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Evolution and application of Lean manufacturing in the production industry: advances and trends (2015-2025) through neutrosophic cognitive mapping analysis of critical success factors

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Abstract. This article examines how Lean manufacturing evolved between 2015 and 2025—a decade marked by rapid technological disruption and the rise of artificial intelligence (AI). The research identifies critical success factors of Lean and analyzes how AI has reshaped its implementation. To address the uncertainty and complexity of expert evaluations, Neutrosophic Cognitive Mapping (NCM) is used as a methodological tool. NCM not only maps interrelated success factors but also incorporates the ambiguity inherent in human and technological assessments. Results show that AI boosts Lean's effectiveness through predictive analytics and inventory optimization but reveals limitations when workforce training is insufficient. This intersection of Lean and AI provides valuable insights into how their convergence enhances industrial competitiveness, sustainability, and cost efficiency. While prior studies explored Lean's fundamentals, few have focused on its transformation through AI. This research fills that gap, highlighting intelligent automation as a key breakthrough and offering practical guidance for implementation in diverse manufacturing contexts. Ultimately, the study contributes both theoretically and practically, helping industries adopt Lean practices for an AI-driven world.

Keywords: Lean Manufacturing, Artificial Intelligence, Production Industry, Neutrosophic Cognitive Mapping, Critical Success Factors, Sustainability.

1. Introduction

Lean Manufacturing has been an approach to maximizing efficiency and minimizing waste and has become one of the pillars of the manufacturing industry over the years, especially from 2015 to 2025, a period that has been integrated by the introduction of new technologies [1]. This article will study the transformation and applicable sectors of this initiative and, in the areas of critical success factors, will analyze how this has happened in the past. The importance of Lean Manufacturing through the decades is undeniable because, with sustainability, industrialization, and competitiveness as global goals, it is important to investigate these keys. Recently, it has been shown that Lean is a living concept, that adapts to new situations, especially when it was shown to benefit from digital tools. Historically, the basic principles of Lean were inferred in Japan after World War II and widely adopted, with Toyota being the first brand to implement it in its life cycle [2]. From 2015 to 2025, the growth of the Internet and automation from the Fourth Industrial Revolution has made it a more digitalized concept in the last decade, especially with Machine Learning and the Internet of Things. , allowing adjustments in production by managing ' big data' [3]. Between 2015 and 2025, a transformation towards a more agile industry has been seen, although sometimes confronted with significant problems, from organizational resistance to technological transformation and training [4]. However, not everything is known yet. What are the critical factors between 2015-2025 that have shaped its evolution and failures 2015-2025 in all parts of the world, with a focus on the contemporary world full of ambiguity The problem is that no critical factor has been discussed from a combination of both technical and human that recognizes contemporary ambiguity [5]. This article will solve it through an innovative approach.

The purpose of this research is twofold. First, to answer the posed question by analyzing the results of Lean in the manufacturing industry from 2015 to 2025 using neutrosophic cognitive mapping concerning the most relevant success factors. Second, to offer the possibility of applying success factors through practical strategies in their current implementation. These two intentions align with the answer to the question. One solution is theoretical and the other practical, so the article contains their development, analysis and methodical implementation with an effective purpose.

2. Preliminaries.

2.1. Neutrosophic Cognitive Maps.

Neutrosophic Cognitive Maps represent a significant evolution in the field of complex data representation and analysis. This unconventional methodology not only seeks to capture the inherent complexity of human perceptions, but also integrates principles of neutrosophic theory, which deals with truth, falsity, and indeterminacy simultaneously. This innovative approach is especially relevant in contexts where ambiguity and uncertainty are key factors in decision-making and the understanding of complex phenomena [6].

From a conceptual point of view, Neutrosophic Cognitive Maps allow to visualize and structure relationships between concepts that may be ambiguous or contradictory according to different perspectives. This not only broadens the spectrum of analysis by including divergent opinions and perceptions but also promotes a deeper and more holistic understanding of the problems investigated [7]. This ability to handle the inherent vagueness of human reality is crucial in disciplines such as philosophy, psychology, and sociology, where subjective interpretations play a central role in the construction of knowledge. In practical terms, Neutrosophic Cognitive Maps find application in a variety of fields, from scientific research to strategic planning and business decision-making. Their methodological flexibility allows researchers and practitioners to explore and analyze complex and multidimensional data in a structured and comprehensive manner. This methodology not only offers a visual representation of the inherent complexity of the systems and processes studied but also facilitates the identification of hidden patterns and subtle connections that could be overlooked with more traditional approaches. However, like any emerging methodology, Neutrosophic Cognitive Mapping faces challenges and criticisms. One of the main challenges lies in the difficulty of quantifying and validating the indeterminacy and vagueness represented in these maps. Objectively assessing the quality and reliability of the data entered into the maps can be challenging, especially when dealing with subjective or qualitative information. Furthermore, the interpretation of the results can vary significantly depending on the theoretical framework and underlying assumptions of those using this methodology [8].

Despite these challenges, Neutrosophic Cognitive Maps offer considerable potential for advancing the understanding and modeling of complex systems in an increasingly interconnected and dynamic world. By integrating principles of neutrosophic theory, these maps not only address reality in all its complexity and ambiguity but also promote an inclusive and multidimensional approach to research and decision-making. This is especially valuable in contexts where the diversity of opinions and perspectives enriches the analysis process and contributes to more robust and adaptive solutions. In conclusion, Neutrosophic Cognitive Maps represent a powerful and promising tool for researchers and practitioners seeking to navigate the complexity of the contemporary world. Their ability to represent and analyze vagueness and indeterminacy offers new opportunities for understanding and addressing complex problems in fields as diverse as business management, public policy, and social science. As research in this area advances, it is crucial to continue exploring and refining this methodology to maximize its usefulness and accuracy in the information and knowledge age [9].

This section contains the basic concepts of neutrosophic cognitive maps and the algorithms associated with them.

Definition 1 : ([10-12]) Let X be a universe of discourse. A *neutrosophic set* (NS) is characterized by three membership functions, $u_A(x), r_A(x), v_A(x) : X \to]^-_r0, 1^+[$ which satisfy the condition $^-_r0 \le \inf u_A(x) + \inf r_A(x) + \inf v_A(x) \le \sup u_A(x) + \sup r_A(x) + \sup v_A(x) \le 3^+$ for all $x \in X$. $u_A(x), r_A(x)$ and $v_A(x)$ are the truthiness, indeterminacy, and falsity membership functions of x in A, respectively, and their images are standard or nonstandard subsets of $]^-_r0, 1^+[$.

Definition 2 : ([10-12]) Let X be a universe of discourse. A *single-valued neutrosophic set* (SVNS) A in X is a set of the form:

$$A = \{\langle x, u_A(x), r_A(x), v_A(x)\rangle : x \in X\} \quad (1)$$

Where $u_A, r_A, v_A : X \to [0,1]$, satisfies the condition $0 \le u_A(x) + r_A(x) + v_A(x) \le 3$ for all $x \in X$. $u_A(x), r_A(x)$ and $v_A(x)$ denotes the truthiness, indeterminacy, and falsity membership functions of x in A, respectively. For convenience, a *single-valued neutrosophic number* (SVNN) will be expressed as $A = (a, b, c)$, where $a, b, c \in [0,1]$ and satisfy $0 \le a + b + c \le 3$.

Other important definitions are related to graphics.

Definition 3 : ([11, 12-13]) A *neutrosophic graph* is a graph that contains at least one indeterminate edge, which is represented by dotted lines.

Definition 4 : ([11, 12-13]) A *neutrosophic directed graph* is a directed graph that contains at least one indeterminate edge, which is represented by dotted lines.

Definition 5 : ([11, 12-13]) A *neutrosophic cognitive map* (NCM) is a neutrosophic directed graph, whose nodes represent concepts and whose edges represent causal relationships between edges.

If $C_1, C_2, \dots, C_k$ there are k nodes, each of them C_i $(i = 1, 2, \dots, k)$ can be represented by a vector $(x_1, x_2, \dots, x_k)$ where $x_i \in \{0, 1, I\}$. $x_i = 0$ means that the node C_i is in the on state, , $x_i = 1$ means that the node C_i is in the off state, and , $x_i = I$ means that the node C_i is in an indeterminate state, at a specific time or in a specific situation.

If C_m and C_n are two nodes in the NCM, a directed edge from C_m to C_n is called *a connection* and represents causality from C_m to C_n. Each node in the NCM is associated with a weight within the set $\{-1, 0, 1, I\}$. If α_{mn} denotes the edge weight C_mC_n, $\alpha_{mn} \in \{-1, 0, 1, I\}$ then we have the following:

$\alpha_{mn} = 0$ *if* hC_m does not affect C_n,

$\alpha_{mn} = 1$ if an increase (decrease) in C_m produces an increase (decrease) in C_n,

$\alpha_{mn} = -1$ if an increase (decrease) in C_m produces a decrease (increase) in C_n,

$\alpha_{mn} = I$ if the effect of C_m ignition C_n is indeterminate.

Definition 6 : ([14]) An NCM that has edges with weights $\{-1, 0, 1, I\}$ is called *a simple neutrosophic cognitive map*.

Definition 7 : ([14]) If $C_1, C_2, \dots, C_k$ are the nodes of an NCM. The *neutrosophic matrix* N(E) is defined as $N(E) = (\alpha_{mn})$, where α_{mn} denotes the weight of the directed edge C_mC_n, such that $\alpha_{mn} \in \{-1, 0, 1, I\}$. N(E) is called *neutrosophic adjacency* NCM *matrix* .

Definition 8 : ([14]) Let be $C_1, C_2, \ldots, C_k$ the nodes of an NCM. Let $A = (a_1, a_2, \ldots, a_k)$, where $a_m \in \{-1, 0, 1, I\}$. A is called *the instantaneous state. Neutrosophic vector* and means a position of the on -on-off-indeterminate state of the node at a given instant.

$a_m = 0$ if $C_m$disabled (has no effect),

$a_m = 1$ if $C_m$it is activated (has an effect),

$a_m = I$ if C_m It is indeterminate (its effect cannot be determined).

Definition 9 : ([14]) Let , , ,…, be $C_1, C_2, \ldots, C_k$the nodes of an NCM. Let $\overrightarrow{C_1C_2}$, $\overrightarrow{C_2C_3}$, $\overrightarrow{C_3C_4}$,…,$\overrightarrow{C_mC_n}$ be the edges of the NCM, then the edges constitute a *directed cycle*.

The NCM is called *cyclic* if it has a directed cycle. It is called *acyclic.* if you do not have a directed cycle.

Definition 10 : ([14]) An NCM that contains cycles is said to have *feedback* . When there is feedback in the NCM it is said to be a *dynamical system* .

Definition 11 : ([14]) Let $\overrightarrow{C_1C_2}$, $\overrightarrow{C_2C_3}$, $\overrightarrow{C_3C_4}$,…,$\overrightarrow{C_{k-1}C_k}$ be a cycle. When $C_m$it is activated and its causality flows along the edges of the cycle and is then the cause of $C_m$itself, then the dynamical system circulates. This is true for each node $C_m$with $m = 1, 2, \ldots, k$. The equilibrium state of this dynamical system is called the *hidden pattern* .

Definition 12 : ([14]) If the equilibrium state of a dynamical system is a unique state, then it is called *a fixed point* .

An example of a fixed point is when a dynamical system starts being triggered by C_l. If the NCM is assumed to sit atC_l and C_k, that is, the state remains as $(1, 0, \ldots, 0, 1)$, then this neutrosophic state vector is called a *fixed point* .

Definition 13 : ([14]) If the NCM is established with a neutrosophic state vector that repeats in the form:

$A_1 \to A_2 \to \cdots \to A_m \to A_1$, then the equilibrium is called the NCM *limit cycle* .

Method for determining hidden patterns

Let be $C_1, C_2, \ldots, C_k$the nodes of the feedback NCM. Let E be the associated adjacency matrix. A hidden pattern is found when is activated and C_la vector input is provided. $A_1 = (1, 0, 0, \ldots, 0)$The data must pass through the neutrosophic matrix $N(E)$, which is obtained by multiplyingA_1 by the matrix $N(E)$ [15].

Leave$A_1N(E) = (\alpha_1, \alpha_2, \ldots, \alpha_k)$ with the threshold operation of replacing $\alpha_m$by 1 if $\alpha_m > p$ and α_m by 0 if $\alpha_m < p$(*p is a* suitable positive integer) and α_m is replaced by I if it is not an integer. The resulting concept is updated; the vector $C_1$is included in the updated vector by transforming the first coordinate of the resulting vector to 1.

Yeah$A_1N(E) \to A_2$ It is assumed, then $A_2N(E)$ is considered, and the same procedure is repeated until a limit cycle or fixed point is reached.

Definition 14 : ([16,17]) A *neutrosophic number* N is defined as a number as follows:

$$N = d + I \tag{2}$$

Where d is called *determinate part* and call me the *indeterminate part* .

Given $N_1 = a_1 + b_1 I$ and $N_2 = a_2 + b_2 I$ are two neutrosophic numbers, some operations between them are defined as follows:

$N_1 + N_2 = a_1 + a_1 + (b_1 + b_2)I$(Addition) ;

$N_1 - N_2 = a_1 - a_1 + (b_1 - b_2)I$(Difference),

$N_1 \times N_2 = a_1 a_2 + (a_1 b_2 + b_1 a_2 + b_1 b_2)I$ (Product),

$\frac{N_1}{N_2} = \frac{a_1 + b_1 I}{a_2 + b_2 I} = \frac{a_1}{a_2} + \frac{a_2 b_1 - a_1 b_2}{a_2(a_2 + b_2)} I$(Division).

2.2. Lean Manufacturing.

Lean manufacturing, a revolutionary approach that emerged in the 20th century, seeks to eliminate waste and optimize processes in the productive industry. This paradigm, popularized by Toyota, has transformed the way companies manage resources and generate value [18]. Its relevance lies in its ability to adapt to diverse contexts, from mass production to customized environments, offering an effective response to the demands of efficiency in a globalized world. However, its implementation is not without challenges, which invites an in-depth analysis of its strengths and limitations. Historically, Lean was consolidated as a system that prioritizes continuous flow and the reduction of non-value-added activities, concepts that Taiichi Ohno perfected in post-war Japan . Over time, its influence extended beyond the automotive industry, permeating sectors such as electronics and healthcare [18]. In recent decades, the integration of digital technologies has given a new impetus to this approach, allowing unprecedented precision in the identification of inefficiencies [19]. However, this development raises questions about its universal applicability in industries with high variability.

One of the pillars of Lean is its emphasis on continuous improvement, known as kaizen , which encourages active employee participation in problem-solving. This aspect is key to its success, as it aligns organizational objectives with staff commitment [20]. However, the reliance on a collaborative culture can become an obstacle in contexts where a rigid hierarchy or resistance to change predominates, limiting its impact. Therefore, its effectiveness varies depending on the cultural and organizational environment. Furthermore, Lean manufacturing stands out for its focus on just-in-time delivery, minimizing inventories, and accelerating production cycles [21]. While this strategy reduces costs and improves customer response, it also exposes companies to risks due to supply chain disruptions, as evidenced during recent global crises [22]. This double-edged sword demands meticulous planning and adaptability that not all organizations possess, which calls into question its suitability in unpredictable scenarios.

The arrival of Industry 4.0 has enriched Lean with tools such as data analytics and automation, enhancing its ability to optimize processes in real-time [22]. For example, smart sensors and predictive algorithms make it possible to anticipate failures and dynamically adjust production. Although this synergy amplifies the benefits of Lean, it also increases the complexity of its implementation, demanding significant investments in technology and training [23]. Consequently, small businesses may be left behind, highlighting an accessibility gap. From another perspective, sustainability emerges as an added value of Lean, since its focus on eliminating waste aligns industries with environmental goals. Reducing the use of materials and energy not only benefits the economic balance but also responds to growing expectations of social responsibility. However, this ecological potential depends on conscious execution; otherwise, the obsession with efficiency could lead to practices that prioritize the short-term over long-term impact.

Critically, the universality of Lean has been questioned due to its origin in specific contexts, such as post-war Japanese industry, suggesting that its effectiveness may not be homogeneous [10]. Studies show that in emerging markets, where infrastructure and economic stability vary, results are inconsistent. This disparity invites reflection on the need to adapt Lean to local realities, rather than assuming it as a standardized solution.

In Lean's favor, its flexibility to integrate with other approaches, such as Six Sigma or Agile, broadens its scope and strengthens its application. This hybridization capacity keeps it relevant, allowing companies to customize strategies according to their needs. However, this versatility requires skilled leadership that balances multiple methodologies without losing focus on Lean's fundamental principles, a challenge that is not always successfully overcome. In practical terms, Lean manufacturing has proven to be a catalyst for competitiveness, especially in sectors where speed and quality are crucial. Companies that implement it rigorously report significant improvements in indicators such as delivery time and customer satisfaction. However, success is not automatic: it requires a cultural and structural transformation that many organizations underestimate, which can lead to partial failures or premature abandonment. In conclusion, Lean manufacturing is a powerful but complex approach, the assessment of which depends on its execution and context. Its benefits—efficiency, sustainability, and adaptability—are undeniable, but they are determined by factors such as organizational preparation, technological investment, and flexibility in the face of unforeseen events. Although it remains an essential tool for modern industry, its future will depend on its ability to evolve alongside the changing demands of the global environment.

3. Material and Methods

3.1 Research Design

This study employed a descriptive-exploratory design with a neutrosophic cognitive mapping (NCM) approach to analyze the critical success factors (CSFs) in the evolution of Lean manufacturing between 2015 and 2025. The method integrates expert knowledge and neutrosophic logic to model interrelationships among complex, ambiguous variables influenced by human and technological dimensions.

3.2 Selection of Critical Success Factors

A systematic literature review and expert consultation led to the identification of five key CSFs:

F1. Artificial Intelligence Integration

F2. Human Capital Development

F3. Digital Process Transformation

F4. Adaptive Organizational Culture

F5. Sustainability and Environmental Impact

These were selected based on their relevance to Lean implementation under Industry 4.0 dynamics.

3.3 Expert Participation

A total of 40 experts in Lean manufacturing and digital transformation were surveyed. Participants included operations managers, industrial engineers, AI consultants, and academics, each with over eight years of experience. Experts evaluated the influence of each factor over the others using a scale from −5 to +5, with the option of assigning an indeterminate (I) value to reflect uncertainty.

3.4 Construction of the Neutrosophic Cognitive Map

Let $E = \{e_1. e_2, \dots, e_n\}$ be the set of experts. Each expert provided influence ratings $R_{ijk} \in \{-5, \dots, 5, I\}$ between factor F_j and F_k . An algorithm was applied to process these inputs:

- If the mode across expert ratings R_{ijk} is unimodal, it becomes the consensus value $\bar{R}_{ijk}$; otherwise, further comparison with the reverse direction is considered.
- If both directions present non-unimodal distributions, that is, no value occurs significantly more frequently than the others in either of the two relationships, then the relationship is classified as indeterminate (I)

This process yielded a neutrosophic adjacency matrix, used to construct the NCM.

3.5 Dynamic Simulation and Convergence Analysis

To assess systemic behavior, all $2^5 - 1 = 31$ non-null activation vectors were simulated. Each factor could be in the state: active (1), inactive (0), or indeterminate (I). The simulations identified convergence patterns and activation frequencies for each factor, indicating their robustness and dependency within the Lean ecosystem.

3.6 Tools and Validation

Data analysis and visualization were carried out using Python, including the NCMPy package for neutrosophic modeling. Internal validation was ensured through consistency checks across expert inputs and dynamic iterations [24, 25].

4. Results and Discussion

4.1 Study variables

First, we specify the critical success factors to consider for the analysis of Lean manufacturing in the period 2015-2025:

1. **Artificial Intelligence (AI) Integration**: Implementation of AI systems for process optimization, predictive maintenance, automated quality control, and data-driven decision-making. Includes machine learning, computer vision, and expert systems applied to Lean environments.
2. **Human Capital Development**: Continuous training and adaptation of the workforce to new technologies, including training programs in digital tools, technical competencies, and soft skills necessary for the new Lean manufacturing.
3. **Digital Process Transformation**: Digitization of traditional operations, implementation of IoT (Internet of Things), cyber-physical systems, and integration platforms that enable real-time monitoring and complete traceability.
4. **Adaptive Organizational Culture**: Creating an organizational environment that fosters continuous improvement, resilience to change, and the agile adoption of new methodologies and technologies associated with Lean.
5. **Sustainability and Environmental Impact**: Integration of sustainable practices within the Lean paradigm, resource optimization, waste reduction, and minimization of the carbon footprint in production processes.

3.2 Neutrosophic Cognitive Mapping Analysis

Let $E=\{e_1, e_2, ..., e_n\}$ be the set of n experts in Lean manufacturing and advanced technology implementation. R_{ijk} symbolizes the relationship between the j- th and k -th factor ($j,k \in \{1,2, \dots ,5\}$, $j\neq k$) according to expert e_i ($i=1,2,\dots,n$) such that $R_{ijk} \in \{-5,-4,\dots,-1,0,1,\dots,4,5,I\}$.

The numerical values of R_{ijk} are calculated, then $\hat{R}_{ijk}=R_{ijk}$, and if $R_{ijk}=I$ then $\hat{R}_{ijk}=I$ holds.

For each fixed pair $j,k \in \{1,2, \dots ,5\}$, $\bar{R}_{jk}$ is calculated as follows:

- If the mode of $\hat{R}_{ijk}$ for $i=1, 2,\dots ,n$ is unimodal, we take $\bar{R}_{jk}=\mathrm{mode}(\hat{R}_{ijk})$ and $\bar{R}_{kj}=0$.
- If the mode of $\hat{R}_{ijk}$ for $i= 1,2,\dots ,n$ is not unimodal, it is defined:
    - If $\hat{R}_{ikj}$ for $i= 1,2,\dots ,n$ is unimodal, take $\bar{R}_{kj}=\mathrm{mode}(\hat{R}_{ikj})$ and $\bar{R}_{jk}=0$.
    - If $\hat{R}_{ikj}$ for $i= 1,2,\dots ,n$ is not unimodal, then $\bar{R}_{jk}=\bar{R}_{kj}=I$ is taken.

In this way, the adjacency matrix is formed with the $\bar{R}_{jk}$ elements obtained from this algorithm.

To obtain the weights and create the NCM, 40 specialists in Lean manufacturing and technology implementation were surveyed. These included operations directors, industrial consultants, academics, and experts in AI applied to manufacturing, all with at least eight years of experience in the sector. The resulting Adjacency Matrix is summarized in Table 1.

Table 1. Adjacency matrix of critical success factors in Lean manufacturing according to the 40 experts surveyed.

Factor	F1 (IA)	F2 (Human Capital)	F3 (Digital Transformation)	F4 (Organizational Culture)	F5 (Sustainability)
F1 (IA)	0	I	4	2	3
F2 (Human Capital)	3	0	2	4	I
F3 (Digital Transformation)	4	3	0	1	2
F4 (Organizational Culture)	I	4	3	0	2
F5 (Sustainability)	1	I	2	2	0

Figure 1 contains the NCM graph according to the adjacency matrix established in Table 1.

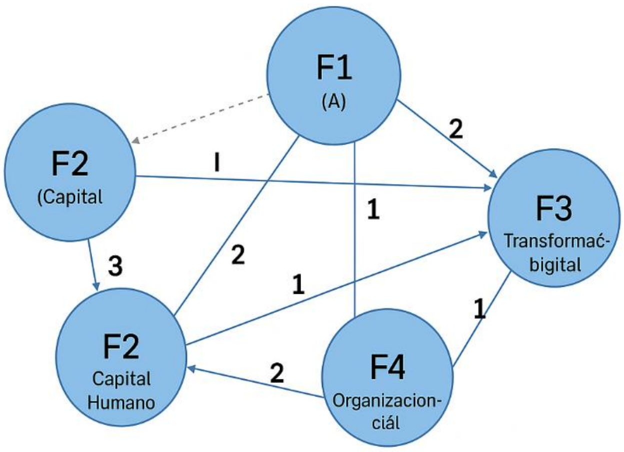

Figure 1. Neutrosophic Cognitive Map obtained from the experts]

All possible cases of convergence were studied when at least one of the factors was activated. This occurs in a total number of cases equal to 2^5-1=31. Table 2 summarizes the results in absolute and relative frequencies for each of the three possible states: activated (1), deactivated (0), or indeterminate

(I).

Table 2. Absolute and relative frequency of convergence of the system in each of the possible values.

Factor	0	%	1	%	I	%
F1 (IA)	2	6.45	21	67.74	8	25.81
F2 (Human Capital)	4	12.90	18	58.06	9	29.03
F3 (Digital Transformation)	1	3.23	25	80.65	5	16.13
F4 (Organizational Culture)	6	19.35	14	45.16	11	35.48
F5 (Sustainability)	8	25.81	12	38.71	11	35.48

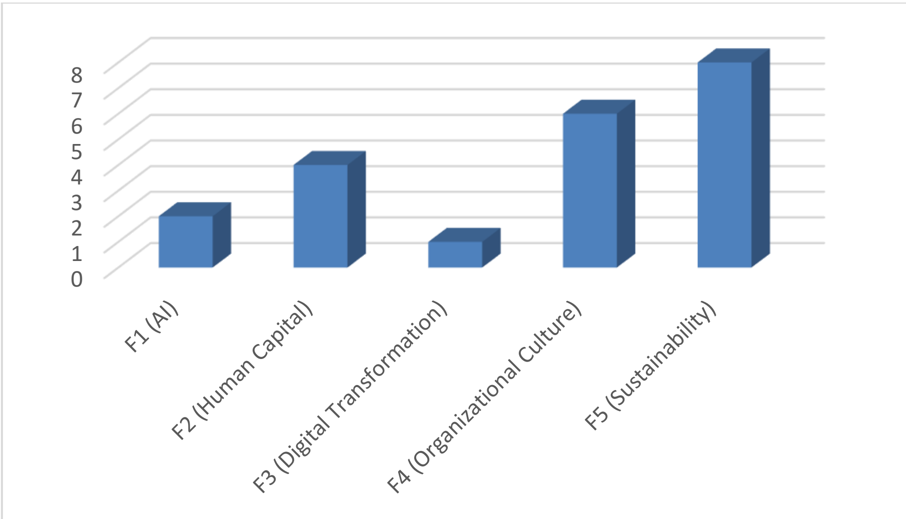

Figure 2: Absolute frequency of convergence of the system (0)

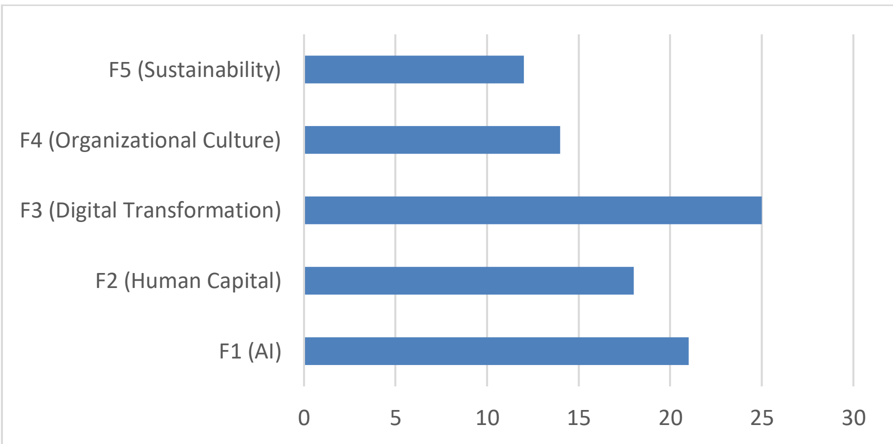

Figure 3: Absolute frequency of convergence of the system (1)

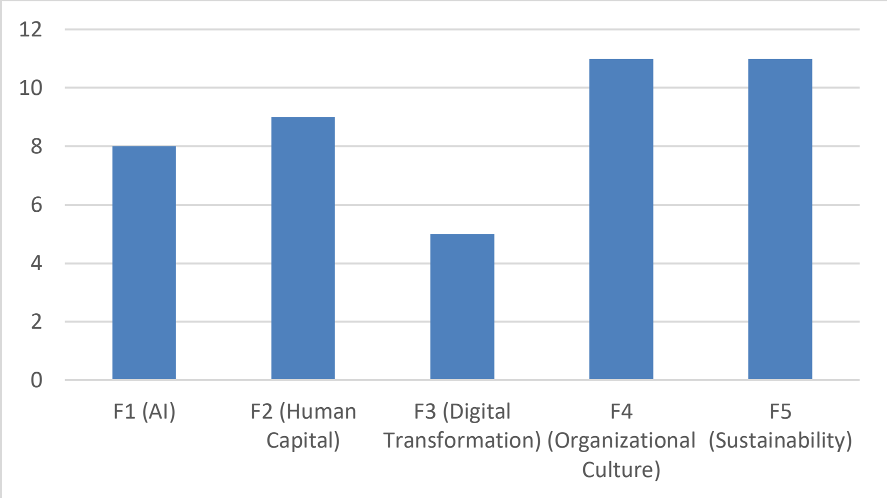

Figure 4: Absolute frequency of convergence of the system (I)

4.3 Interpretation of Results

The results shown in Table 2 confirm the complexity of the Lean manufacturing ecosystem in its evolution during the period 2015-2025, highlighting the dynamic interrelationships between the critical success factors analyzed.

The most robust factor is F3, or "Digital Process Transformation," which is activated in 80.65% of the possible initial conditions, while remaining undetermined in only 16.13% of cases. This suggests that process digitalization acts as a fundamental and catalytic element in the evolution of Lean manufacturing, forming a solid foundation upon which the other factors develop.

F1, or "Artificial Intelligence Integration," also shows remarkable performance, activating in 67.74% of the possible initial conditions. This high activation rate confirms the central role that AI has played in the transformation of Lean systems over the past decade, serving as a key driver of efficiency and optimization.

F2 or "Human Capital Development" is activated in 58.06% of cases, highlighting that, despite technological advancements, the human factor remains an essential component for the success of Lean manufacturing. This result reinforces the idea that technology alone is insufficient without proper staff training and adaptation.

Factors F4 "Adaptive Organizational Culture" and F5 "Sustainability and Environmental Impact" exhibit similar behaviors, with activation rates of 45.16% and 38.71% respectively, and an indeterminacy of 35.48% in both cases. These values reveal that, although they are important components, their effective implementation depends largely on specific contextual conditions and the maturity of the other factors.

A more detailed analysis shows that the most efficient combination for implementing successful Lean manufacturing over the period studied is to simultaneously activate factors F1, F2, and F3 (x_0 = (1,1,1,0,0)), that is, integrating Artificial Intelligence, developing Human Capital, and executing the Digital Transformation of Processes. This combination generates a domino effect that eventually also activates factors F4 and F5, creating a complete and balanced Lean ecosystem.

It is also observed that when F3 "Digital Transformation" and F4 "Adaptive Organizational Culture" are activated simultaneously (x_0 =(0,0,1,1,0)), there is a robust activation of F1 "AI Integration" and F2 "Human Capital Development". This suggests that an appropriate organizational culture, combined with the necessary digital infrastructure, provides fertile ground for the effective adoption of AI technologies and the development of corresponding human competencies.

It is notable that in no case does the isolated activation of F5 "Sustainability" significantly activate the other factors, indicating that, although sustainability is a desirable outcome, it does not act as a primary driver of Lean transformation, but rather as a consequence or complement to the other factors when these are properly implemented.

5. Discussion.

5.1 Relationship Analysis

The evolution of Lean manufacturing over the period 2015-2025 has been marked by complex interactions between the critical success factors identified in this study. The neutrosophic cognitive mapping analysis reveals significant patterns that warrant attention:

1. **Technology-Human Synergy** : There is a strong bidirectional relationship between F1 (AI) and F2 (Human Capital), as evidenced by the indeterminacy (I) in the adjacency matrix between these factors. This indeterminacy reflects the complexity of the relationship: on the one hand, AI drives new training needs; on the other, a well-trained workforce facilitates the adoption of more advanced AI solutions. This nonlinear dynamic has been characteristic of Lean environments over the past decade.
2. **Foundational Effect of Digital Transformation** : F3 shows the highest activation rate (80.65%), acting as an enabling platform for the other factors. The data suggests that process digitalization is not just another factor, but a structural prerequisite for the evolution of modern Lean manufacturing. The strong influence of F3 on F1 (value 4 in the matrix) indicates that digital transformation creates the necessary ecosystem for effective AI implementations.
3. **Culture as a Catalyst** : F4 (Organizational Culture) shows a determining influence on F2 (value 4 in the matrix), confirming that the cultural environment of the organization significantly conditions the development of human capital. The indeterminacy (I) between F4 and F1 reflects the complex nature of how organizational culture interacts with AI adoption, which varies significantly depending on the specific context of each industry.
4. **Sustainability as an Emergent Outcome** : F5 shows the lowest autonomous activation rate (38.71%), but is positively influenced by all the other factors. This suggests that sustainability in modern Lean environments tends to emerge as a consequence of the successful implementation of the other factors, rather than as an initial driving force.
5. **Indeterminacy Effects** : The presence of indeterminate (I) values in the adjacency matrix, particularly between F1-F2, F2-F5, and F4-F1, reflects the uncertainty inherent in some aspects of Lean manufacturing evolution. These indeterminacies represent areas where specific contextual factors, regional or sectoral differences, and organizational maturity play a decisive role in how relationships between factors develop.

5.2 Strategic Recommendations

Based on the neutrosophic analysis conducted, the following recommendations are offered for organizations seeking to optimize their Lean manufacturing implementation in the current context:

1. **Prioritize Digital Infrastructure** : Given the foundational role of F3 (Digital Transformation), organizations must first establish a robust digital infrastructure before moving

toward more sophisticated AI implementations. This includes real-time data collection systems, IoT connectivity , and information integration platforms.

2. **Adopt a Sequential Approach** : The most effective implementation follows the sequence F3 → F4 → F2 → F1 → F5. It is advisable to start with basic digital transformation , build an appropriate organizational culture, develop the necessary human capital, integrate AI solutions, and finally consolidate sustainable practices .
3. **Managing the Human-Technology Duality** : Given the uncertainty between F1 and F2, organizations must develop adaptive strategies that continually evolve staff training as new AI solutions are implemented. Training programs must be proactive, not simply reactive, to technological changes.
4. **Deliberately Cultivate Organizational Culture** : The significant influence of F4 on other factors suggests that Lean transformation initiatives should explicitly include cultural change management programs, with specific metrics to assess organizational adaptability and openness to new methodologies.
5. **Integrate Sustainability as a Planned Outcome** : While F5 typically emerges as a consequence of other factors, organizations can accelerate its development by establishing sustainability metrics from the outset that integrate naturally with Lean efficiency and digital transformation objectives.
6. **Proactively Manage Zones of Indeterminacy** : For relationships with a value of I in the adjacency matrix, it is recommended to develop contextualized assessment frameworks that allow each organization to determine how these relationships will manifest in its specific environment, considering variables such as industrial sector, organizational size, and technological maturity.
7. **Establish Adaptive Feedback Loops** : The dynamic nature of the relationships between factors suggests implementing continuous feedback loops that allow the Lean implementation strategy to be adjusted based on intermediate results and changes in the technological and market environment.

These recommendations, derived from neutrosophic analysis, offer a practical framework for navigating the complexity inherent in the evolution of Lean manufacturing in the era of digital transformation and artificial intelligence, enabling organizations to maximize the benefits of this methodology in an increasingly demanding and technologically advanced industrial environment.

6. Conclusion

The assessment of Lean Manufacturing development and implementation from 2015 to 2025 through neutrsophic cognitive mapping reveals a fluid ecosystem where digital transformation stands out as the strongest driver. Activated in over 80% of potential scenarios, other key success factors like AI integration and human capital development play significant roles, with similarly high activation rates emphasizing their focused and innovative processing tendencies. Furthermore, organizational culture and sustainability, while operating independently less dominantly, emerge as most fit in tandem—with one another—proven in the presence of a strong human and technological foundation. Ultimately, these findings indicate that relationships among drivers are significantly interdependent where Lean is successfully given appropriate resources. Practically, the findings serve as step-by-step guidance for industries intending to sustain competitive advantage in a global arena. The focus on digitalization coupled with proper implementation and training of all human resources will improve operational efficiency while opening the door to more advanced AI-based solutions. In addition, organizations can use this information to ensure that Lean efforts support sustainable goals, transforming an emerging finding into a planned goal that will enhance both economic impact and environmental footprint over time. This study contributes to the field of industrial management by applying an alternative approach involving neutralsensory cognitive mapping which assesses ideas uniquely attuned to uncertainty and non-causal relationships. Therefore, it adds to the theoretical body of literature regarding Lean's trajectory over the past decade, emphasizing technology's role in developing supportive implementation ideas over time while flagging the need for a continued human-tech integrated approach. Beyond theory, it offers a framework businesses can adapt to their specific contextual realities, thus contributing to further understanding and application of the methodology going forward.

However, it's not without limitations. The reliance on expert opinions introduces a level of subjectivity that may skew the consistency of findings, particularly within varying industrial contexts. Furthermore, the choice to focus on a set timeline (2015-2025) and five chosen factors excludes the potential for new variables to arise that will hold importance down the line, limiting the long-term potential of the findings. Future research should seek to expand the factors analyzed through additional methodologies—data-driven simulations or machine learning predictive models, for example, could enhance the certainty of the interactions determined. Additional factors such as supply chain resilience or global regulatory policies would also add depth. Finally, assessing these findings across specific industrial sectors or varying geographical areas would help to corroborate and modify these findings so that Lean Manufacturing continues to respond to challenges in a rapidly evolving world.

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