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Measuring manufacturing system complexity: a literature review

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Abstract
The measurement of complexity is a metric that can be used as a restructuring parameter in a production system, and it is also useful for the analysis of improvements based on the impact of operational indicators. This article aims to review the literature on the measurement of complexity in manufacturing systems. For this purpose, a systematic method based on six stages has been used, with the support of databases and computer media. In terms of contribution, it is worth highlighting that the theory of complexity is immersed in manufacturing systems, represented in approaches, methods, elements and models for its measurement. From the results, the research aims to find vectors for future challenges and gaps that support the strengthening of the industrial environment.

Keywords Complexity · Manufacturing systems · Measuring

Introduction

Manufacturing systems are constantly changing, due to the growth of economies, the effects of globalization and the accelerated pace of new technologies. Given the above, the manufacturing industry in search of being increasingly competitive manages improvement processes oriented towards its products, structure, quality, production and above all towards the positive impact of operational performance indicators, such as cycle time, products in process, finished products, throughput and production costs. It should be noted that in this manufacturing environment, associated resources such as human beings, materials, machinery, equipment, tools and information are involved, which when interacting with each other generate an increase in complexity.

According to Fernández et al. (2005), complexity is based on the knowledge of a real world that, even if one has all the relevant information about the system, generates uncertainty when recognizing its characteristics, properties and behavior. (Probst, 2013) Complexity is a quality of the system whose level depends on the set of elements that are related and interact, resulting in changes of states in the system. Consequently, (Gare, 2000; Stacey et al., 2000) propose that the complexity of a system depends on the dissimilarity, variety and number of parts and relationships existing in a system. In the research carried out, (Wu et al., 2007) they show the scientific community that there is a direct relationship between inventory costs and manufacturing complexity. On the other hand (Bozarth et al., 2009) they establish that complexity impacts unfavorably on the competitive performance of companies.

Likewise (Kochan et al., 2018) they establish that the impact is reflected on the productivity and quality of the processes. In view of the above, several authors have sought to simplify manufacturing systems by measuring complexity (Salum, 2000). According to Sivadasan et al. (2006), complexity can be measured by comparing actual and planned performance, where accurate decision making becomes difficult due to variability.

Consequently, uncontrolled complexity leads to increased operational costs and expenses.

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For this reason (Sivadasan et al., 2006) establishes that in order to manage its measurement, it is necessary to take into account the determining factors associated with a production system. More recent research addresses elements such as (i) plant design and structure (Broniatowski & Moses, 2016; Jung et al., 2020; Schoettl et al., 2014), (ii) the production process (Gomes et al., 2019; Modrak & Soltysova, 2018; Zhang & Li, 2011; Zuzana et al., 2019), (iii) the human aspect (Brinzer & Banerjee, 2017), (iv) production indicators (Malone & Wolfarth, 2013; Mattsson et al., 2012; Townsend & Urbanic, 2015; Wu et al., 2007), (v) the supply chain (Bozarth et al., 2009; Gravier & Kelly, 2012; Hamta et al., 2018; Kavilal et al., 2018; Modrak & Marton, 2014; Piya et al., 2020; Sivadasan et al., 2006) and (vi) production planning and scheduling (Fan et al., 2017a; Jonsson & Ivert, 2015; Liu et al., 2008; Rao & Efstathiou, 2006). This is where the innovation component lies, as current manufacturing models are geared towards mass customisation and lean strategies, focusing on high quality, low cost, agile, flexible and efficient designs.

It is evident that recent research is framed within the interest of the thematic axis addressed, an aspect that makes the present work relevant. From another perspective, (Vidal & Hernández, 2021a) in his research work shows that complexity studies in Latin American countries such as Colombia, Argentina, Chile, Ecuador and others, associated with business environments have a high degree of scarcity, therefore, it is a weak aspect in manufacturing systems and supply chains.

The literature distinguishes different approaches and methods to measure complexity, including non-linear dynamics, information theory, hybrid methods, enumeration, and others. Similarly, there are different types of models classified from a conceptual, theoretical and mathematical perspective.

This article presents a literary exploration on the measurement of complexity in manufacturing systems, allowing to find answers to relevant questions regarding the subject and to demonstrate literally the importance of the measurement of complexity in manufacturing management, the most outstanding references, the approaches, methods and types of models more common and used. The work is divided into three sections, first the method is developed, followed by the results and finally the conclusions.

Method

For the development of the literary exploration, a proposed methodology was built, which includes five stages (i) Guiding questions, (ii) Information sources and search strategy, (iii) Study selection, (iv) Inclusion and exclusion criteria and (v) Answers to questions. Figure 1 shows the systematisation of the literature review.

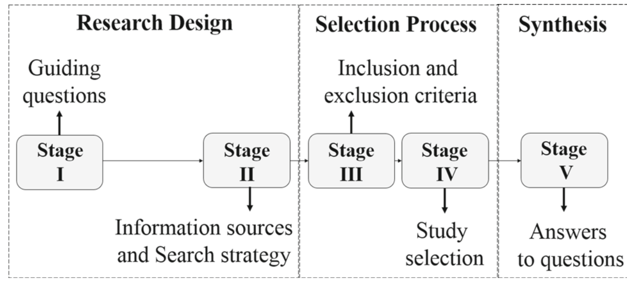


Fig. 1 Systematisation of the literature review

Guiding Questions

Complexity in a manufacturing environment has several consequences that affect the optimal performance of operations and influence decision making. According to Aelker et al. (2013), it is of vital importance to identify and measure it quantitatively, in order to avoid, reduce or eliminate it. Because they have an impact on operational costs and performance indicators related to lead times, service levels, plan mismatches and inventories. In a manufacturing system, various departments, resources and workstations interact and must work in a synchronised and integrated manner to ensure a smooth flow of materials, documents and information. This variety, uncertainty and diversity result in a high level of complexity, which ultimately affects what is planned and scheduled.

Although complexity has been studied, there is no common approach and many models are theoretical. According to Peter Drucker, manufacturing systems must be measurable and quantifiable, given that what is measured can be controlled, however it must be taken into account that measuring complexity is not a simple matter (Vidal & Hernández, 2021b). With this in mind, some guiding questions have been defined to find answers to specific issues of the described problem.

- Q1.Why is measuring complexity important in manufacturing management?
- Q2.What are the considerations for measuring complexity?
- Q3.What are the most outstanding references in complexity measurement?
- Q4.What approaches and methods exist to measure complexity in a manufacturing environment?
- Q5.What kind of models stand out to measure complexity in a manufacturing
- environment?

Information sources and search strategy

Five databases were selected to ensure that the guiding questions were covered. These databases are Scopus, Springer, Elsevier, Taylor & Francis and Google Scholar as a search engine for other sources.

Scientific databases were used as an information search strategy. The keywords used were "measurement", "method", "complexity", "manufacturing" and "production". For these queries, the operators "AND" and "OR" were used between each of the keywords. Subsequently, filters were applied for publication type, publication date, discipline and language. The results were extracted, organised and analysed using programmes such as Excel, Publish or Perish and VosViewer.

Study selection

Eligible studies were selected in three stages. (i) Titles were screened for terms indicating complexity, measurement, manufacturing, production and system. Only the most relevant were selected. (ii) abstracts were examined for studies investigating methods of measuring complexity in manufacturing systems. And (iii) a pre-reading of the paper was done to check for the existence of the application of some kind of method.

Inclusion and exclusion criteria

According to Kitchenham and Charters (2007), the inclusion and exclusion criteria allow prioritising those articles that provide information for the guiding questions formulated in item 2.1. Given the above, articles were excluded according to the assessment described in items 2.4 according to their title, abstract and document review.

With regard to the inclusion criteria, only articles published in English were included. With subject areas belonging to the discipline of engineering specifically in the industrial field. And with respect to the time horizon of the search, only papers published from the year 2000 onwards were included.

Answers to questions

This section presents an outline of the literature reviewed. First, theoretical premises are shown, accompanied by concepts, methods and evaluations. All this from a spectrum of evolution from 2000 to 2021. Including an overview of gaps identified in addressing each of the guiding questions (Q).

Question report (Q1)

The study of complexity comprises a broad vision that involves different scenarios linked to inhuman, human and intangible aspects (Simon, 2002; Wiendahl & Worbs, 2003). From a systematic approach, (Meyers, 2009) states that the complexity of the system must be consistent with the volume of information required. They (Wagensberg, 2007) also define it as the magnitude of variables needed to determine the state of the system. Entering into an industrial environment, (Garbie & Shikdar, 2011) state that complexity has started to be considered as a new form of evaluation of industrial companies, being also one of the useful tools for the analysis of improvements and business restructuring.

There are different types of complexity in manufacturing systems. According to their classification, according to their origin, for (Isik, 2010) there are three categories: internal, external and total. Internal complexity is linked to the elements that interact within the company, and that can be affected by external elements, called external complexity, which is associated with suppliers or customers. And total complexity encompasses all internal and external complexity (Vidal & Hernández, 2021b).

Depending on time and its behaviour, according to Gaio et al. (2002), complexity in manufacturing systems can be static or dynamic. Static complexity refers to a characteristic that can be associated with the structure of the facility and dynamic complexity refers to the behaviour of the system over time.

In summary, manufacturing systems are complex, so several authors have tried to simplify manufacturing systems. To do so, some have used classical comparison parameters, such as manufacturing time (Salum, 2000), distances between stations (Kim et al., 2002), material handling costs (Sherali et al., 2003) and product quality (Li et al., 2005); and others from complexity measurement (Efthymiou et al., 2016; Jacobs, 2007; Wu et al., 2002). According to Wu et al. (2013), complexity measurement in systems and manufacturing is a metric that serves as a parameter to establish improvement plans, and they establish that systems with a high degree of complexity tend to have a higher number of problems compared to simpler systems. Therefore, measuring complexity in manufacturing systems will allow managers to investigate and compare different types of configurations, structures and designs, evaluate system behaviour and facilitate accurate decision-making.

Question report (Q2)

Measuring complexity is an objective metric, so it is obtained from data obtained reliably from constant monitoring of the system. This consideration is vital if management is to have a useful and valid measure to support decisions. The researcher (McCarthy et al., 2000), argued that, in addition to validity, the complexity metric should consider separate additive measurements, thus simplifying the calculation and providing better analysis. According to Wu et al. (2013), when measuring complexity, the structure of the system on the one

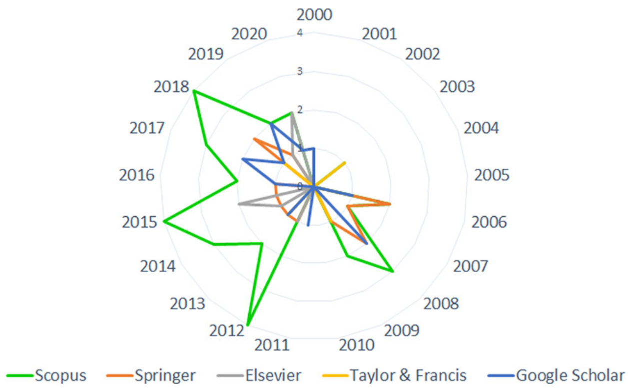


Fig. 2 Volume of publications per year in database

hand and the uncertainty of the system on the other must be considered.

According to Vanmali et al. (2013), static complexity relates to the volume of products, number of processes, and number of machines, among others. And dynamic complexity measures performance over time, such as corrective maintenance of the machine.

Question report (Q3)

To construct the search query in each of the databases a specific path was structured: ("Complexity" AND "manufacturing" OR "Production" AND "Measuring" OR "Measurement"). A certain number of publications related to the research topic were found. Figure 2 shows the volume per year in each source consulted. The results show a high research development in the last 10 years.

It is important to highlight the authors with the highest number of citations, which is an indication of the quality of the contributions and the generation of new knowledge for science. Table 1 shows the number of citations per published work, highlighting the prevalence of citations in Springer and Elsevier databases. Given the above, authors such as Andersson and Bellgran (2015), Fera et al. (2018), Broniatowski andMoses (2016) and Smart et al. (2013).

In terms of contribution to the measurement of complexity, it is notorious that in the last ten years, there has been an increase in the consideration of factors such as design or structure (Ds) and process (Pr). And the little development towards elements such as persons (Pe), products (Pd), planning and scheduling (Ps).

Based on information from Scopus, a study of the most used words taking into account 6489 terms, including titles, abstract and keywords, allowed to visualise a research focus on complexity. Figure 3 shows a clear trend in case studies of design and manufacturing systems, using quantitative model-oriented measurement methods such as optimisation, algorithms and process simulation. Given the above, in a research presented by Vidal et al., 2021a; Vidal et al., 2021b) at the third international conference SUSCOM-2021, a hybrid conceptual model based on complexity index heuristics and entropic measurements is proposed. This supports the application of mathematical models, providing relevant, structured and organised information for manufacturing decision makers.

Question report (Q4)

According to Efthymiou et al. (2014), the most common approaches to measure complexity addressed in the literature are non-linear dynamics (DT), information theory (IT), hybrid methods (H), other approaches (OA) and quantitative index (QI). Table 2 shows a classification of the different methods applied to measure complexity in systems, relating different characteristics, such as: Qualitative (Ql), Quantitative (Qn), Static (S), Dynamic (D), Static and Dynamic (S&D), Objective (O) and Subjective (Sb). The prevalence towards quantitative and objective is evident.

Chaos and non-linear dynamics theory (DT) Non-linear dynamics is a set of mathematical techniques from chaos theory that are used to measure dynamic complexity (Chryssolouris et al., 2013). According to Reigeluth (2004), chaos theory is a theoretical and descriptive analysis of the unstable behavior of dynamic systems, meaning that dynamics is the evolution of the system over time, unstable in the absence of repetitive patterns, and non-linear since what comes out is not proportional to what goes in. According to Efthymiou et al. (2012), in the Chaos and Non-linear dynamics theory there are three types of methods that are used to measure the stability of a system.

(i) Phase portraits (PP), According to Elias and Namboothiri (2014); Sun & Wu, 2012; Yan et al., 2012) a graphical method is applicable to look at the system dynamics by means of maps. Consequently (Donner et al., 2008) by means of the simulation of non-linear dynamic discrete events, they study and evaluate manufacturing systems in push and pull scenarios for production control.

(ii) Lyapunov Exponents (LE), this method allows the assessment of the unstable behaviour of dynamic systems. According to Wolf (2014), Lyapunov's exponents are measures that allow to quantify the sensitivity of a system, when it contains at least one positive exponent it is defined as unstable and depending on the magnitude in a time horizon its dynamism can be visualized. From an industrial environment (Papakostas & Mourtzis, 2007), who analyze the chaotic dynamism through the use of exponents, and Lyaponuv (Wang et al., 2005), use the method for inventory control based

Table 1 Relationship of citations and the elements of manufacturing system

Authors	Cites	Ds	Pr	Pd	Pe	Ps
Turco & Maggioni (2020)	6				●	
Brinzer & Schneider (2020)	2		●			
Jung et al. (2020)	0	●				
Gomes et al. (2019)	6		●			
Zuzana et al. (2019)	0		●			
Juffs & Han (2019)	0		●			
Fera et al. (2018)	52		●			
Kavilal et al. (2018) (Kavilal et al., 2018)	17	●				
Modrak & Soltysova (2018)	14	●				
Hamta et al. (2018)	12	●				
Guoliang et al. (2017)	15	●				
Brinzer & Banerjee (2017)	12				●	
Raihanian & Behdad (2017)	3	●				
Fan et al. (2017a)	0	●				
He et al. (2017)	0		●			
Broniatowski & Moses (2016) (Broniatowski & Moses, 2016)	46	●				
Schlick & Demissie (2016)	0		●			
Andersson & Bellgran (2015)	117		●			
Jonsson & Ivert (2015)	36					●
Drzymalski (2015)	9		●			
Townsend & Urbanic (2015)	7		●			
Youn (2014)	31		●			
Schoettl et al. (2014)	5	●				
Modrak & Marton (2014)	0	●				
Smart et al. (2013)	42					●
Malone & Wolfarth (2013)	15		●			
Grussenmeyer & Blecker (2013)	5		●			
Zhang (2012)	37					●
Mattsson et al. (2012)	30	●	●	●	●	
Gravier & Kelly (2012)	3	●				
Ma et al. (2012)	1				●	
Mattsson et al. (2011)	25	●	●	●	●	

on the diversification of product batches for unstable demand, appear.

(iii) Bifurcation diagrams (BD), this method allows through a graphic scheme to show the behavior of a manufacturing process, so that the elements and parameters that lead to an unstable type of behavior can be identified.

Some researchers have developed work with this type of method, given the case developed by Scholz-Reiter et al. (2002) those who control manufacturing systems based on bifurcation diagrams, specifically in the inventory management process. In (Papakostas & Mourtzis, 2007), the instability of a manufacturing system is graphically evaluated through demand management analysis, taking into account quantitative time series methods.

The search queries used are shown below: ("Complexity" AND "Method" AND "Phase Portraits"); ("Complexity" AND "Method" AND "Lyapunov Exponents"); ("Complexity" AND "Method" AND "Bifurcation Diagrams"). Table 3 shows a review of studies of complexity measurement methods using chaos theory mathematical techniques, identifying three effects on dynamic complexity. using chaos theory mathematical techniques, identifying three effects on dynamic complexity (i) Production volume, (ii) Production planning and scheduling and (iii) Process uncertainty. The predominance of the Lyapunov Exponents (LE) method is

Fig. 3 Most relevant words

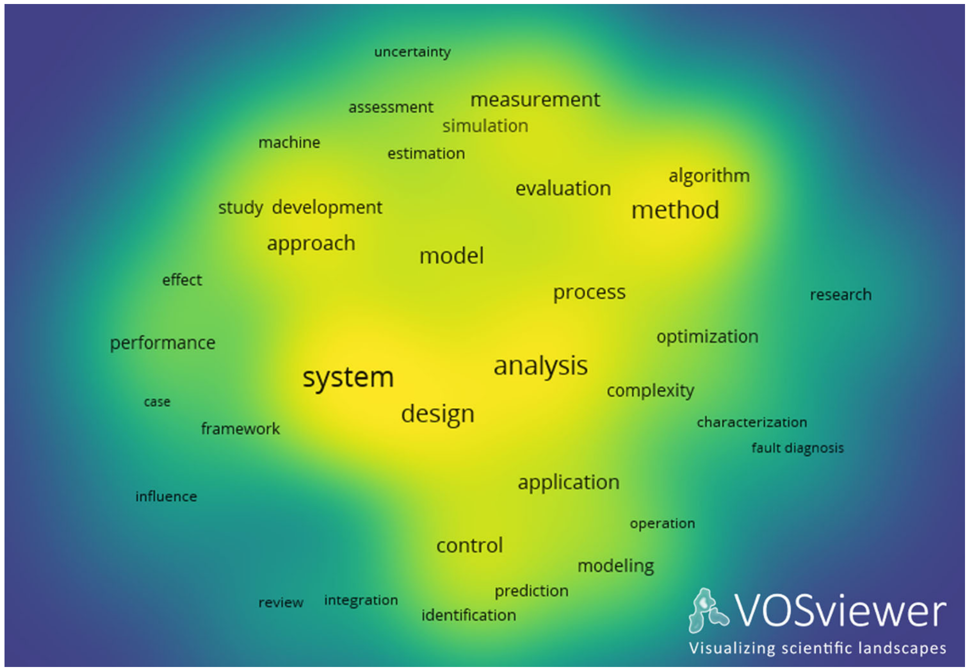


Table 2 Characteristics of approaches and methods

Approach	Method	Ql	Qn	S	D	S&D	O	Sb
DT	Phase Portraits (PP)		●		●		●	
	Lyapunov Exponents (LE)		●		●		●	
	Bifurcation Diagrams (BD)		●		●		●	
IT	Shannon Entropy (SE)		●			●	●	
	E-Machines (EM)		●			●	●	
	Kolmogorov (K)		●			●	●	
H	Heuristic (H)		●	●			●	
OA	Fluid Dynamics (FD)		●			●	●	
	Questionnaires (Q)	●				●		●
QI	Complexity Calculator (CXC)		●			●	●	
	Complexity Index (CXI)	●	●		●			●
	Manufacturing Complexity (MCI)		●		●		●	
	Robustness Index (RI)		●		●			●

evident, with the effect of production planning and scheduling being less analysed.

Information theory (IT) Information theory has its beginnings in the work of Shannon (1948), who introduced a metric for quantifying information, taken as a measure of entropy and used to measure the uncertainty of the random variables of a system. This measure was taken to an industrial level, to calculate the complexity of manufacturing systems thanks to the research work of Wu et al. (2013). According to Calinescu (2000), information theory measures the complexity of a system as a function of the volume of information. Taking this into account (Calinescu, 2000; Sivadasan et al., 2002), they state that a system with high complexity requires a higher volume of information. According to Efthymiou et al. (2012), there are three types of measurement methods in Information Theory:

(i) Shannon entropy (SE), which is based on analytical equations to measure complexity, facilitating analysis in different types of scenarios and providing a quantitative basis for decision-making. Some authors who applied this type of method in manufacturing systems stand out (Vanmali et al., 2013), who used entropy to

Table 3 Evaluation relationship with respect to chaos theory and nonlinear dynamics (DT)

Method	Authors	Dynamic			Evaluation
		I	II	III	
Phase Portraits (PP)	Pan & Chen (2016)			●	Equipment downtime and productivity
	Donner et al. (2008)		●		Performance control strategies
	Giannelos et al. (2007)		●		Lead time delays
	Peters et al. (2004)			●	Throughput time and production rates
	Chryssolouris et al. (2004)		●		Lead time delays
Lyapunov Exponents (LE)	Ma et al. (2019)	●			Speed of price adjustment and discounting
	Ndofor et al. (2018) (Ndofor et al., 2018)			●	Level of unpredictability in production sectors
	Guo (2018)			●	Identifying chaotic parameters
	Yu et al. (2017)			●	Analysis on daily closing price
	Donner et al. (2015)			●	Dynamic transitions in non-stationary systems
	Leverick et al. (2015) (Leverick et al., 2015)			●	Comparing dynamic characteristics over time
	Elias & Narayanan (2014)	●			Transitions of operation and working material
	Wolf et al. (2014) (Wolf, 2014)	●			Volume growth rate monitoring
	Chryssolouris et al. (2013)			●	Relationship between flexibility and complexity
	Sun & Wu (2012)			●	Stability analysis of nonlinear systems
	Yan et al. (2012)			●	Dynamic changes of machine state
	Benaissa et al. (2008)			●	Dynamic behavior of dynamic systems
	Papakostas & Mourtzis (2007)	●			Adaptability of a manufacturing system
	Makui & Madadi (2007)	●			Supply chain behavior
Bifurcation Diagrams (BD)	Ma et al. (2019)	●			Speed of price adjustment and discounting
	Kwuimy et al. (2014) (Kwuimy et al., 2014)			●	Level of complexity and transition of movement
	Wang et al. (2010)	●			Production capacity with chaotic behaviors
	Papakostas & Mourtzis (2007)	●			Adaptability of a manufacturing system
	Scholz-Reiter et al. (2002)		●		Dynamic behavior of the production system

measure complexity in shop-floor type systems. Similarly, (Efstathiou et al., 2002) used the entropy metric to assess static and dynamic complexity in manufacturing systems. From the supply chain point of view (Isik, 2010) propose a measure of the total static and dynamic complexity in the supply chain. Similarly, (Modrak & Semanco, 2012) identify the best configuration of a supply network by measuring the complexity entropy. More recently, (Wu et al., 2018) address structural models based on Shannon entropy for sustainable engineering studies.

(ii) E-Machines (EM), this method can be used to measure dynamic complexity, based on the different states that a machine can have in a time horizon. In practice, research has appeared such as that of Vanmali et al. (2013), which evaluated the performance and complexity of a system based on considerations of machine capacity and the probabilities of the different states. Also, (Garbie, 2012) worked on a research project under a complexity simulation approach in terms of the probability of machine states considering product quantities and inventory costs.

(iii) Kolmogorov (K), this method provides a measure of entropic complexity that allows to evaluate and analyse the behaviour over time of different manufacturing components. From the point of view of applicability, the work developed by Mourtzis et al. (2013); Mourtzis et al., 2015), which studies the uncertainty of performance indicators in centralised and decentralised production systems in supply chains, stands out.

The search queries used are shown below: ("Complexity" AND "Method" AND "Shannon Entropy"); ("Complexity" AND "Method" AND "E-Machines"); ("Complexity" AND "Method" AND "Kolmogorov"). Table 4 shows a review of complexity measurement studies with respect to Information Theory (IT). Five effects on static complexity have been identified (i) Number and variety of products, (ii) Number of parts, (iii) Product structure, (iv) Number of machines or work centres and (v) Plant layout. And three effects on dynamic complexity already defined in the previous section. The Kolmogorov (K) method prevails, with the effect of product structure, production volume and production planning and scheduling being less analysed.

Quantitative index (QI) The methods of the quantitative index are the techniques that allow you to measure the complexity of manufacturing systems from an analytical perspective, the methods used and the products in European countries. In literature there are several methods such as: (i) Complexity Calculator (CXC), developed by Zeltzer et al. (2013) in an applied research project called Belgian Complex, in which its objective was to characterize the complexity of specific workstations in manufacturing systems. (ii) Complexity Index (CXI), According to Mattsson et al. (2011) this method helps companies to understand their production system based on the experience of the workers. (iii) Manufacturing Complexity Index (MCI), that model was raised by Urbanic and ElMaraghy (2006), who from three elements such as the flow of information, diversity and variability measure the complexity of a manufacturing system. (iv) Robustness Index (RI), developed by Mattsson et al. (2011), who determine the production capacity of a system and, based on changes in product development, identify whether the system is robust. The search queries used are shown below: ("Complexity" AND "Method" AND "Complexity Calculator"); ("Complexity" AND "Method" AND "Complexity Index"); ("Complexity" AND "Method" AND "Manufacturing Complexity Index"); ("Complexity" AND "Method" AND "Robustness Index"). Table 5 shows little evidence of the effect of number of parts and production planning and scheduling.

Hybrid (H) Some research proposes hybrid approaches, which are the result of a combination of information theory and quantitative indices (ElMaraghy & Urbanic, 2003). Quantitative methods are those that classify products, resources and machines according to criteria of quantity and attributes. In the literature some research works stand out in ElMaraghy and Urbanic (2003) (Gabriel, 2007) they propose a measurement of complexity based on information theory taking into account characteristics of the product and the process, in this research they measure the effect of resources within the manufacturing system. Consequently, (ElMaraghy et al., 2005), they determine the measurement of complexity in manufacturing systems considering aspects such as the availability of the resources used. (Németh & Földesi, 2009) shows an indicator that allows for the measurement of complexity based on knowledge of the number of stations and links between them. More recently, (ElMaraghy et al., 2014), they propose six types of complexity indices for plant distribution characteristics.

The search queries used are shown below: ("Complexity" AND "Method" AND "Shannon Entropy" AND "Complexity Calculator"); ("Complexity" AND "Method" AND "Shannon Entropy" AND "Complexity Index"); ("Complexity" AND "Method" AND "Shannon Entropy" AND " Manufacturing Complexity Index"); ("Complexity" AND "Method" AND “Shannon Entropy" AND "Robustness Index"). The same structure was used for the E-Machines and Kolmogorov methods.

Table 5 shows a review of complexity measurement studies using a hybrid approach. The research evidences a combination of information theory and quantitative indices, showing a tendency towards static complexity and low projection to dynamic complexity.

Other approaches In this section are those methods that are not associated with any of the above approaches. According to Efthymiou et al. (2012), within other approaches there are two types of methods, (i) Fluid dynamics (FD), this method is used from the estimation of performance indicators around the planning, programming and control of production (Bertsimas et al., 2017; Dai & Prabhakar, 2000; Efthymiou et al., 2009). (ii) Questionnaries (Q), this method allows to measure the complexity in systems from structured questionnaires using Likert scales, applied to managers and head of production of the companies, finally the results obtained are analyzed statistically. Some of these studies (Guimaraes et al., 2009), in which a questionnaire was applied to a sample of 500 plant managers to corroborate the performance of a system in terms of complexity, stand out. In (Bozarth et al., 2009), questionnaires are used in 209 manufacturing

Table 4 Evaluation relationship with respect to information theory (IT)

Method	Authors	Static					Dynamic			Evaluation
		I	II	III	IV	V	I	II	III	
Shannon Entropy (SE)	Zuzana et al. (2019)				●					Analysis of static complexity
	Zhang et al. (2017)								●	Shortest path in complex networks
	Manns et al. (2016)							●		Data-driven human motion variation
	Sharma et al. (2016)		●		●					Failure diagnosis and severity in bearings
	Modrak et al. (2014)	●								Product variety in complex processes
	Vanmali et al. (2013)		●		●	●				Analysis of static complexity
	Modrak & Marton (2013)	●		●						Correlation between supply chains
	Modrak & Semanco (2012)		●							Identifying a better configuration variant
	Modrak & Marton (2012)		●							Structural design of the supply chain
	Isik (2010)		●	●						Complexity of information and material flows
	Bone et al. (2010)	●	●	●						Correlation between system architecture
	Efstathiou et al. (2002)		●						●	Evaluation of structural and dynamic complexity
E-Machines (EM)	Vanmali et al. (2013)		●		●	●				Analysis of static complexity
	Kamrani & Adat (2008)	●								Risks associated with product variety
	Park et al. (2006)								●	Stock price index
	Elmaraghy et al. (2000)				●			●		Minimizing waiting interval and flow time
Kolmogorov (K)	Fan et al. (2018)				●					Operation time and high human error rates
	Mizgier (2017)	●								Supply chain risk
	Jiang et al. (2015) (Jiang et al., 2015)				●					Bearing defects in machines
	Kandjani et al. (2015)							●		Complexity of projects in planning stage
	Mourtzis et al. (2015)						●	●		Performance of decentralized manufacturing networks
	Leverick et al. (2015) (Elias & Namboothiri, 2014)								●	Comparing dynamic characteristics of time series
	Cui et al. (2015)								●	Control system information
	Li et al. (2013)								●	Reducing data complexity
	Modrak & Marton (2013)	●		●						Correlation between supply chains
	Yusuf et al. (2013)					●			●	Complexity of location of viable stockpiles
	De Biagi & Chiaia (2013)					●				Structural robustness
	Mourtzis et al. (2013)	●				●	●			Design and operation of manufacturing networks

Table 4 (continued)

Method	Authors	Static					Dynamic			Evaluation
		I	II	III	IV	V	I	II	III	
	Allaire et al. (2012)								●	Resource allocation to reduce complexity
	Elmaraghy et al. (2012)	●	●	●		●				Complexity of design, products and manufacturing
	Khan & Angeles (2011)								●	Complexity of kinematic chains
	Isik (2010)		●	●						Complexity of information and material flows
	Frizelle & Suhov (2008)	●					●		●	Effective comparisons with queues in the system
	Li & Chandra (2007)								●	Integration of generic knowledge
	Frizelle & Suhov (2001)	●					●		●	Behavior of queues in the system

plants in various industries in seven countries in different geographical regions of the world to study which sources add complexity and impact on business performance. More recently (Eckstein et al., 2015) questionnaires from 143 German companies are investigating the effects of product complexity on the agility and adaptability of the supply chain in terms of cost and operational performance.

The search queries used are shown below: ("Complexity" AND "Method" AND "Fluid dynamics"); ("Complexity" AND "Method" AND "Questionnaries"). Table 5 shows the prevalence of the questionnaire method (Q) over the fluid dynamics method (FD), being less analyzed the effect on static complexity: Product structure, number of machines or work centers and plant layout, and on dynamic complexity: Production volume and Production planning and scheduling.

Question report (Q5)

There are different models to measure complexity, (i) conceptual models, (ii) theoretical models and (iii) mathematical models. The literature review shows the application of theoretical, conceptual and mathematical models, the latter being the trend-setters. The studies developed by Vidal et al., 2021a; Vidal et al., 2021b) corroborate that they can work in a hybrid way as the conceptual ones guarantee a better understanding of the mathematical models. The search queries used are shown below: ("Complexity" AND "Models" AND "Conceptual"); ("Complexity" AND "Models" AND "Theoretical"); ("Complexity" AND "Models" AND "Mathematical"). From Table 6 it can be abstracted that the models encompass performance indicators in addition to complexity, which allow in a complementary way to evaluate manufacturing systems, such as: (i) Finished products, (ii) Cycle time, (iii) In-process products, (iv) Throughput, (v) Productivity, (vi) Efficiency and (vii) Cost of production.

Results

In this section, a comparison of overall results is presented, taking into account the five questions (Q) formulated. Figure 4 illustrates a bar chart according to the number of publications over the last ten (10) years. It is evident that there is a growing interest from the scientific community on topics related to approaches and methods for measuring complexity in a manufacturing environment (Q4) and the types of models for its measurement (Q5).

The bar chart in Fig. 5 illustrates the number of articles according to publication type, grouped according to question Q. The prevalence of journal publications is evident for all questions. This indicates that there is a high level of maturity and quality in the contribution to science, given the rigorous and demanding nature of this type of publication.

Findings on Q1

The objective of question Q1 is to identify the importance of measuring complexity in manufacturing management. To achieve the objective, from the selected articles, several were identified that contribute to provide an answer (see Fig. 6).

Findings on Q2

The objective of question Q2 is to find the considerations to be taken into account for measuring complexity in manufacturing systems. Table 7 shows the considerations (i) quantity

Table 5 Evaluation relationship with respect to hybrid (H), other approaches (OA) and quantitative index (QI)

Method	Authors	Static					Dynamic			Evaluation
		I	II	III	IV	V	I	II	III	
Complexity Calculator (CXC)	Van Landeghem et al. (2016)	●	●	●						Impact on the human operator within manufacturing
	Tarrar et al. (2016)				●	●				Measuring complexity for work improvement
	Mattsson et al. (2014)								●	Comparative analysis of quantitative methods
	Zeltzer et al. (2013)				●				●	Complexity in production performance
Complexity Index (CXI)	Falck et al. (2017)	●		●	●					Evaluating assembly complexity
	Mattsson et al. (2016)				●	●				Station design, work variation and disturbances
	Mattsson et al. (2014)								●	Comparative analysis of quantitative methods
	Mattsson et al. (2011)						●		●	Rebalancing level in production lines
Manufacturing Complexity Index	Mattsson et al. (2014)								●	Comparative analysis of quantitative methods
	Urbanic & ElMaraghy (2006) (Urbanic & ElMaraghy, 2006)	●			●	●			●	Evaluate elements of manufacturing complexity
Robustness Index (RI)	Mattsson et al. (2014)								●	Comparative analysis of quantitative methods
	Mattsson et al. (2011)						●		●	Rebalancing level in production lines
Heuristic and Information Theory (H)	ElMaraghy et al. (2014)				●	●				Structural complexity of manufacturing systems
	Romano (2009)	●	●			●				Configuration of supply networks
	Németh & Foldesi (2009)		●	●		●				Complexity and length of the supply chain
	Battini et al. (2007)	●	●		●					Analysis of supply chain networks
	Gabriel (2007)				●	●				Complexity on manufacturing performance
	ElMaraghy et al. (2005)	●	●	●						Analysis of the number and variety of components
	ElMaraghy & Urbanic (2003)	●	●	●	●					Effects of worker attributes on the system
Fluid Dynamics (FD)	Mourtzis & Doukas (2014) (Mourtzis & Doukas, 2014)						●	●		Design and planning of systems and networks
	Romano (2009)	●	●			●				Configuration of supply networks
	Efthymiou et al. (2009)							●		Modelling and understanding production system
Questionnaires (Q)	Brinzer & Schneider (2020)	●	●							Identifying relevant complexity driver
	Eckstein et al. (2015)	●	●							Moderating effect of product complexity

Table 5 (continued)

Method	Authors	Static					Dynamic			Evaluation
		I	II	III	IV	V	I	II	III	
	Blome et al. (2014)	●							●	Knowledge transfer and flexibility
	Abdullah et al. (2014)								●	Impact of Operational Complexity
	Manuj & Sahin (2011)						●		●	Drivers of supply chain complexity
	Bozarth et al. (2009)							●	●	Impact on manufacturing plant performance
	Größler et al. (2006)								●	Adapting processes in the face of increasing complexity
	Perona & Miragliotta (2004)	●	●	●					●	The impact of flexible process capability on the product-process
	Novak & Eppinger (2001)	●	●							Product complexity and the supply chain
	Guimaraes et al. (2009)				●	●				System complexity in relation to performance

of products, (ii) volume of resources, (iii) system structure, (iv) uncertainty and (v) additive measures for calculation. It is evident the recommendation by researchers in recent years towards elements such as system structure and uncertainty.

Findings on Q3

The aim of question Q3 is to find the most relevant benchmarks in complexity measurement. From what is structured in Table 1, it is noticeable that in the last ten years the consideration of factors such as design or structure (Ds) and process (Pr) has increased. And little development towards elements such as people (Pe), products (Pd), planning and programming (Ps). Figure 7 shows a more detailed study, considering the most current publications, thus providing a spectrum of possible future work in this area of research.

Findings on Q4

The aim of question Q4 is to find out what approaches and methods exist to measure complexity in a manufacturing environment. Table 8 shows characteristic aspects between the different approaches, which allow to compare them and thus to establish advantages and disadvantages.

From Fig. 8 it can be seen the predominance of the Lyapunov Exponents (LE), Kolmogorov (K), Shannon Entropy and Questionnaires (Q) methods. Figure 9 shows that of the elements addressed, the least analysed is the effect of production planning and scheduling, production volume and structural characteristics associated with the product and the plant. At the same time, there is a tendency towards static complexity and a low projection towards dynamic complexity.

Findings on Q5

The aim of question Q5 is to find out what type of models are used to measure complexity in a manufacturing environment. From the research in Table 6, Fig. 10 shows a high dominance of the different models towards static complexity and little development towards dynamic and mixed complexity. At the same time, it is worth highlighting a greater inclination towards mathematical models, which are also supported by conceptual and theoretical models.

Conclusion

In this paper, a systematic literature review has been carried out, synthesising the contributions of publications during the period 2000–2021. The review process was carried out with rigour, selecting and critically evaluating the predominant research over this period. It should be noted that the search for information was limited to the discipline of engineering, specifically in the industrial field, and to the thematic area of measuring complexity in manufacturing systems. This facilitates a greater approach and depth on the set of references studied. The review showed that complexity theory is immersed in manufacturing systems, due to the high variety, diversity and uncertainty in each of its components and

Table 6 List of outstanding model types for measuring complexity

Model	Complexity	Authors	Evaluation
Conceptual model	Static	Niu et al. (2020)	Development of the complexity of the dispatch area tasks
		Modrak & Soltysova (2018)	Operational complexity for the selection of the optimal design alternative
		Rios et al. (2015)	Analysis from the conceptual model working with people
		Modrak & Marton (2013)	Definition of a methodological structure for assembly lines in supply chains
		Mattsson et al. (2011)	Measure production complexity specifically by workstation
		Hussain et al. (2005)	Measuring structural complexity of a conceptual model
	Dynamic	Huang et al. (2014)	Complexity Conceptual Model of Lean Construction
		Dekkers et al. (2012)	Evaluation of suppliers in order to identify predominantly threaten the performance
	Static and dynamic	Eckstein et al. (2015)	Understand the interrelationships of a supply chain from a measure of complexity of agility
		Watkins & Kelley (2001) (Watkins & Kelley, 2001)	Structural complexity of the product, process and machine readiness
Theoretical Model	Static	Nagpal et al. (2013)	Complexity metric for multidimensional models for data warehouse
		Schoenherr (2010)	Complexity in the introduction of new products specifically ecological
		Schuh & Eversheim (2004)	Understand the factors that drive complexity in manufacturing systems
		Seuring et al. (2004)	Minimization of the number of derivative changes at the start of production
		Lin et al. (2001)	Reduction in the amount of resources used in a production process

Table 6 (continued)

Model	Complexity	Authors	Evaluation
	Dynamic	Clark & Jacques (2012)	The absolute complexity of a system from its configuration and structure
	Static and dynamic	Giachetti et al. (2003)	Structural and operational complexity considering the main characteristics of the system
Mathematical Model	Static	Zuzana et al. (2019)	Measuring Production Process Complexity
		Manuel et al. (2018)	Simulation and comparison of mathematical models of increasing levels of complexity
		ElMaraghy et al. (2014)	Evaluate the structural complexity of a manufacturing system in the physical environment
		Modrak et al. (2014)	Complexity based on product configuration and variations
		Cho et al. (2009)	Static complexity according to the operational efficiency of the machines
		Hu et al. (2008)	Measure performance from system configuration in assembly processes
		Arteta & Giachetti (2004)	Measure complexity by considering structural changes in the process
	Dynamic	Lazarev & Nekrasov (2017)	Mathematical models for enterprise resource scheduling:
		Zatopek & Urednicek (2017)	Dynamic behaviour comparison of three different mathematical model complexities
		Fan et al. (2017b)	They quantify the complexity from the human factor with respect to operating time
		Garbie & Shikdar (2011)	Complexity assessment based on a fuzzy logic approach
		Huatuco et al. (2009)	Balance of production with considerations of capacity and products in process
		Lee et al. (2006)	Analysis of the manufacturing system in search of fulfilling the relations of precedence
		Sivadasan et al. (2002) (Efstathiou et al., 2002)	Evaluation of critical stages of the production process with considerations of dynamic complexity

Table 6 (continued)

Model	Complexity	Authors	Evaluation
	Static and dynamic	Vidal et al. (2022)	Complexity in manufacturing systems under flow shop and hybrid environments
		Trabelsi et al. (2011)	Complexity and matematical model for flowshop problem subject to different types of constraint
		Isik (2010)	Measurements of structural and operational complexity in a manufacturing system
		Wu et al. (2007)	Comparative analysis between the operational costs and the complexity of the system
		ElMaraghy et al. (2005)	Measurement of complexity by means of process coding
		Efstathiou et al. (2012)	Evaluation of the complexity of manufacturing systems through experience

Fig. 4 Number of publications per year according to Q

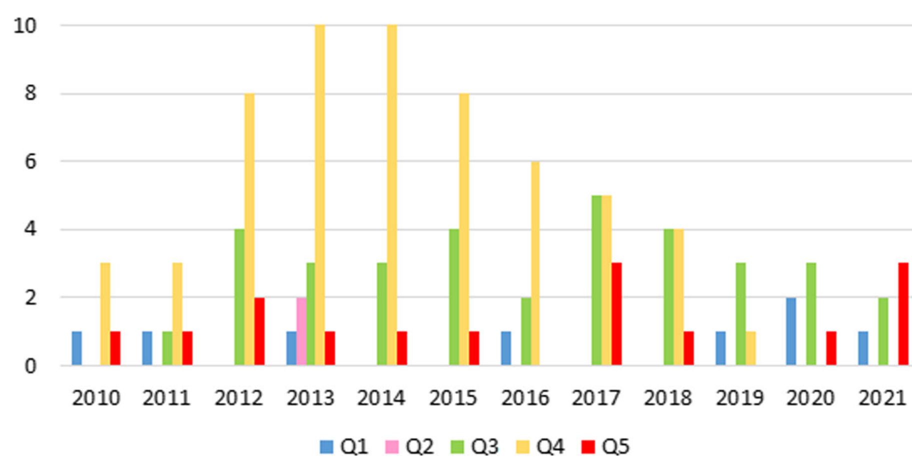
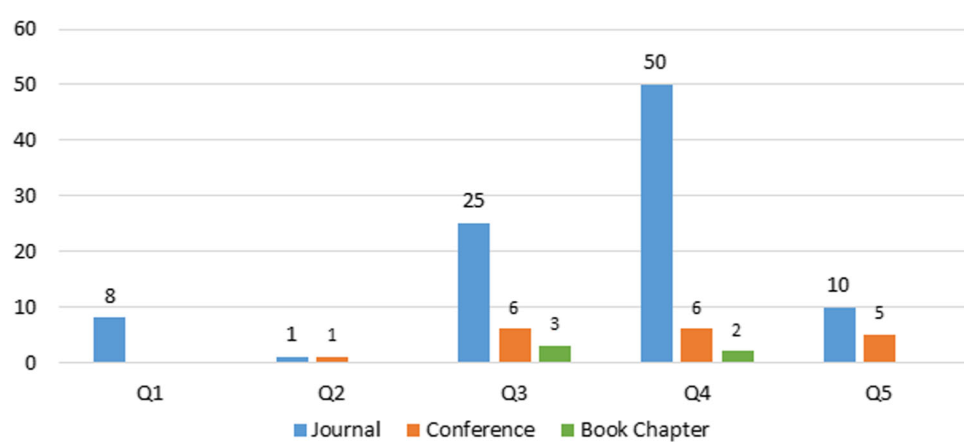


Fig. 5 Number of selected articles based on publication type



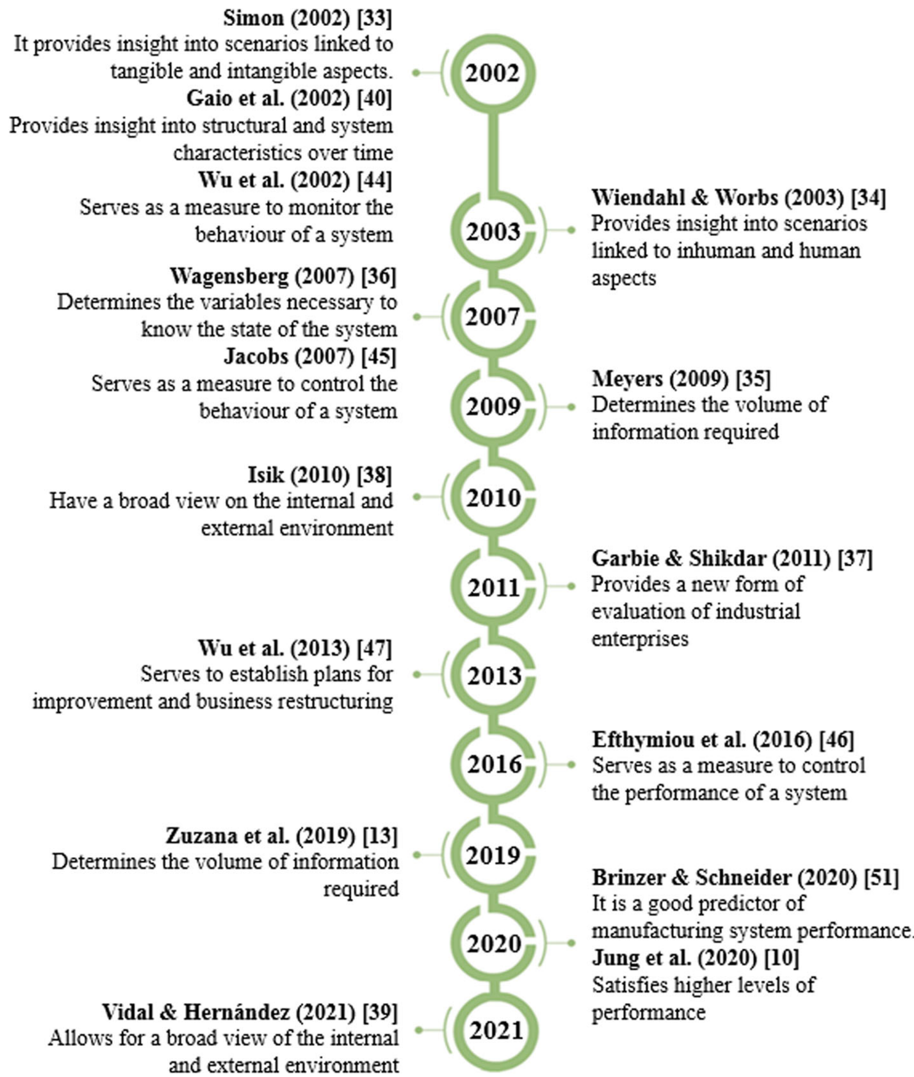


Fig. 6 Characteristics of importance identified

stages. Different approaches, methods, elements and models to measure complexity are distinguished in the literature, the most common approaches such as non-linear dynamics (ND), information theory (IT), hybrid methods (H), quantitative index (QI) and other approaches (OA). The characteristics of each approach were schematically demonstrated, opening up a spectrum for future challenges. In particular, the objectives were achieved, based on five designed questions (Q). The results show (i) A growing interest from the scientific community in issues related to approaches, methods and types of models for measuring complexity in a manufacturing environment. (ii) Recommendations by researchers in recent years towards system structural elements and uncertainty. (iii) Gaps or little development towards key elements for measurement such as people (Pe), products (Pd), planning and scheduling (Ps). (iv) Positive trend towards Lyapunov Exponents (LE), Kolmogorov (K), Shannon Entropy and Questionnaires (Q) methods. (v) High predominance of models towards static complexity and little development towards dynamic and mixed complexity. (vi) Greater inclination towards mathematical models, linked to optimisation techniques, algorithms and process simulation, and (vii) The use of performance indicators in addition to complexity for the measurement and evaluation of manufacturing systems. In summary, the measurement of complexity in manufacturing systems serves as a reference to focus improvement processes, allowing the management, reduction or elimination of high complexity in workstations, products, manufacturing processes and random variables that generate uncertainty in the system.

Table 7 Considerations for measuring complexity

Year	Quantity of products	Volume of resources	System structure	Uncertainty	Additive measures
2021	Vidal & Hernández (2021b)	Vidal & Hernández (2021b)	Vidal et al. (2022)	Vidal & Hernández (Vidal & Hernández, 2021b)	
2020			Jung et al. (2020)		
2019			Zuzana et al. (2019)	Gomes et al. (2019)	
2018	Modrak & Soltysova (2018)	Modrak & Soltysova (2018)		Huang et al. (2018)	
2016	Coronado (2016)			Coronado (2016)	
2015	Park & Kremer (2015)				
2013	Serdarasan (2013)	Vanmali et al. (2013)		Serdarasan (2013)	Serdarasan (2013)
2012		Elmaraghy et al. (2012)		Elmaraghy et al. (2012)	
2009	Bozarth et al. (2009)	Bozarth et al. (2009)			Bozarth et al. (2009)
2006	Größler et al. (2006)		Größler et al. (2006)		Größler et al. (2006)
2004		Seuring et al. (2004)			Perona & Miragliotta (2004)
2000					McCarthy et al. (2000)

Fig. 7 Research spectrum of compeljity measurement

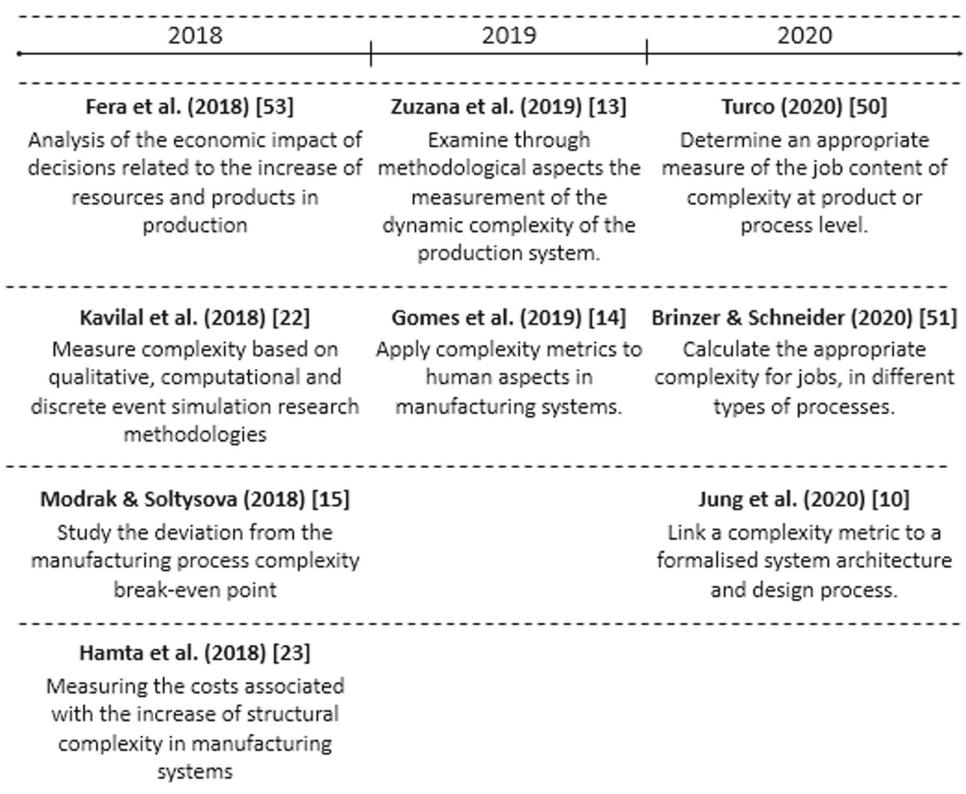


Table 8 Comparison between different characteristics

Comparison characteristics	DT	IT	QI	H	OA
Allows only dynamic complexity to be measured	●				
Allows to measure static and dynamic complexity		●	●	●	●
Analyses stochastic or random models		●	●	●	●
Apply visualisation techniques	●				
Applicable only for continuous models	●				
Applicable only for discrete models		●	●	●	●
Develops an analytical and quantitative perspective	●	●	●	●	●
Diversity in measurement				●	
Enable process stability	●				
Helps to understand the system		●	●	●	●
Integrates measures of complexity				●	
More complex analysis	●				
Models cannot be simplified	●				
Only applicable for dynamic models	●				
Reduces the degree of uncertainty in the systems		●	●	●	●
Specific location or machining centre	●				

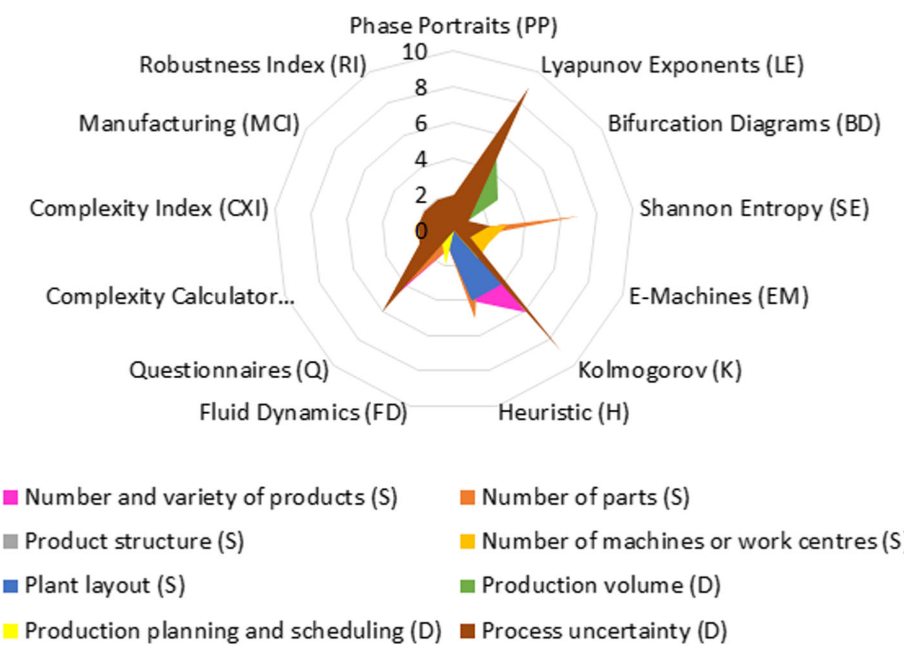


Fig. 8 Comparison between types of approaches

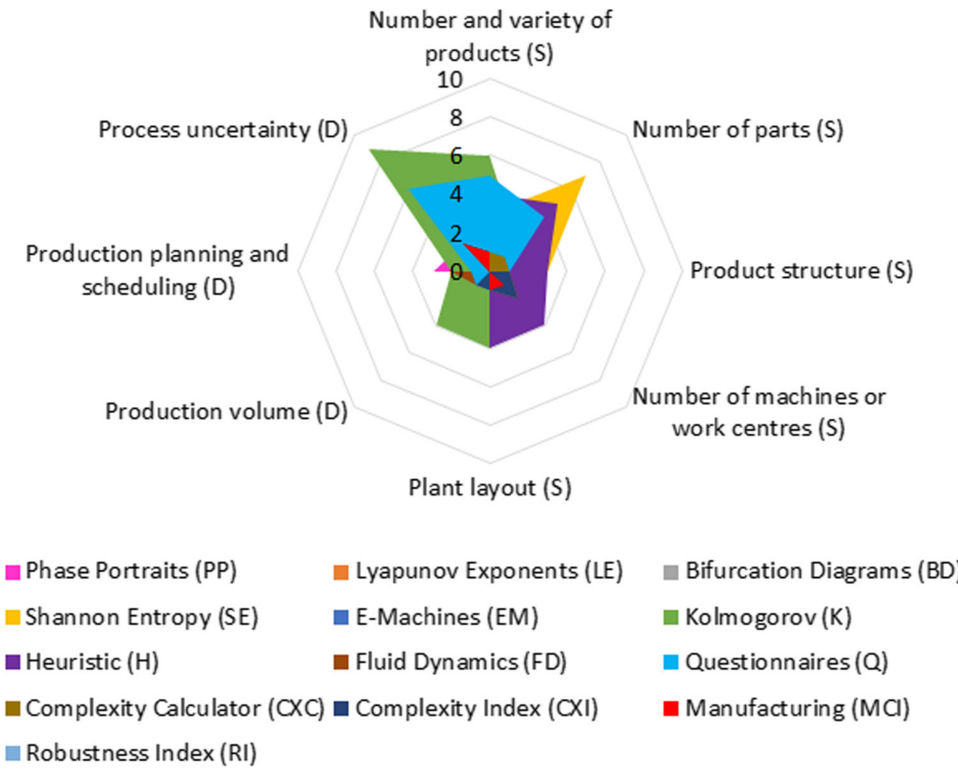


Fig. 9 Comparison between types of elements

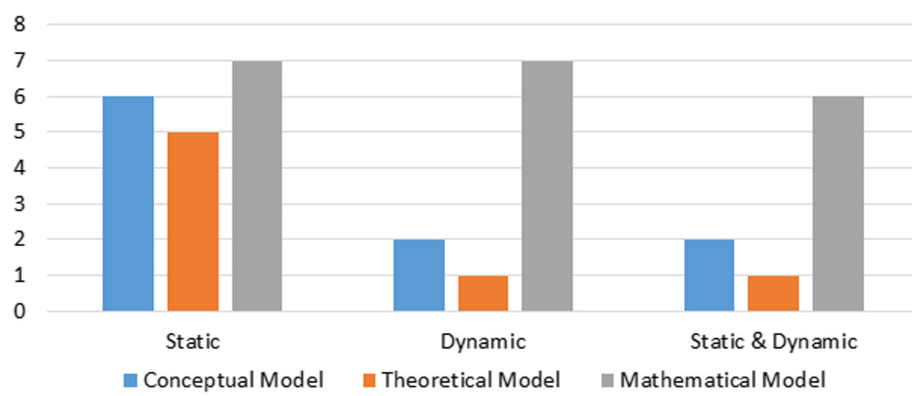


Fig. 10 Comparison between model types

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