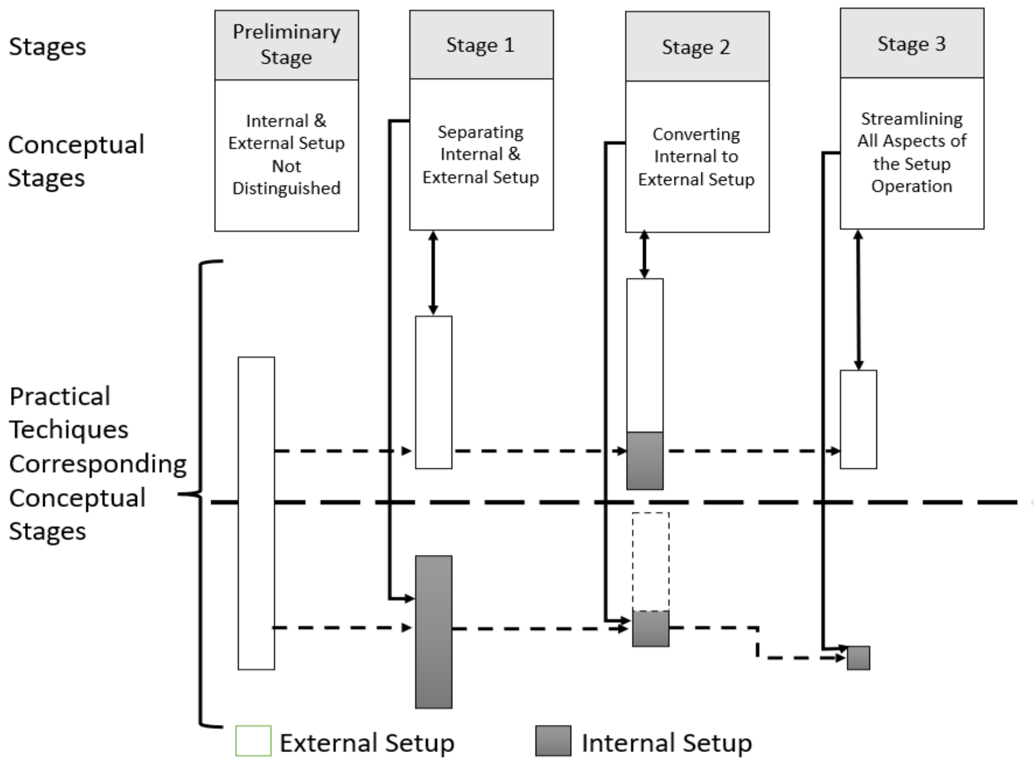
Where:

- kj: Preparation costs
- Qj: ELSP lot size
- hj': Storage cost
- Sj: Setup time
- λj: Annual demand
- Pj: Production rate
- T: Cycle time
- TC: Total Minimum Cost

3.3 Scenario 2 - SMED Method

According to Desai and Warkhedkar [16] the SMED methodology includes three main steps, (i) Separation of internal and external configuration, this includes tools such as the use of checklists, the definition of roles for each worker and the improvement of tool transport. (ii) Conversion of internal setup to external setup, supported by pre-preparation of setup operations, automation of operations and use of different tools and (iii) Simplification of all aspects of the setup operation, by improving tool transport and storage, elimination of set-ups, calibrations and adjustments and automation of operations (see figure 7).

Figure-7. Stages of the SMED methodology



Source: Adapted from Desai, M. & Warkhedkar, R. (2011)[60].

3.4 Measuring Static Complexity

The measurement of static complexity will be done from the perspective of information theory. This will be done by calculating the entropy of the system through the amount of information expected to describe the state of the system. Information theory has been the most widely used technique for measuring complexity in manufacturing systems and in supply chains by Vidal et al. [64]. The complexity calculation is performed for a whole year's data. For this purpose, the probability of the resource states must be calculated, taking into account the set-up times, the production time and the idle time in the system. The static complexity is calculated as shown in equation 4.

$$HSR = -\sum_{i=1}^{M}\sum_{j=1}^{N_j} p_{ij}\log_2 p_{ij} \qquad (3)$$

Where, M represents the number of productive resources, Nj the possible states of the system (setup, production, idle) and Pij the probability that resource j is in state i. This measure shows the intrinsic difficulties of the process to produce a number of parts in a time interval. The first application of entropy was made by Karp and Ronen in 1992 [39] when measuring the dynamic complexity in a manufacturing system. Entropy as a measure of complexity has been used to analyze manufacturing shops by Vidal et al. [64]. An entropy-based tool has also been used in the development of a tool to calculate static, dynamic and decisional complexity for production systems by Efstathiou et al. [19]. In assembly lines to determine the best assembly configuration by Fujimoto et al. [21] and for line balancing with mixed models to minimize complexity by Hu et al. [33] In the organization of business processes in manufacturing by Arteta and Giachetti [5] and in the comparison of different production scheduling techniques by Huaccho et al. [34]. In Herrera and Coronado

[30] a measure of the total static and dynamic complexity in the supply chain is proposed. In Vidal et al. [66] the static complexity measure is used to identify the best configuration that has possible influence on supply chain performance.

4. RESULT

This section presents the results obtained separated by sections, (i) Scenario 1 - ESLP Model and (ii) Scenario 2 - SMED Method.

4.1 Scenario 1 - ESLP Model

This scenario consists of adding products iteratively up to a maximum of 7 products to be processed in this machine, where each of them has a constant demand. Table 1 shows the characteristics of each of the products.

Table 1. Product data, batch sizes and their total cost

SKU		P1	P2	P3	P4	P5	P6	P7
Annual Demand	Di	4520	6600	2340	2600	8800	6200	5200
Production Rate	Pi	35800	62600	71000	41000	46800	71200	56000
Setup Time (hr)	Si	3	2	5	2	5	3	5
Holding Cost (usd)	h'i	7,7	5,1	10,8	3,8	6,8	5,6	6,2
Setup Cost (usd)	ki	330	220	550	220	550	330	500

Given the above, the batch sizes are calculated by applying the ELSP model based on the Common-Cycle-Approach (Common-Cycle-Approach) model proposed by Hansmann [27], which seeks to obtain cyclic co-production schedules of a given duration (Common-Cycle) that are repeated periodically for a multi-product system. The mathematical model was built and solved using the optimization software GAMS version 24.1.3, by means of a MINLP (Mixed Integer Non-Linear Programming) optimization problem with a T=0.15. Applying equation 1, the results are shown in table 2. It is assumed that the company has a total available time for production of 2000 hours per year.

Table 2. Results of the ESLP model with T= 0.15

SKU	Dj/Pj	Qj	Annual Cost	Setup Time	Make Time
P1	0,13	698,22	4.820,95	19,42	252,51
P2	0,11	1.019,53	4.034,18	12,95	210,86
P3	0,03	361,47	5.510,59	32,37	65,92
P4	0,06	401,63	2.189,30	12,95	126,83
P5	0,19	1.359,37	8.175,54	32,37	376,07
P6	0,09	957,74	4.827,53	19,42	174,16
P7	0,09	803,27	6.046,57	32,37	185,71
Total Annual Cost			35.604,66	Idle Time	446,10

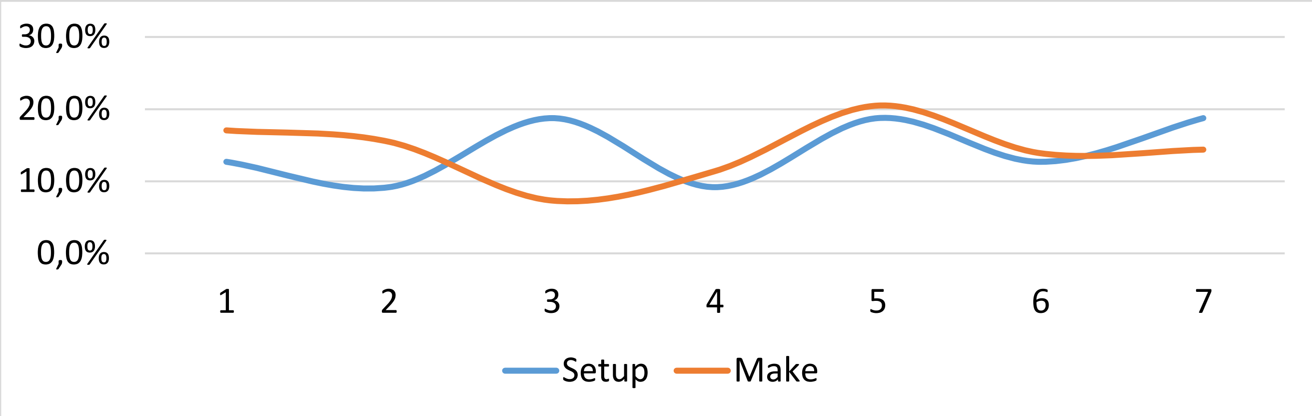
Continuing with the methodological proposal, based on the results obtained and using equation 4, the static complexity is calculated. The calculations show a complexity equal to 3.207 bits. Table 3 shows the calculations of this indicator.

Table 3. Calculation of the static complexity from the ESLP model

SKU	Probability		Static Complexity	
	Setup	Make	Setup	Make
P1	0,010	0,126	-0,065	-0,377
P2	0,006	0,105	-0,047	-0,342
P3	0,016	0,033	-0,096	-0,162
P4	0,006	0,063	-0,047	-0,252
P5	0,016	0,188	-0,096	-0,453
P6	0,010	0,087	-0,065	-0,307
P7	0,016	0,093	-0,096	-0,318
Idle Probability		0,223	Idle Complexity	-0,483
Total Static Complexity			3,207	

This complexity index measures variety, being most affected by manufacturing at 69%, by setup at 16% and by idle at 15%. In fact, the occurrence of the idle state corresponds to a reduced complexity. A more detailed analysis to investigate the effect of each product on the static complexity can be seen in figure 8, where products 3, 5 and 7 stand out for setup with 18.8% and product 5 for manufacturing, the latter having the highest incidence in both aspects.

Fig. 8. Incidence of products on static complexity



4.2 Scenario 2 - SMED Method

Based on the methodology discussed in the previous section, each of the stages is carried out, (i) Separation of the internal and external configuration, using a checklist with time records to identify internal and external activities, such as preparing the matrix, preparing cleaning products, preparing inks and cleaning the matrix.

Table 4. Results of the ESLP model with T= 0.11

SKU	Dj/Pj	Qj	Annual Cost	Setup Time	Make Time
P1	0,13	493,72	3.408,92	13,73	252,51
P2	0,11	720,92	2.852,60	9,16	210,86
P3	0,03	255,60	3.896,58	22,89	65,92
P4	0,06	284,00	1.548,07	9,16	126,83
P5	0,19	961,22	5.780,98	22,89	376,07
P6	0,09	677,22	3.413,58	13,73	174,16
P7	0,09	567,99	4.275,57	22,89	185,71
Total Annual Cost			25.176,30	Idle Time	493,50

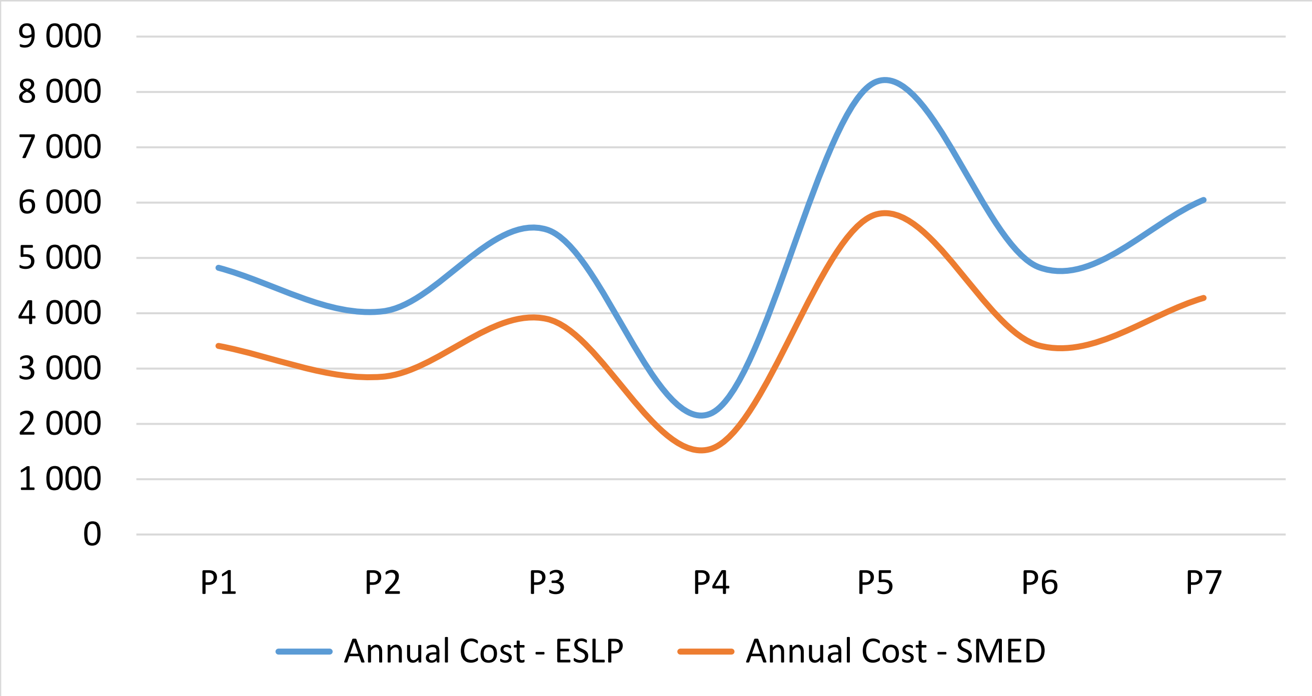
Similarly, activities that do not add value to the process were eliminated, and activities were developed taking advantage of the idle product of the previous order. (ii) Conversion of internal configuration into external configuration, this stage is implemented with the support of the expert responsible, based on the information provided. (iii) Simplification of all aspects of the configuration operation, using the implementation of formats to guarantee the execution and control of the operations. This leads to a reduction in setup times of approximately 50%. The calculation of the batch sizes is applied from the ELSP model based on the common cycle with a T=0.11 and the results are shown in table 4. Based on this information, the setup, make and idle probabilities are calculated. The calculations show a complexity equal to 3,102 bits. Table 5 shows the calculations of this indicator.

Table 5. Static complexity calculation from the SMED method

SKU	Probability		Static Complexity	
	Setup	Make	Setup	Make
P1	0,0069	0,1263	-0,049	-0,377
P2	0,0046	0,1054	-0,036	-0,342
P3	0,0114	0,0330	-0,074	-0,162
P4	0,0046	0,0634	-0,036	-0,252
P5	0,0114	0,1880	-0,074	-0,453
P6	0,0069	0,0871	-0,049	-0,307
P7	0,0114	0,0929	-0,074	-0,318
Idle Probabiity		0,2468	Idle Complexity	-0,498
Total Static Complexity			3,102	

According to the results with respect to the complexity, manufacturing represents 71%, setup 13% and idle 16%, showing an improvement with respect to the calculations with the ELSP model. In the same way, the same products continue to stand out for both setup and manufacturing. A comparison of the overall results shows a decrease in static complexity by 3.3% and total costs by 29.3%. In figure 9 it is evident that the costs per product are lower when SMED is implemented, with products 3, 5 and 7 standing out with high costs due to their correlation with complexity. In summary, the results respond to the hypothesis and corroborate the alternative hypothesis (H1) that the application of the SMED method does reduce the static complexity of the manufacturing system.

Fig. 9. Comparison of total annual costs per product



5 DISCUSSION

The industrial environment is becoming increasingly complex and competitive where organizations must respond to different market conditions by reconfiguring their processes, products and services. Regarding static complexity, it has been studied that it has a negative effect on productivity and quality by Macduffie et al. [47], due to the variety of components, parts, machines, equipment, tools, activities and tasks. Generating difficulties in the design and operation of production lines by Hu [33], as well as Vidal et al. [65] that it has an impact on operational costs. Studies by Bick and Drexl [9] state that 25% of the total costs of manufacturing companies are due to complexity within the process. The above is an enabling scenario to look for different and innovative approaches to reduce, avoid or control complexity. The literature review shows that the thematic axes are increasingly studied by the scientific community and that the theory of competition is of high interest in recent years, since it is immersed and latent in manufacturing systems, due to the instability and uncertainty in the components of the process.

The methodological proposal addresses a scenario with the ELSP model and another with SMED, allowing a comparative experimental analysis, being this evaluation not very widespread in practice. From equation 4, the calculation of the static complexity is determined, the results show an index of 3.207 bits for scenario (1) and 3.102 bits for scenario (2), representing a negative variation rate of 3.27%. In synthesis the investigative work allowed to obtain satisfactory findings that support the decision making in the managerial levels of the companies, the hypotheses raised are corroborated, showing the economic saving in the production costs.

6 CONCLUSIONS

The management of complexity is essential to evaluate and analyze production systems, providing support to decision-makers. For this it is important to identify it, measure it, reduce it or eliminate it, being possible from the identification of the factors, effects and methodologies oriented to the continuous improvement of the processes. This research work develops an experimental case based on the improvement of static complexity using the SMED methodology, a modern method that is not widely used in practice, which allows the reduction of machine changeover time, directly impacting on productivity, efficiency and operational costs. Initially, a review of the literature is made in which the little relation of its applicability with respect to the measurement of the complexity in the systems is abstracted. The methodological proposal proposes two scenarios, one where the ELSP model is developed and the other where the SMED is approached, in both of which static complexity is studied and calculated, and a comparative analysis is developed. For its development, a set of seven (7) products is established in the same machine that has a finite production capacity, with the assumption that the demand for each one is stationary and known. The results show that with the implementation of the SMED technique, the reduction of setup time is reduced by approximately 50%, as well as a reduction of static complexity by 3.3% and total costs by 29.3%. The products with the greatest impact on this indicator are identified as 3, 5 and 7. The findings respond to the hypothesis put forward and corroborate the alternative hypothesis (H1) that the application of the SMED method has a positive impact on the reduction of static complexity in manufacturing systems, constituting a significant economic saving for the company that will be tangible in the medium and long term. As future bets, it is recommended to experiment with the type of dynamic complexity, supported with discrete event simulation techniques, as well as to develop the ELSP model with stochastic demand parameter and apply other types of methodologies of the lean philosophy.

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