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Abstract
This paper provides a comprehensive review of the scientific works that define a method for measuring or a measure of complexity in manufacturing systems. We analyse a total of 39 peer-reviewed journal articles by reference, methodology, theoretical background, type of complexity, unit of analysis and main topic (i.e. product, process, resources and overall system). We then provide a conceptual framework that identify six classes of measures by object of the measure (i.e. structure or behaviour of the measured system) and process of application of the measurement.

Keywords: Manufacturing, Complexity measure, Literature review

Introduction

The challenges of the current competitive environment such as globalization, shorter technology lifecycles and higher customisation requirements, resulted in an explosion of the variety of products, markets and processes that increased the complexity and the uncertainty faced by companies. As diversity, uncertainty, dynamism, and thus complexity of the external environment increase, organizations tend to configure manufacturing operations in a more complex way to aptly adapt to the fast pace of change.

In this line, Complexity Sciences, that study complex systems behaviour in evolving and adapting with external environment, can represent a new approach and a useful perspective for understanding manufacturing phenomena in front of variability and uncertainty of today's competitive challenges (McCarthy et al., 2010).

According to Calinescu et al. (1998) and Kamrani et al. (2011), complexity in manufacturing systems can be defined as a systematic characteristic that integrates key dimensions of the manufacturing environment within the organization such as structural aspects (size and variety), decision-making processes, information, dynamical aspects (in terms of uncertainty and control) and firm's objectives – i.e. costs and value. Being a systematic feature means that it is affected not only by the size and other structural properties of the manufacturing system, but also by the interdependences of the components (since each element depends on and influences the other) and the dynamic behaviour emerging from these relationships, that cannot be predicted from the individual components of the system (Cho et al., 2009).

The assessment of this systematic characteristic and in particular the discrimination between the complexity that leads to the creation of value for customers and the negative one (defined by Huaccho Huatuco et al. (2001) as "not value-adding complexity" – i.e. due to unexpected and not tolerated events such as delays, failures and reworks) is then relevant. In last decades the interest of academia towards modelling and "operationalisation of complexity in the form of a quantifiable complexity level" (Windt et al., 2008) in manufacturing organizations increased. Also from practitioners' point of view, measuring the level of complexity of the manufacturing system represents a key support to major operational decisions in production planning and control, since it's a prerequisite for comprehending and managing complexity at this stage (Efthymiou et al., 2014; Frizelle and Woodcock, 1995).

Starting from the well-established definition of manufacturing systems as being complex (McCarthy et al., 2010), several approaches and methods for measurement of complexity in manufacturing environment were developed. In this line, Frizelle and Suhov (2008) argue that literature covering the applications of measurement "is almost boundless". Due to the variety, uncertainty and higher order interactions among sources of complexity in manufacturing systems, as well as the computational effort associated to their modelling (Calinescu et al., 1998), a globally recognised and unifying framework that summarises both qualitative and quantitative analysis of manufacturing complexity is still lacking (Cho et al., 2009).

The purpose of this paper is to carry out a comprehensive review of the scientific works that define a method for measuring or a measure of complexity and to provide a conceptual framework that summarises the research results, in particular for works that deliver quantitative metrics.

The study wants to extend previous reviews on complexity in manufacturing, such as the one carried out by Efthymiou et al. (2012), that proposes a taxonomy of the approaches for quantitative analysis of manufacturing systems complexity, but without providing a deepen and crossed analysis of the variables of measurement, and the one carried by Garbie (2012), that performs a comprehensive research on complexity management in industrial firms without a summarizing framework.

In this sense, following the literature analysis, we derived a conceptual framework that identifies six classes of complexity measures in manufacturing systems, providing a comprehensive view of the different applications in operational contexts.

This work is organized as follows. In the first section the review methodology, the underlying research questions and the selection and evaluation criteria for articles are presented. In the next section, we analyse and synthesise the reviewed literature and then present the results and the framework development. The paper concludes with the key findings, implications for managers and paths for further investigation.

Methodology

For the purpose of this work, a systematic review of the literature related to the measures and the methods for analysis and measurement of complexity of manufacturing systems was performed.

Systematic reviews represent a major approach in evidence-based practice, since they allow a comprehensive identification of all research studies relevant to the review questions, a critical interpretation with specific criteria for highlighting the value of a body of previous literature, and an appraising research for transferring the synthesized findings both to academics and practitioners and policymakers (Rousseau et al., 2008; Denyer and Tranfield, 2009). Moreover, they address the underlying principles of transparency, clearness, and heuristics that enable high-quality research by minimizing bias and errors due to a stronger focus on objective observation and repeatability of results (Tranfield et al., 2003).

The process of selection and analysis of literature was then conducted following the methodology of “systematic review” that has been proposed by Rousseau et al. (2008) and Tranfield et al. (2003) in order to ensure inclusivity, objectivity and rigorousness.

Studies selection and evaluation process

As first step we formulated the two research questions of the review. In order to provide an insightful conceptual framework as a comprehensive summary of literature on measurement of complexity in manufacturing systems, the performed literature review aims to answer the following questions:

RQ1: What are the measures of manufacturing complexity proposed in literature?

RQ2: What is a classification of these measures?

In answering these research questions, the literature survey was undertaken by searching for different combinations of keywords, i.e. (“Manufacturing system” OR “Production” OR “Manufactur*” OR “Operations”) together with the phrases (“Complexity measure” OR “Measur* complexity”), ("Complexity metric" OR "Metric* of complexity"), ("Complexity analy*" OR "Analy* complexity"), ("Complexity evaluat*" OR "evaluat* complexity"), (“Complexity model” OR "Model* complexity"), ("Complexity assess*" OR "Assess* complexity"), ("Complexity map*" OR "Map* complexity"). The keyword research was carried out in major electronic databases, including Ebsco, Emerald, Science Direct, ISI Web of Science and JSTOR, as well as Scopus.

The following studies selection and evaluation process is illustrated in Figure 1.

First, we scanned the databases for the defined keywords without any reduction in the scope of journals and without time limits. To ensure the rigor of this systematic review, each contribution was independently read by the two authors to reduce subjective bias and enhance validity.

The first reading of titles and abstracts allowed to determine the collected works' relevancy to the first research question, in particular concerning the subject area of design, planning and operation by production management and control of manufacturing systems. Thus, contributions in other fields related to manufacturing sectors such as computer science and software development, and supply chain management – defined in terms of supplier-customer interface (Sivadasan et al., 2002) – were excluded.

In particular supply chain complexity at supplier-customer interface refers to transmission of operational complexity at interfaces between levels of supply chain and focuses indeed on complexity components at manufacturing system's boundaries, while we analyse internal complexity at plant level (Hu et al., 2008) – due to products portfolio, internal processes configuration, technologies.

Duplications were excluded as well. With this filter the analysis resulted in a preliminary sample of 530 articles.

As second step we excluded journal articles that weren't clearly focused on measurement or definition of models for measurement of complexity in manufacturing environment for the purpose of this study – i.e. that simply cited measures of complexity without further analysis, discussion, or detail. This selection was then limited to studies from peer-reviewed journal literature, ensuring a rigorous quality control of research results (Denyer and Tranfield, 2009). The outcome of this step was the identification of 32 contributions.

We then considered as one (selecting the most recent) the articles published by same author(s) that developed measurement frameworks in consecutive publications by adopting same assumptions and basic lines of reasoning. These are EIMaraghy and Urbanic (2003, 2004), selecting EIMaraghy and Urbanic (2004), and Zhang (2011, 2012), selecting Zhang (2012).

Finally, by reading the remaining 30 papers in their entirety, again by two authors autonomously, and their references lists, we identified other 9 additional papers that were relevant for the research topic.

The result of the review process was a total of 39 academic journal articles over a period of 20 years (from 1995 to 2014).

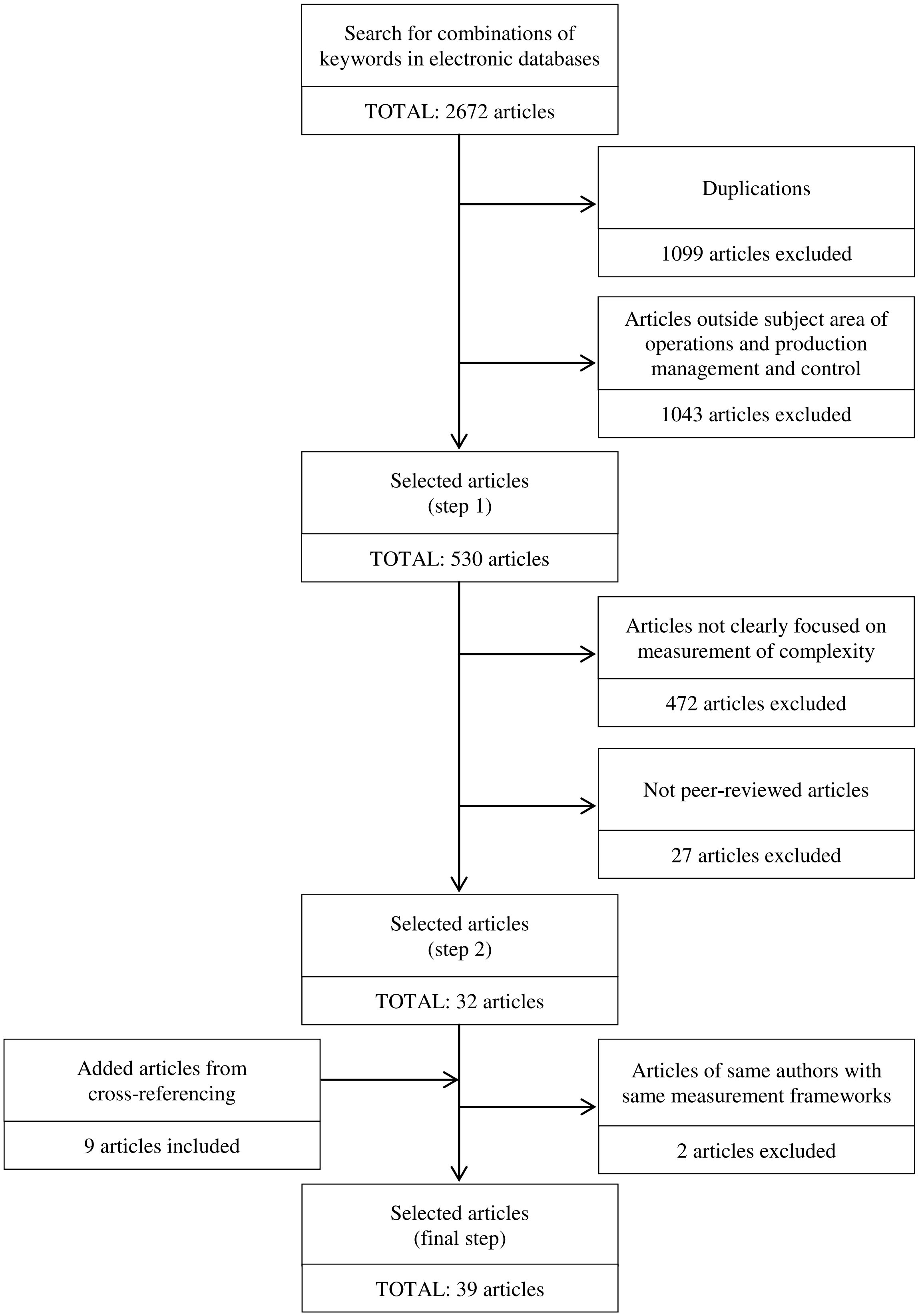

Figure 1 – Review process for selection of relevant contributions

Analysis of results

This section provides a comprehensive view of the outcomes of this review to address the underlying research questions.

Analysis of journal publications

The 39 selected articles were published in 23 interdisciplinary academic journals. More than half were contributed by leading journals such as *CIRP Annals - Manufacturing Technology*, *International Journal of Production Research*, *International Journal of Computer Integrated Manufacturing* and *IIE Transactions*, as shown in Table 1.

The numerous comprehensive studies on well-known journals on measurement of complexity in manufacturing environment highlights how this topic represents a basic prerequisite for comprehending and managing complexity, both from academic and practitioners point of view.

Table 1 – Number of articles published by academic journal

Academic journal publication	*No. of articles per journal*
CIRP Annals - Manufacturing Technology	6
International Journal of Production Research	6
Engineering Economist	2
IIE Transactions	2
International Journal of Advanced Manufacturing Technology	2
International Journal of Computer Integrated Manufacturing	2
Journal of the Operational Research Society	2
Research in Engineering Design	2
Advanced Materials Research	1
Assembly Automation	1
CIRP Journal of Manufacturing Science and Technology	1
International Journal of Flexible Manufacturing Systems	1
International Journal of Industrial and Systems Engineering	1
International Journal of Industrial Engineering	1
International Journal of Operations and Production Management	1
International Journal of Production Economics	1
Journal of Manufacturing Science and Engineering	1
Journal of Manufacturing Systems	1
Journal of Mechanical Design	1
Journal of Systems Integration	1
Lecture Notes in Computer Science	1
Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences	1
Strojniski Vestnik/Journal of Mechanical Engineering	1
TOTAL	39

As concern the year of publication, while we did not place a restriction on the publication date, our review identified a concentration of publications during the period 2008 – 2014 (70% of the sample), with a peak in 2011 and 2012 (13% and 15% respectively). This is due probably to the fact that awareness of the importance of studying measurement of complexity in operations grew with the recent initiatives of major research centres on these topics – i.e. Santa Fe Institute and University of Cambridge – such as the special issue "Tackling Industrial Complexity: The Ideas That Make a Difference" promoted by Frizelle and Richards within the 2002 conference of the Manufacturing Complexity Network. Furthermore, complexity in manufacturing systems has been the subject of numerous Ph.D. dissertations and master theses in the last few years (see ElMaraghy et al. (2012) for the complete list of this kind of publications).

Analysis of reviewed articles

Table 2 classifies all reviewed articles by reference, methodology, theoretical background, type of complexity and unit of analysis.

Regarding surveyed articles' research methodologies, we classified them into conceptual (including mathematical models), case study or multiple case studies and simulation. This type of classification allows indeed to highlight scope of applicability of the measure. The following in-depth analysis on the targeted unit of the proposed measures shows whether the measurement process was focused on the product, on a specific type of manufacturing plant/layout of application or not (i.e. the unit of analysis was general or not specified).

We furthermore identified the different types of manufacturing complexity starting from the definitions discussed in the literature, that distinguish from each other according to the variables and issues of manufacturing system being investigated.

Wiendahl and Scholtissek (1994) divided manufacturing complexity into complexity of the products themselves and complexity in production. This distinction was later rephrased by Efthymiou et al. (2012), that defined complexity into two types dependent upon the domain, namely the *functional* and the *physical* domains.

In the functional domain, complexity is contextual to engineering design and is defined as a measure of uncertainty in achieving (and then not satisfying) a set of tasks defined by the functional requirements of the system. This type of complexity can be further divided into time-independent – referring to uncertainty at all times, due to designer lacks in knowledge or understanding of the system and its components – and time-dependent, that increases as a function of time or exists in a finite time period, depending on the number of possible combinations of system's states (Suh, 1999).

The complexity in production or in physical domain refers to complexity of production structures, or *structural complexity*, and complexity of production procedures, or *dynamic complexity* (Wiendahl and Scholtissek, 1994). More specifically, according to many scholars (among others Deshmukh et al. (1998), Elmaraghy et al. (2012)):

- *structural or static complexity* of a manufacturing system is characterised by the design dimension or architecture of the system (given by the different system components and how they relate to each other) and its state at a given time;
- *dynamic or operational complexity* concerns unpredictability in the behaviour of the system over a period of time and relates to its real-time operation, material flow patterns, modules reliability and variations that occur in dates and amounts, due to different causes, e.g. material shortness, breakdowns, absenteeism of machines, that negatively affect companies performances.

Following these definitions, we then distinguished type of complexity in Product/ Functional, Static/structural and Dynamic/operational.

Table 2 – Analysis of reviewed literature

No.	*Reference*	*Research Methodology*	*Theoretical background*	*Type of complexity*	*Unit of analysis*
1	Ameri et al. (2008)	Conceptual	Axiomatic Design	Product / Functional	design products with different physical and functional structures
2	Cho et al. (2009)	Conceptual	Information Theory	Static / structural	general manufacturing systems, not specified
3	Deshmukh et al. (1998)	Conceptual	Information Theory	Static / structural	systems producing discrete parts without assembly / disassembly operations
4	Dierneder and Scheidl (2001)	Conceptual	Axiomatic Design	Product / Functional	general product design process, not specified
5	Efthymiou et al. (2014)	Simulation	Information Theory	Dynamic / operational	assembly lines
6	El-Haik and Yang (1999)	Conceptual	Axiomatic Design	Product / Functional	general engineering design process, not specified
7	ElMaraghy and Urbanic (2004)	Conceptual	Information Theory	Dynamic / operational	products and machining processes
8	ElMaraghy et al. (2014)	Multiple case studies	Theory of graphs	Static / structural	different class of manufacturing systems layout
9	ElMaraghy et al. (2005)	Conceptual	Information Theory	Static / structural	general manufacturing systems, not specified
10	Frizelle and Suhov (2008)	Multiple case studies	Information Theory	Dynamic / operational	input-output systems with queuing behaviour
11	Frizelle and Woodcock (1995)	Multiple case studies	Information Theory	Dynamic / operational	production systems and subsystems (e.g. lines)
12	Garbie and Shikdar (2011)	Multiple case studies	Optimization	Dynamic / operational	manufacturing system at organisational level
13	Guide et al. (1997)	Simulation	Optimization	Dynamic / operational	different dimensions of product reassembly
14	He and Zhu (2013)	Conceptual	Information Theory	Static / structural, Dynamic / operational	different layers of assembly system
15	Hu et al. (2008)	Conceptual	Information Theory	Static / structural	mixed-model assembly workstations and systems
16	Jenab and Liu (2010)	Multiple case studies	Theory of graphs	Static / structural	job shop manufacturing systems
17	Kamrani et al. (2011)	Simulation	Information Theory	Dynamic / operational	assembly systems with high product variety
18	Kuzgunkaya and ElMaraghy (2006)	Conceptual	Information Theory	Static / structural	different manufacturing system configurations

19	Makui and Aryanezhad (2003)	Conceptual	Information Theory	Static / structural	general manufacturing systems, not specified
20	Martinez-Olvera (2012)	Simulation	Information Theory	Static / structural	job shop manufacturing systems
21	Orfi et al. (2011)	Conceptual	Information Theory	Product / Functional, Static / structural	general dimensions of families of products and production systems
22	Orfi et al. (2012)	Case study	Information Theory	Product / Functional, Static / structural	different product lines
23	Papakostas et al. (2009)	Simulation	Nonlinear dynamics	Dynamic / operational	different configurations of manufacturing models
24	Samy and ElMaraghy (2010)	Multiple case studies	Information Theory	Product / Functional	product design for assembly processes
25	Samy and ElMaraghy (2012a)	Case study	Information Theory	Static / structural	automated assembly systems structure
26	Samy and ElMaraghy (2012b)	Conceptual	Information Theory	Product / Functional, Static / structural	product design and automated assembly systems
27	Sarkis (1997)	Simulation	Optimization	Dynamic / operational	flexible manufacturing systems
28	Smart et al. (2013)	Conceptual	Information Theory	Dynamic / operational	general manufacturing systems, not specified
29	Sobrinho (1999)	Conceptual	Theory of graphs	Static / structural	single production processes
30	Suh (1999)	Conceptual	Axiomatic Design	Product / Functional	generic product at design level
31	Summers and Shah (2010)	Conceptual	Information Theory, Axiomatic Design	Static / structural	mechanical system (product or process) design
32	Valentan et al. (2011)	Simulation	Optimization	Static / structural	models for technology of manufacturing procedures
33	Vrabic and Butala (2011)	Case study	Information Theory	Dynamic / operational	manufacturing processes
34	Vrabic and Butala (2012)	Simulation	Information Theory	Dynamic / operational	different configurations of manufacturing systems
35	Wang and Hu (2010)	Simulation	Information Theory	Static / structural	different configurations of assembly systems
36	Yu and Efstathiou (2006)	Simulation	Information Theory	Static / structural	manufacturing systems including rework cells

37	Zeltzer et al. (2013)	Simulation	Optimization	Static / structural	mixed-model assembly workstations
38	Zhang (2012)	Case study	Information Theory	Static / structural, Dynamic / operational	cellular manufacturing system
39	Zhu et al. (2008)	Conceptual	Information Theory	Static / structural	mixed-model assembly lines

From the analysis of the research methodologies it emerges that most of scholars developed simulations and conceptual papers, without identifying a specific context of application. This highlights again that the computational effort associated to the modelling of the interactions between interactions among sources of complexity in manufacturing systems (Calinescu et al., 1998) makes its measurability even harder. In this line, many scholars tested their measures or models on single work stations (e.g. Zeltzer et al. (2013) in mixed-model assembly workstations), single processes (e.g. Dierneder and Scheidl (2001) in product design and Efthymiou et al. (2014) in assembly lines) or specific type of manufacturing systems (e.g. Jenab and Liu (2010) in job shop manufacturing systems, Sarkis (1997) in flexible manufacturing systems and Zhang (2011, 2012) in cellular manufacturing systems).

Concerning the theoretical background of analysed papers, we identified five main theories: Information Theory, Axiomatic Design, Theory of graphs, Optimization and Nonlinear dynamics. Information Theory and Axiomatic Design, as most present theoretical background in numerous papers, are discussed in detail in the following paragraphs.

Theory of graphs was mentioned referring to articles that represented the targeted system as a graph – set of nodes and arches – and developing measures for graphs analysis. For example, Jenab and Liu (2010) measured the relative manufacturing complexity and manufacturing similarity for products in job shops, by representing relations between product and processing time and types of resources or skills required for product in a graph-based model.

The underlying theory indicated as Optimization refers to articles developing mathematical models that use deterministic indexes. Garbie and Shikdar (2011) evaluated complexity of manufacturing system at organizational level from relationships of different elements of manufacturing environment such as product structure, system design and status of operating resources with the use of a fuzzy logic approach Guide et al. (1997) proposed a mathematical model for product structure complexity considered in the dimensions of reassembly, depth and routing, in scheduling decisions. Sarkis (1997) used DEA models for measuring complexity by number of machine tools and industrial robots within a system. Valentan et al. (2011) modelled parts complexity in function of the technology used in the manufacturing procedures.

Finally, Papakostas et al. (2009) investigated the complexity of manufacturing systems as stability of the system in function of workload changes, using discrete event simulation and Nonlinear dynamics theory.

Information Theory

The majority of reviewed articles refer to Information Theory introduced by Shannon in his work on a mathematical theory of information or general theory of communication (Shannon, 1948). From an information-theoretic perspective, entropy is defined as the amount of information required to describe the state of the system. Hence, since the complexity of a system increases with increasing levels of disorder and uncertainty, in other words with increasing entropy, the level of complexity can be measured as an increase in the amount of information required to describe the state of the system (Calinescu et al., 1998).

From this theoretical perspectives Cho et al. (2009), Deshmukh et al. (1998), ElMaraghy et al. (2005) and Makui and Aryanezhad (2003) proposed structural complexity measures in general manufacturing systems producing discrete parts. Cho et al. (2009) characterised complexity as function of interactions among machines that influence each another in terms of queuing times and self-interactions in terms of processing times. Also Deshmukh et al. (1998) evaluated interactions among machines as key driver of complexity, together with processing requirements and mix of parts to be produced. Makui and Aryanezhad (2003) measured static complexity of function of number and possible states of resource considering the different distributions and weights of the different states. ElMaraghy et al. (2005) measured a Structural Complexity Index that captures the variety and amount of information present in a system and its components, i.e. rsources number, configuration and availability.

Other scholars, such as He and Zhu (2013), Hu et al. (2008), Wang and Hu (2010) and Zeltzer et al. (2013), measured structural or static complexity at the different levels of assembly workstations, lines or systems. In this sense they focused on key elements of assembly processes as variables affecting complexity, e.g. the assembly technology (He and Zhu, 2013), configuration of assembly stations (Wang and Hu, 2010), product variety (Hu et al., 2008), tools per workstation (Zeltzer et al., 2013).

Later Wang and Hu (2010) presented a measure of manufacturing complexity based on the choices of assembly activities that operators make in serial, manual mixed-model assembly lines, in response to the products variations.

Other authors that focused on the operators role in determining total complexity were ElMaraghy and Urbanic (2004), that developed metrics for measuring product complexity, process complexity and operational complexity within the manufacturing system in relation to the effects of human worker attributes (characteristics, needs, skills and capabilities) and their perception of the tasks' complexity. They introduced a methodology for systematically modelling the complexity for any manufacturing environment based on three elements: total quantity of information, diversity of information and the information content, which corresponds to the effort to produce a feature within a product. Later Kuzgunkaya and ElMaraghy (2006) used the same elements to measure the structural complexity of manufacturing systems based on the complexity inherent in the structure of its components: machines, buffers, and Material Handling Systems (MHS).

Orfi et al. (2011, 2012) measured product complexity for different product families in five main dimensions (variety, functional index, structural index, design index, and production index) that were identified as strictly connected to production process (lines) complexity in terms of process variety, specificity and coupling.

Finally, many articles are focused on measurement of dynamic or operational complexity as emerging from interactions between main elements of the manufacturing system. Frizelle and Woodcock (1995) studied complexity as function of the behaviour of the queues (in terms of length, variability and composition) and states of resources (distinguishing between programmable and not programmable). Also Frizelle and Suhov (2008) focused on dynamics of their internal queues. Kamrani et al. (2011) built a simulation model of dynamic complexity by concentrating on effect of high product variety. Vrabic and Butala (2011, 2012) derived the measure of operational complexity from statistical complexity, by mapping casual states of the process (operation state and process parameters) in different configurations of manufacturing systems. Finally, Zhang (2012) measured dynamic complexity in terms of schedule adherence (as degree of accordance between the actual states of resources and the original scheduling plan) in the schedule horizon.

Axiomatic Design

On the amount of information used as a measure of complexity is based also the Axiomatic Design Theory by Suh (1999), that has been successfully applied in the design of engineered systems including in manufacturing. In this domain Suh (1999) defined complexity as a measure of uncertainty of design parameters in achieving the set of functional requirements to be satisfied. In this line, Summers and Shah (2010) described the design process as an iterative problem solving process that aims to find solutions satisfying the functional requirements by combination of designer experience, rules, procedures, or domain knowledge used. They identified three aspects to measuring complexity of a generic mechanical system (product or process): size, coupling and solvability. From the same assumptions El-Haik and Yang (1999) identified as key components of complexity in design the variability of design parameters and the vulnerability in achieving the functional requirements. Starting from the second information axiom in Axiomatic Design – that states that a good design requires minimal information – Ameri et al. (2008) developed two measures of size and coupling complexities of design products with different physical and functional structures. Dierneder and Scheidl (2001) defined instead complexity as "not a unique property of a system per se but a matter of human comprehension of it", identifying three complexity values for different design stages: functional, technical and reliability product complexity.

Discussion

In this section an analysis concerning the main topic of the reviewed articles is proposed (Table 3). In detail this last parameter refers to main elements and parameters of manufacturing system considered in the measurement system, and their interactions observed in order to quantify the overall level of complexity. We identified six main classes of macro-elements of analysis in the reviewed measures/models:

- Product in the functional domain (at design and engineering level)
- Product in the physical domain (at production level)
- Process (at production level)
- Human resources
- Physical resources (i.e. machines/stations, tools or buffers)
- System (as a whole, concerning performances and production management).

Table 3 – Main topics of complexity measurement in reviewed literature

Macro-elements	*Elements*	*Articles*
Product (functional domain)	Functional tree / requirements	4, 6, 30, 31
	Controllable attributes (e.g. material, width, height)	1, 7, 21, 22, 24, 25, 26, 30, 32
	Non-controllable attributes (e.g. weight, area, inertia)	1, 24, 25, 26, 30
	Relations between design variables	1, 6
	Functional / design couplings	1, 4, 21, 22, 30, 31
	Technical design parameters	4, 7, 21, 22, 30, 31
	Specifications	7, 21, 22, 32
	Reliability (manufacturing / assembling)	4, 6, 29
	Vulnerability	6
	Solvability	31
Product (physical domain)	Part mix / components (number)	3, 7, 12, 15, 20, 24, 25, 26, 29, 37, 39
	Products (number / variety / variants)	12, 15, 18, 21, 22, 35, 37
	Bill of material / product structure	11, 20, 21, 22, 29, 39, 13
	Commonality of components	21, 22
Process	Processes (number)	3, 12
	Steps / tasks	7, 14, 16, 20, 23, 29, 33, 34, 13
	Routings / sequences / paths	2, 17, 20, 21, 22, 33, 34, 36, 13
	Queueing / arrivals times / rates	2, 3, 10, 11, 12, 28, 36
	Sequence constraints	3, 14
	Sequence / routing flexibility	3, 21, 22, 36, 39
	Process / operation / job / task times	5, 12, 14, 16, 23, 27, 32, 38, 39
	Setup times	5, 14
	Motions / directions of assembly	24, 25, 26, 37
	Technology	14, 37
	Packaging type	37
	Variability (manufacturing / assembling)	14, 21, 22, 24, 25, 26, 35, 38, 39
Human Resources	Operators / personnel	7, 9, 15, 16, 27, 37, 38
	Physical effort	7, 24, 25, 26, 29
	Cognitive effort	7
	Operator's choices	15, 35, 39
	Skills / experience / knowledge	16, 30, 31
Physical resources	Machines / stations (number)	2, 3, 7 , 9, 14, 16, 17, 18, 19, 20, 24, 25, 26, 33, 34, 38
	Machines / stations (type)	8, 18, 27
	Machines / stations (sequence layout)	8, 18, 14, 24, 25, 26, 39
	Interactions / relations between resources	2, 8, 14, 15, 16, 39
	Tools / equipment	7, 14, 15, 27, 33, 34, 37, 39
	Gauges	7
	States of resources (planned or actual)	10, 11, 15, 17, 19, 28, 33, 34, 36, 38
	Modules / areas / Work centres / units	8, 11, 20, 38, 13

System	Buffers	9, 18, 24, 25, 26
	Machines reliability	18
	Performance indicators	5, 21, 22
	Material flows / handling	8, 9, 14, 15, 18, 24, 25, 26, 27
	Planning decisions	12, 14, 17

From this analysis emerge the elements that were mostly analysed in complexity measurement. Many scholars referred to product attributes controllable by the designer, to design parameters and to functional couplings in developing measures of product complexity in the functional domain. In the physical domain, all key elements characterising products (the part mix, the variety and the product structure) are taken in account in the same percentage. From resources point of view, human resources are considered a key factor in determining manufacturing complexity only in few paper, while parameters of physical resources such as number and type of machines, their states (planned or actual), their interactions and the use of tools are cited in numerous works. Finally, as regards processes, many papers concentrate on number of tasks, routings, processing or queueing times in both operations and assembly sequences, including also material flows between the single work stations and in general in the manufacturing system.

The developed classification can be used as a first decision support tool to identify and manage major sources of complexity. Following this preliminary analysis, a conceptual framework summarising and consolidating the previous analysis results is proposed. The framework is built by selecting two key variables for measurement:

- the *object* of the measure: we distinguished between the structure (or configuration) of the system (related to the key components of a systems – i.e. the overall manufacturing system or the product – and their interdependencies) and the behaviour of the system (in terms of randomness and unpredictability of the behaviour emerging from the interactions between the system's components) as key characteristics of complex systems;
- the *process* of application of the measurement: in this case we analysed the types of manufacturing processes involved (i.e. product design, production operations and assembly operations), since they identify different production management and control (and accordingly complexity measurement) strategies.

From the intersection of the two variables we obtained six classes of measures of manufacturing complexity, that represent an important process-oriented reference for addressing measurement of complexity in each operational context. A measure can be part of more than one class, if it was derived in function of different main components (e.g. ElMaraghy and Urbanic (2004) included both product and process complexity in their measure).

In particular the first two classes of measures, within product design process, are identified referring to the division of the domains for products presented in Table 3, where we distinguished between product in functional domain (translated in *structure*) and product in physical domain (translated in *behaviour*, since we included elements of physical layout of product, that emerge in relation with processes and resources of the manufacturing system at production planning stage).

We then defined the six classes of measures as shown below, starting from definitions and names of the measures included in the same class.

Table 4 – Conceptual framework classifying complexity measures in manufacturing systems

		TYPE OF MANUFACTURING PROCESS		
		Product design	Production operations	Assembly Operations
OBJECT	Structure / configuration	1 *Measures of product structure complexity at design stage* (1, 4, 6, 21, 22, 30)	3 *Measures of manufacturing system structure for production operations* (2, 3, 8, 9, 16, 18, 19, 20, 29, 31, 32, 36, 38)	5 *Measures of manufacturing system structure for assembly operations* (14, 15, 25, 35, 37, 39)
	Behaviour	2 *Measures of product behaviour complexity at production stage* (21, 22, 24, 26, 31)	4 *Measures of manufacturing system behaviour for production operations* (7, 10, 11, 12, 23, 27, 28, 33, 34, 38)	6 *Measures of manufacturing system behaviour for assembly operations* (5, 13, 14, 17, 24, 26)

1) Measures of product structure complexity at design stage

This class includes *Size complexity* and *Coupling complexity* from [1], *Functional Product Complexity*, *Technical Product Complexity* and *Reliability Product Complexity* from [4], the *component of complexity due to variability* and the *component of complexity due to vulnerability* in engineering design from [6], some of the *Product complexity dimensions* (*Variety*, *Functional Index*, *Design Index*) from [21], the *Customer Sensitivity Level*, *Tolerance Level*, *Interconnectivity Level*, *Coupling Level* from [22], the *Time-Independent Complexities* (*Real Complexity*, *Imaginary Complexity* and *Absolute Complexity*) and the *Time-Dependent Complexity* (*Time-Dependent Combinatorial Complexity* and *Time-Dependent Periodic Complexity*) from [30].

2) *Measures of product behaviour complexity at production stage*

This class includes the other *Product complexity dimensions* from [21] not included in class 1 (*Structural Index*, *Production Index*), the *Product Variety Index*, *Component Variety Ratio*, *Process Variety Ratio*, *Part-Level Index* from [22], the *Product assembly complexity* from [24], the *Handling attributes complexity* and *Insertion attributes complexity* of parts from [26], the measures of *Complexity as Coupling* and *Complexity as Solvability* from [31].

3) *Measures of manufacturing system structure for production operations*
This class includes the *Interaction-based complexity measure* from [2], the *Static complexity* from [3], the *Layout structural complexity* from [8], the *Structural Complexity Index* from [9], the *Manufacturing complexity graph-based model* from [16], the *Structural complexity of manufacturing systems configurations* from [18], the *Static complexity* from [19], the complexity in terms of *BOM's blocking effect to process flow* from [20], the *Component Scope Measures* and *Process Scope Measures* from [29], the *Complexity as Size* from [31], the *model complexity* for manufacturing procedures from [32], the *sequence disorder complexity* and the *router complexity* from [36], the *Static entropy* from [38].

4) *Measures of manufacturing system behaviour for production operations*
This class includes the *Operational Complexity Index* from [7], the *entropy rates* of queues from [10], the *dynamic complexity* derived from queuing observation from [11], the *complexity level in industrial organisations* from [12], the *time-dependent combinatorial complexity of the manufacturing systems* from [23], the *technical complexity* in flexible manufacturing systems [27], the *dynamic complexity as deviation from schedule* from [28], the *Operational complexity* from [33], the *Statistical complexity* calculated from the observation of manufacturing processes from [34], the *average Dynamic entropy* from [38].

5) *Measures of manufacturing system structure for assembly operations*
This class includes the *Static complexity* (divided in *Assembly technology complexity* and *Static structure complexity*) and the *Process complexity* (divided in *Assembly process complexity* and *Material distribution complexity*) from [14], the *Station level complexity* and *System level complexity* for mixed-model assembly systems from [15], the *Complexity index for assembly system modules*, the *Equipment complexity* and the *System complexity model for assembly systems* from [25], the measures for *complexity of mixed-model assembly systems (MAS) with different configurations* from [35], the measurement of impacts of variables driving complexity in mixed-model assembly workstations from [37], the *Operator Choice Complexity* at station level in mixed-model assembly lines in [39]

6) *Measures of manufacturing system behaviour for assembly operations*
Finally, this class includes the manufacturing system weighted mean unpredictability in assembly lines from [5], the *Reassembly complexity* and the *Routeing Complexity* from [13], the *Control complexity* from [14], the *dynamic complexity* of operations in assembly systems in [24], the Assembly equipment complexity from [26].

Most studied measures then fall within class 3, concerning manufacturing system structure (or configuration) for production operations. This can be explained by the less computational effort required in measuring effects of systems components and interactions to overall system complexity, compared to one required to measure its emerging behaviour – that implies systems for control and real-time interventions. Moreover, measures clearly defined for assembly processes requires in average taking in account numerous variables, from motions/directions of assembly to handling attributes of components to be assembly (Samy and ElMaraghy, 2012b). The distribution of works among the other classes of complexity measures is quite homogenous.

Conclusion

The above findings result from an exhaustive and structured review of extant research on measuring complexity of manufacturing systems. By means of a systematic literature review methodology we obtained an overview of the relevant studies and extracted the different criteria used in development of a complexity measure in manufacturing context.

We identified five main theoretical backgrounds (Information Theory, Axiomatic Design, Theory of graphs, Optimization and Nonlinear dynamics) and six main classes of macro-elements of analysis in the reviewed measures/models – i.e. product in the functional domain (at design and engineering level), product in the physical domain (at production level), process (at production level), human resources, physical resources (i.e. machines/stations, tools or buffers) and system (as a whole, concerning performances and production management). Starting from this previous analysis, we built a framework that classifies the reviewed works by the object of the measure (i.e. structure or behaviour of the measured system) and process of application of the measurement (i.e. product design, production operations and assembly operations), obtaining a quite homogenous distribution between the resulting six classes. Measures of complexity of system structure or configuration regarding production operations emerged as the most numerous ones, probable to the minor computational effort required.

This work extends the review carried out by (Efthymiou et al., 2012), that identified four main categories of approaches for quantitative analysis of manufacturing systems complexity, based on their theoretical foundations, i.e. chaos and non-linear dynamics theory, information theory, hybrid and other. The new framework defines indeed six new classes of complexity and in addition is based on key dimensions of measurement, offering a practical reference for identifying the most appropriate metrics for different manufacturing organizations, with different objectives and production strategies.

The paper is then valuable both to scholars and practitioners dealing with manufacturing issues, since it provides comprehensive insights and guidance for different directions of application of quantitative complexity analysis.

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