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Product complexity and quality in assembly processes: state-of-art and challenges for Human-Robot Collaboration

Capponi, M.¹⁾, Mastrogiacomo, L.¹⁾, Antonelli, D.¹⁾, Franceschini, F.¹⁾

¹⁾ Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Turin, Italy

STRUCTURED ABSTRACT

Purpose - It is widely accepted in quality management that product complexity is a primary cause of defects. A primary goal of this work is to provide a comprehensive review of complexity assessment methods to highlight different approaches and their application purposes. Moreover, the spread of collaborative robotics in industrial environments has also led to the consideration of a new definition of assembly complexity. This article attempts to fill this gap, with the specific aim of understanding which of the available methods may be suitable for modelling “complexity” in human-robot collaboration (HRC).

Design/methodology/approach – A systematic literature review of complexity assessment methods in manufacturing is carried out. From this analysis, three main approaches to complexity assessment emerged. A practical case is then introduced to test each of the three previous approaches and to highlight their strengths and weaknesses, with a special focus on their future adaptation to a collaborative assembly process.

Findings - To date, none of complexity assessment methods is specifically able to face the problem of interaction between agents (i.e., humans and robots). Only system-centered approaches hypothesize a holistic view of complexity, including some variables that are also crucial in the assessment of human-robot collaboration.

Originality/value – This article aims to extend the concept of industrial quality to HRC. In this framework, it cannot be ignored the fact that the dynamics of interaction between agents can equally influence both process and product quality.

Keywords: Complexity assessment, Assembly process, Quality control, Human-Robot collaboration

Paper type: Research paper

1. INTRODUCTION

The world of manufacturing has been facing new challenges in recent years. The spread of Industry 4.0 principles has put humans back at the center of manufacturing processes, introducing the concept of human-centered manufacturing (Mital and Pennathur, 2004; Oztemel and Gursev, 2020; Xu *et al.*, 2018). One of the most promising enabling technologies of this transition is collaborative robotics. Unlike traditional robots, humans and cobots work simultaneously in a shared workspace (Bauer *et al.*, 2008; Goodrich and Schultz, 2008). In this way, humans can be replaced by machines in the most exhausting and repetitive operations, but at the same time they make up for the rigidity of robots with their flexibility and dexterity in the most complicated operations. Collaborative robotics is widely used in assembly processes where humans and cobots cooperate basing on a predefined assignment of tasks with the common goal of assembling a product. In literature, this process is known as collaborative (or HRC) assembly. Considering this, traditional quality control paradigms should also be revisited. Many studies showed that structurally complex products can increase the probability of defects in manually assembled products (Genta *et al.*, 2018; Su *et al.*, 2009; Verna *et al.*, 2021). Although product complexity remains an important source of defects, it is necessary to adopt a multidimensional approach for the assessment of complexity in a collaborative assembly, including variables such as safety, human-robot communication, task organization, physical and psychological well-being of operators. While much research has been done on the assessment of complexity of a manual assembly, there is a gap of knowledge about effects of the variables that may impact the complexity of collaborative assembly. The complexity of human-robot interaction, indeed, may negatively affect the entire assembly process and lead to the occurrence of new process defects and thus product defects. This work attempts to preliminarily answer the following research question: *Are existing complexity assessment methods suitable to analyze HRC in collaborative settings?* This paper is organized in the following way. The first section provides an extensive literature review on assembly complexity methods, identifying three main approaches. In the second part a practical case study is introduced to comparatively evaluate different approaches. The final section concerns a preliminary analysis performed to identify which crucial dimensions in assessing the complexity of collaborative assembly would be covered or uncovered by existing methods.

2. ASSEMBLY COMPLEXITY: A LITERATURE REVIEW

This section contains an extensive literature overview on methods for assessing manufacturing complexity in assembly tasks.

2.1. Methodology

The literature review is based on the analysis of a sample of journal articles obtained throughout the following Scopus query string: “(*TITLE-ABS-KEY* ((*"structural complexity"* OR *"product complexity"* OR *"process complexity"* OR *"task complexity"* OR *"complexity analysis"* OR *"complexity metrics"* OR *"Perceived production complexity"* OR *"operational complexity"* OR *"manufacturing complexity"* OR *"production complexity"*) AND (*"manufacturing"* OR *"production"* OR *"assembly"*))) AND (*LIMIT-TO* (*SUBJAREA*, *"ENGI"*)) AND (*LIMIT-TO* (*DOCTYPE*, *"ar"*))”. The rationale behind the definition of this query string was to include the following elements:

1. core content: a list of keywords concerning complexity assessment and metrics
2. scope: production systems and more specifically assembly
3. subject area: only papers related to engineering fields
4. document type: article

The initial database was composed of 733 documents from 1970 until 2021. Through a first analysis of titles and abstracts, only documents concerning product and operational complexity from 2010 to 2021 were included, reducing the initial set of 733 papers to 94 significant papers. Hence, papers not referring to complexity in assembly tasks were excluded. After this second filtering, 18 significant papers remained. The last phase of this literature review involved snowballing analysis, i.e., a global analysis of references and citations of the papers in scope, obtaining a final set of 33 documents. In Figure 1 a diagram flow illustrating all the phases of the state-of-the-art analysis is represented.

Basing also on taxonomies already proposed across years (Alkan, Vera, Ahmad, Ahmad, *et al.*, 2018; EIMaraghy and Urbanic, 2004) , three macro areas of complexity methods in assembly processes were identified:

- **Product-centered complexity:** it includes methods that evaluate complexity by focusing mainly on (i) the geometrical and dimensional features of products and (ii) the necessary time to handle parts and perform a specific assembly task.
- **Information-centered complexity:** it includes methods that regard complexity as positively correlated to the quantity and variety of information the assembly operator manages during the process.

- **System-centered complexity:** it includes methods that propose a holistic view of complexity, mainly influenced by variables external to the specific assembly task, such as production layouts, scheduling, external demand, ergonomics, skills, etc.

In Tables 1,2 and 3 the main methods analyzed for each approach are provided.

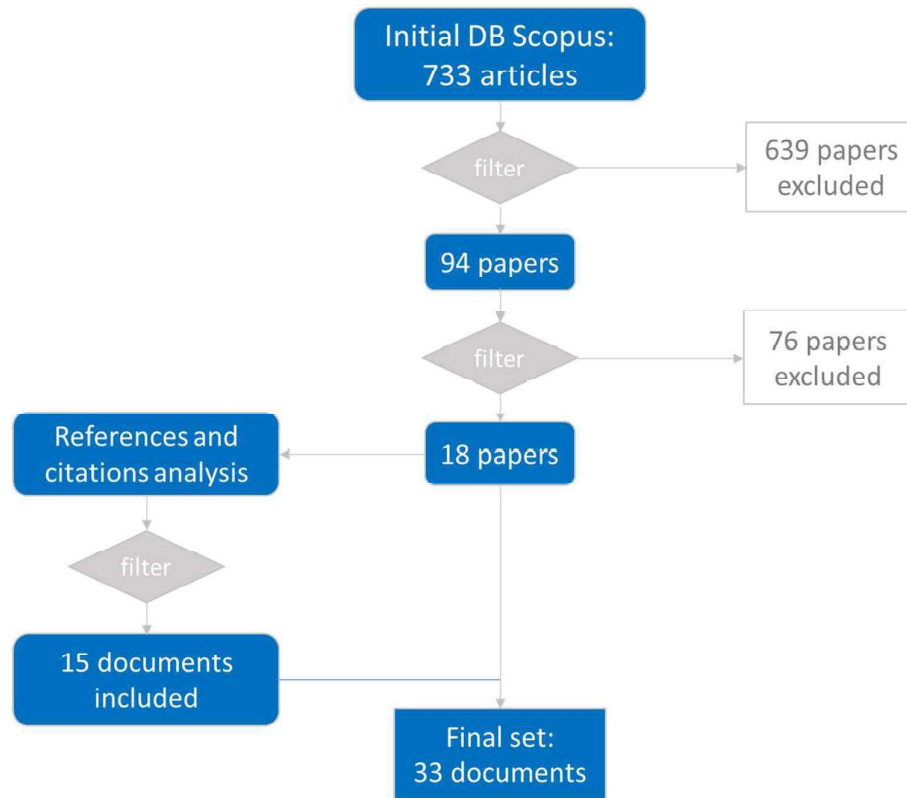


Figure 1 - Diagram flow of literature review analysis about complexity methods in assembly processes

2.2. Product-Centered Complexity

Product-centered complexity models relate complexity to product characteristics. Geometrical and dimensional features of components may affect the difficulty for operators to handle and assemble parts, (Alkan, Vera, Ahmad and Harrison, 2018). Most of methods described in this section derived from principles of design for assembly (Boothroyd, 1994). Design for Assembly (DFA) was introduced with the purpose of increasing assembly efficiency. DFA consists of a set of criteria for the design of a product aimed at reducing assembly times and thus generating benefits in terms of costs and quality (Boothroyd, 1994). Hinckley (1994) proposed an assembly complexity factor depending on assembly times and number of operations. By correlating complexity factor to number of defects detected in the final product, Hinckley (1994) underlined the importance of controlling complexity as a way to reduce costs and improve quality. This model was

subsequently modified by Shibata (2002) who added to Hinckley's factor a new complexity coefficient, namely design-based complexity factor, based on DFA principles developed by Sony Corporation. Su et al. (2009) modified Shibata's design-based complexity factor introducing a new factor calculated with AHP method, using complexity criteria proposed by Ben Arie (1994). This new approach extended the possibility to calculate a design based complexity factor to all electronic and mechanical products (Su *et al.*, 2009). The process-based complexity factor Cf_{Pi} and the design-based complexity factor Cf_{Di} , first introduced by Shibata (2002) and the modified by Su et al. (2009), are the followings:

$$Cf_{P,i} = \sum_{j=1}^{N_{ai}} SST_{ij} - t_0 N_{ai} \quad (1)$$

$$Cf_{D,i} = \sum_{p=1}^l w_p \cdot \frac{1}{e} \sum_{k=1}^e A_{kpi} \quad (2)$$

Where:

- SST_{ij} is the standard time of job j in workstation i
- t_0 is a threshold assembly time and N_{ai} is the number of jobs in workstation i
- w_p is the weight of the parameter p obtained by AHP method
- e is the total number of evaluators and l the total number of parameters
- A_{kpi} represents the evaluation of parameter p for workstation i given by the evaluator k .

Another significant approach to assembly complexity was proposed by Sinha and de Weck (2014) who developed a quantitative measure of product complexity, using an analogy with molecular systems in quantum mechanics. Complexity of a product is determined by complexity of single components C_1 , complexity of interfaces C_2 and topological complexity C_3 as follows (Sinha and de Weck, 2014):

$$C = C_1 + C_2 C_3 \quad (3)$$

A detailed description of (3) is given in section 3.1. Subsequently, Alkan (2019) assimilated complexity of components to the time necessary to handle single parts, complexity of interfaces to the time for joining them and topological complexity to the energy of the adjacency matrix representing the structure of the assembled product. Recently, other studies (Genta *et al.*, 2018; Verna *et al.*, 2021) proposed statistical models to predict product defects using structural complexity factors developed by Su et al. (2009) and Alkan et al. (2018). A different methodology was proposed by Mathieson (2013) who identified three groups of product complexity metrics derived from graph theory (i.e., size, path length and decomposition) and used them to predict assembly times of products.

Table 1 – List of the main product-centered methods

Year	Authors	Main results
1993	Hinckley M.	Definition of a complexity factor depending on total assembly times and number of assembly operations
1994	Ben-Arieh, D.	Set of geometrical-based and type of contact parameters influencing difficulty of assembly operations
2002	Shibata, H.	Definition of a design-based complexity factor and a process-based complexity factor for electronic products
2010	Su Q., et al.	Mathematical model to predict defects based on design and process complexity factors for electro-mechanical products
2012	Mathieson J.L., et al.	Application of graph theory to model product complexity and estimate assembly time
2014	Sinha, K.	Definition of a new model of product complexity through structural, interfaces and topological complexity
2017	Alkan B., et al.	Application of DFA principles to assess structural, interfaces and topological complexity in electronic industry
2018	Genta et al.	Assembly defect prediction using Shibata and Su's models
2019	Alkan B.	Empirical investigation of correlation between perceived assembly complexity and product complexity based on assembly times
2021	Verna et al.	Defect monitoring of assembled products using Alkan's complexity model

2.3. Information-centered methods

Information-centered approach includes methods that relate complexity to quantity and variety of information managed. With reference to a specific assembly task, information means product variants, variety of actions, variety of fasteners, variety of tools, etc. Operators' choice becomes more complex when the variety of information increases. The common feature of methods belonging to this type of approach is the quantification of information, recurring to Shannon's theory (Shannon, 1948). Many studies used the concepts of information theory, such as entropy, to measure complexity in manufacturing systems. The analogy between complexity in assembly task and the information theory is based on the assumption that higher level of complexity means greater quantity of information to be managed (ElMaraghy and Urbanic, 2004; ElMaraghy and Urbanic, 2003). Product variety was a crucial variable in assembly process design for Fujimoto et al. (2003) who defined an entropic measure aimed at managing complexity in an automotive manufacturing environment. A similar analogy was used by Zhu et al. (2008), adapting Shannon's entropy to measure the complexity of operators' choice in mixed model assembly lines where many product variants have to be managed. Ameri et al. (2008) summarized design complexity in two different measures, a size complexity metric based on entropic methods and a decomposability metric derived from graph theory. Wang and Hu (2010) modified the concept of entropy theorized by Zhu et al. (2008) and developed an entropic measure to model operator choice at assembly stations. The authors also introduced a novel idea of complexity based on human and mental fatigue (Wang and Hu, 2010) subsequently used in a non-linear programming algorithm to minimize manufacturing complexity (Wang *et al.*, 2013). Samy and ElMaraghy (2010) hypothesized complexity related to specific geometric characteristics of each part involved, to the number of parts composing the final product, and to the variety of components an operator faces during assembly. The quantity and the variety of information that an operator manages is proportional to the quantity

and variety of parts requested to assemble the final product (Samy and ElMaraghy, 2010, 2012). Equation (4) represents Samy and ElMaraghy's complexity factor.

$$C_{product} = \left[\frac{n_p}{N_p} + CI_{product} \right] [\log_2(N_p + 1)] + \left[\frac{n_s}{N_s} \right] [\log_2(N_s + 1)] \quad (4)$$

Where:

- n_p is the number of unique parts and N_p is the total number of parts
- n_s is the number of unique fasteners and N_s is the total number of fasteners
- $CI_{product}$ is a complexity index (calculated using DFA coefficients).

Modrak et al. (2014) assumed complexity correlated to possible different configurations of products. In this case, a product with many possible different configurations and optional components increases task difficulty and consequently the range of choices for operators. Another approach is proposed by Park and Okudan Kremer (2015) who defined a measure of static complexity in manufacturing through a combination of the mathematical definition of information content with the concept of “degree of commonality” for product families (Simpson and D’Souza, 2004).

Table 2 – List of the main information-centered methods

Year	Authors	Main results
2003	ElMaraghy W.H. and Urbanic R.J.	Model of product complexity based on quantity, variety and content of information managed by assembly operators
2003	Fujimoto H., et al.	Definition of an entropy-based complexity metrics to manage varieties in assembly operations
2004	ElMaraghy W.H. and Urbanic R.J.	Elaboration of an entropy-based metric to assess operational complexity depending on operators' physical and cognitive effort
2008	Ameri F., et al.	Introduction of size and coupling complexities using respectively information entropy metrics and graph theory
2008	Zhu X., et al.	Development of an information-based complexity factor based on product variants
2010	Samy S.N. and ElMaraghy H.	Mathematical model to assess assembly complexity based on quantity and variety of parts and fasteners composing a product
2010	Wang H. and Hu S.J.	Measure of manufacturing complexity based on quantity and variety of operators' choices of assembly activities
2012	Samy S.N. and Elmaraghy H.A.	Information-based model to describe the correlation between parts and assembly equipment complexity
2013	Wang H., et al.	Definition of a manufacturing complexity measure based on the mix of product variants assembled in a specific workstation
2014	Modrak V., et al.	Assembly complexity measure based on possible different combination of customized products
2015	Park K. and Okudan Kremer G.E.	Definition of a complexity metric combining information theory and the concept of commonality of product families

2.4. System-centered approach

In literature some studies extended the concept of production complexity beyond the specific assembly task. System-centered approach aims at providing an overall view of manufacturing complexity, also considering external product demand, production layouts and scheduling, working and ergonomics conditions as sources

of complexity. Due to variety of dimensions assessed in this approach, many different methodologies were used, e.g., information theory, graph theory, surveys, and interviews. Zaeh (2009) proposed a multidimensional analysis to evaluate complexity, consisting of temporal measures, cognitive and knowledge-based factors. Jenab and Liu (2010) elaborated a mathematical method to create a graph in which nodes represented products, while connections between nodes depended on processing times, type of resources and skills required. Abad and Jin (2011) built a quantitative manufacturing complexity metric based on demanded product variety. Concerning budgeting and resource allocation, this contributed to focus on more critical stations and products. Chryssolouris et al. (Chryssolouris *et al.*, 2013) elaborated a graph theory-based measure of manufacturing complexity proportional to machines, products, processes and resources. Information theory principles was also applied to manufacturing systems to provide a method to assess an overall complexity, also considering quantity and variety of machines, material handling equipment and buffers involved in production systems (Samy and ElMaraghy, 2012). ElMaraghy et al. (2014) introduced a method to evaluate structural complexity of a manufacturing layout. In this work the authors proposed a set of parameters to calculate the complexity of the graph representing the flow of material within a manufacturing system (ElMaraghy *et al.*, 2014). Al-Zuheri (2013) connected complexity of assembly tasks to variance of tasks determined by operating times, workers' skills and fatigue. Concerning layout optimization, Modrak and Soltysova (2018) elaborated a new operational complexity parameter derived from an entropic coefficient that takes into account total number of parts, machines and operations and further used to find an optimal production layout. More recently, Busogi et al. (2019) defined a complexity entropic measure as the probability of receiving a demand of product variants with refers to the total demand of a certain product and used it to minimize complexity of product sequencing. Another common approach in assessing the complexity of manufacturing is the use of interviews and surveys. Mattsson et al. (2014, 2016, 2020) introduced a novel index, called "Complexity index" (CXI). Unlike the previous methods analyzed which attempt to objectively quantify complexity, CXI aimed at measuring perceived production complexity, interviewing workers on five topics, i.e., product variants, layout, work content, tools, and information. A similar approach was followed with the introduction of basic complexity criteria, namely CXB (Falck, Tarrar, *et al.*, 2017; Falck, Örtengren, *et al.*, 2017a, 2017b). The number of criteria fulfilled determines the complexity level of the assembly task (Falck, Tarrar, *et al.*, 2017; Falck, Örtengren, *et al.*, 2017a). Finally, Martinez Olvera (2020) developed an entropic value aimed at measuring manufacturing complexity influenced by product variety and industry 4.0 paradigms.

Table 3 – List of the main system-centered methods

Year	Authors	Main results
2009	Zaeh M.F., et al.	Multi-dimensional measure of assembly complexity including also cognitive and knowledge aspects
2010	Jenab K. and Liu D.	Graph-based model to assess system complexity depending on assembly times, resources, and operators' skills
2011	Abad A.G. and Jin J.	Elaboration of a communication-based complexity model depending on product demand
2012	Samy S.N. and ElMaraghy H.	Development of a system complexity measure based on production layouts
2013	Al-Zuheri A.	Introduction of workers' skills and human fatigue in the assessment of assembly complexity
2013	Chryssolouris G., et al.	Definition of a system graph-based complexity measure and analysis of the relationship between system complexity and flexibility
2014	Elmaraghy H., et al.	Mathematical model to assess the complexity of manufacturing layouts
2016	Mattsson S., et al.	Analysis of workers' perceived production complexity using a questionnaire-based method (i.e., CXI assessment)
2017	Falck A.-C., et al.	Definition of a set of complexity criteria to assess assembly workstations
2018	Modrak V. and Soltysova Z.	Elaboration of an entropy-based complexity coefficient based on production system organization
2019	Busogi M., et al.	Entropy-based method depending on external demand of customized products
2020	Martínez-Olvera C.	Development of a complexity measure based on both product variety and the introduction of Industry 4.0 features in production organization

3. A PRACTICAL CASE STUDY: THE MANUAL ASSEMBLY OF A SMALL WATER PUMP

After the general overview of the models provided to analyze complexity, in this section a case study concerning the assembly of a diaphragm water pump is presented (see Figure 2 and Figure 3). The detailed decomposition of the water pump in sub parts and their quantities is provided in Table 4.

Table 4 - Details of parts and quantities of a diaphragm water pump

Parts and fasteners	Code	Quantities
Engine block	EB	1
Rubber feet	RF	1
Ring	R	1
Flange 1	F1	1
Flange 2	F2	1
Diaphragm	D	1
Cover with valves	CV	1
Cover	C	1
Pressure switch	PS	1
Pressure switch diaphragm	PSD	1
Filter	F	1
Flow adapter	FA	2
Screws type 1	S1	2
Screws type 2	S2	6
Screws type 3	S3	3
Screws type 4	S4	3

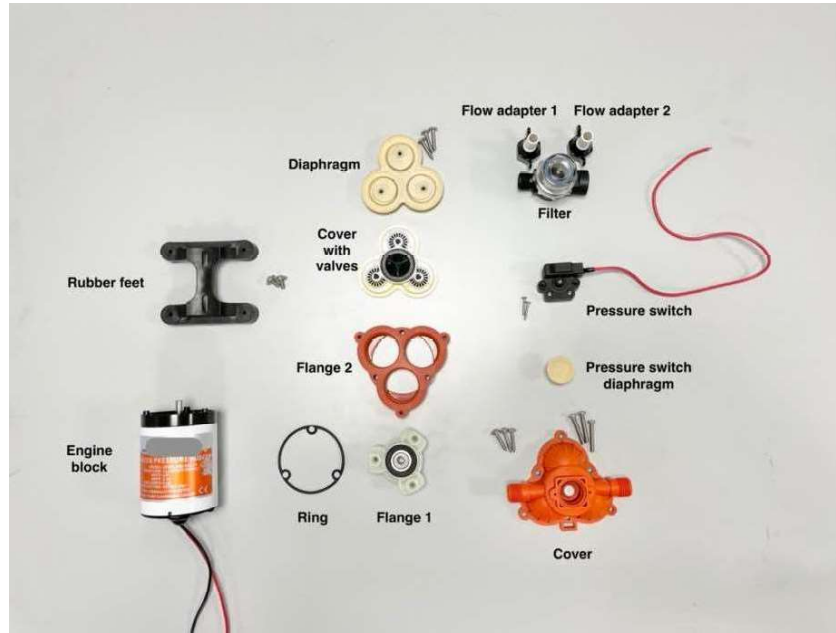


Figure 2 – Parts decomposition of a diaphragm water pump

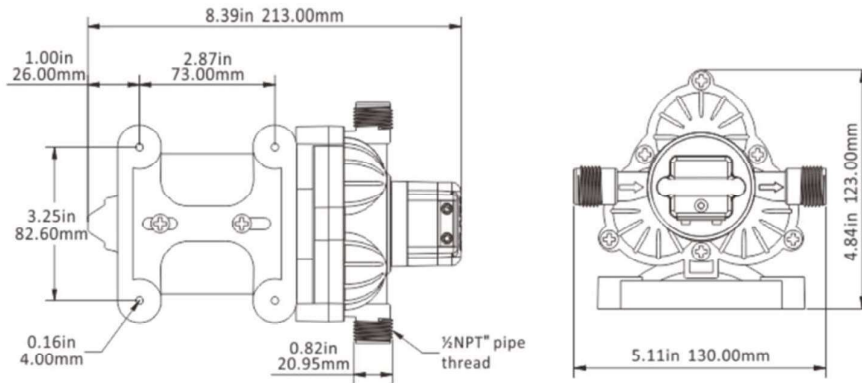


Figure 3 – Back and top view of the assembled diaphragm water pump

For each approach, a representative method to assess assembly complexity is considered. Implemented methods respectively were: Alkan's method; the entropy-based method proposed by Samy and ElMaraghy (2010) and the CXB assessment by Falck et al. (2017a).

3.1 Product-centered approach (Alkan, 2019)

As seen in (3), according to Alkan (2019) product complexity depends on three complexity coefficients:

- Component complexity $C_1 = \sum_{i=1}^N \alpha_i \approx \sum_{i=1}^N t_{handling,i}$, where α_i is the complexity of the i^{th} component approximated with the handling time of each single part (i.e., pick and place)

- Interface complexity $C_2 = \sum_{i=1}^N \sum_{j=1}^N \beta_{ij} A_{ij} \approx \sum_{i=1}^{N-1} \sum_{j=i+1}^N t_{joining,ij} A_{ij}$, where β_{ij} is the complexity of each pair-wise connection calculated using time of joining, (i.e., positioning connectors and joining) and A is the product adjacency matrix defined as follows:

$$A_{ij} = \begin{cases} 1 & \text{if } i - th \text{ and } j - th \text{ part are directly connected} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

- Topological complexity $C_3 = \frac{E(A)}{N}$, where $E(A)$ is the energy of the product adjacency matrix A . According to graph theory, the energy of an adjacency matrix is defined as the sum of its absolute eigenvalues.

In order to compute the complexity of the water pump, average times of handling and joining tasks (Table 5) and the adjacency matrix of the product (Table 6) were computed.

The assembly operation was broken down in elementary tasks and their respective average times were measured. Average times (in seconds) were rounded up to the nearest integer.

Table 5 - Elementary tasks for the assembly of a diaphragm water pump

Elementary task	Average time (s)
Pick and place RF	2
Pick and place EB on RF	6
Screwing EB with RF	45
Insert F1 in F2	8
Pick and place D on F2	5
Screwing D and F1	66
Pick and place CV on D	6
Pick and place C on F2	5
Screwing C and F2	42
Insert R	8
Insert assembled pump head on EB	14
Screwing pump head and EB	45
Pick and place PSD	15
Pick and place PS	5
Screwing PS and C	48
Screwing F	6
Screwing FA1 and FA2	19

Table 6 - Adjacency matrix

A	RF	EB	R	F1	F2	D	CV	FI	C	PS	PSD	FA1	FA2
RF	0	1	0	0	0	0	0	0	0	0	0	0	0
EB	1	0	1	1	1	0	0	0	1	0	0	0	0
R	0	1	0	0	0	0	0	0	0	0	0	0	0
F1	0	1	0	0	1	1	0	0	0	0	0	0	0
F2	0	1	0	1	0	1	0	0	1	0	0	0	0
D	0	0	0	1	1	0	1	0	0	0	0	0	0
CV	0	0	0	0	0	1	0	0	0	0	0	0	0
FI	0	0	0	0	0	0	0	0	1	0	0	1	0
C	0	1	0	0	1	0	0	1	0	1	1	0	1
PS	0	0	0	0	0	0	0	0	1	0	1	0	0
PSD	0	0	0	0	0	0	0	0	1	1	0	0	0
FA1	0	0	0	0	0	0	0	1	0	0	0	0	0
FA2	0	0	0	0	0	0	0	0	1	0	0	0	0

The eigenvalues referring to the adjacency matrix are shown in Table 7.

Table 7 - Eigenvalues of the adjacency matrix

λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9	λ_{10}	λ_{11}	λ_{12}	λ_{13}
-2,45	-1,99	-1,15	-1	-1	-0,61	0	0,21	0,33	1	1,21	2,07	3,38

The three contributes of complexity obtained respectively are:

$$C_1 = \sum_{i=1}^n t_{handling,i} = 44 \text{ s} \quad C_2 = \sum_{i=1}^{n-1} \sum_{j=i+1}^n t_{joining} A_{ij} = 301 \text{ s} \quad C_3 = \frac{\sum_{i=1}^n |\lambda_i|}{n} = 1,262$$

The overall complexity for the water pump is:

$$C = C_1 + C_2 C_3 = 424 \text{ s} = 7.07 \text{ min}$$

The overall domain of product complexity postulated by Alkan is $C \in]0; +\infty[$ as it is a measure of time expressed in seconds. Time is an easy measurable variable, thus avoiding any source of subjectivity in the implementation of the method. On the contrary, the difficulty to compute topological complexity may increase in the presence of products composed of many different parts connected.

To better understand the results obtained, Table 8 shows the maximum and minimum complexity values (in minutes) calculated in the study by Verna et al. (2021) concerning the assembly of a wrapping machine. In

this work, the assembly process was divided into 29 workstations, each characterized by a specific number of components to assemble (n) and elementary operations to be performed.

Table 8 - Maximum and minimum complexity value for the assembly of a wrapping machine (Verna *et al.*, 2021)

Identification	Number of					
number of	elementary	n	$C_1(\text{min})$	$C_2(\text{min})$	$C_3(\text{min})$	$C(\text{min})$
workstation	operations					
9	2	4	0,08	0,33	0,25	0,16
28	9	20	1,26	11,32	0,60	8,05

The complexity values obtained for the assembly of a diaphragm water pump are shown in Table 9.

Table 9 - Complexity values of the assembly of a diaphragm water pump

Number of					
elementary	n	$C_1(\text{min})$	$C_2(\text{min})$	$C_3(\text{min})$	$C(\text{min})$
operations					
17	13	0,73	5,02	1,262	7,07

In this specific case the overall complexity value increases as the number of components increases. The number of elementary operations relatively affects the complexity value, since this mainly depends on the duration of each elementary operation. The topological complexity, on the other hand, has a strong impact on the overall value, reducing the distance between the complexity of the workstation 28 and that of the water pump.

3.2 Information-centered approach (Samy and ElMaraghy, 2010)

Samy and ElMaraghy (2010) proposed an information-based approach to evaluate complexity, combining information entropy with a coefficient derived from DFA principles (Boothroyd, 1994), as seen in (4).

The complexity factor defined by Samy and ElMaraghy is a dimensionless measure of complexity defined in $]0; +\infty[$ as it depends on number of parts and fasteners with $n_p, n_s, N_p, N_s \geq 1$.

In this practical case study DFA tables for manual assembly (Samy and ElMaraghy, 2010) were used for the computation of $CI_{product}$. The calculation of $CI_{product}$ was composed of the following steps:

- Calculation of average handling factor $C_h = \frac{\sum_1^J C_{h,f}}{J}$ and average insertion factor $C_i = \frac{\sum_1^K C_{i,f}}{K}$. The two previous parameters are estimated using complexity assembly factors obtained from DFA analysis (Samy and ElMaraghy, 2010). Experts choose J handling attributes and K insertion attributes

applicable to the component under assessment and calculate a respective average value (i.e., C_h and C_i).

- Calculation of weighted average (handling and insertion) complexity factor

$$C_{part} = \frac{C_h \sum_1^J C_{h,f} + C_i \sum_1^K C_{i,f}}{\sum_1^J C_{h,f} + \sum_1^K C_{i,f}} \quad (6)$$

- Calculation of product complexity index $CI_{product} = \sum_{p=1}^n x_p C_{part}$ where x_p is the percentage of dissimilar parts and n the number of unique parts.

A team of experts evaluated handling and insertion attributes for this specific case study. The value obtained was $CI_{water\ pump} = 0,693$. Being $n_p = 12$, $N_p = 13$, $n_s = 4$ and $N_s = 14$, it resulted that:

$$C_{water\ pump} = 7,27$$

As a reference value, the complexity factor calculated by Samy and ElMaraghy (2010) for the assembly of an automobile engine piston is used. Such a product is composed of 11 parts ($N_p = 11$, $n_p = 8$) and 2 fasteners ($N_s = 2$, $n_s = 1$), $CI_{piston} = 0,83$ and so:

$$C_{piston} = 6,39$$

Samy and ElMaraghy's complexity index is mainly influenced by degree of variety of parts and fasteners. The assembly of the water pump is indeed more complex due to a greater quantity and diversity of components and fasteners. It should be noted, however, that $CI_{water\ pump} < CI_{piston}$, as this depends on the geometrical characteristics of each part and on the characteristics of the fastening process. A major weakness of this method, in fact, is that experts must provide an assessment on insertion and handling attributes. Although based on semi-quantitative criteria, CI value may be also influenced by expert judgements.

3.3 System-centered approach (Falck, A. et al., 2017)

Falck et al. proposed a tool to assess complexity of an assembly task based on expert assessments, namely CXB assessment (Falck, Tarrar, et al., 2017; Falck, Örtengren, et al., 2017a, 2017b). This method is composed of 16 high complexity (HC) criteria corresponding to 16 low complexity (LC) criteria, on which experts assess an assembly process. For each criterion also an interpretation aimed at helping experts in their judgements is provided (Falck, A. et al., 2017a). The detailed set of statements is provided in Appendix A. The number of high complexity (or low complexity) criteria met can range between 0 and 16, determining the level of complexity of the assembly task, as shown in Table 10. The complexity of a task is expressed on a 5-level scale where level 1 indicates a low-complexity task while level 5 indicates a high-complexity task.

Table 10 – Fulfilment of high complexity criteria and corresponding complexity levels (Falck, Örtengren, *et al.*, 2017b)

Complexity level	Number of HC criteria fulfilled	Range
1	0-3	Low
2	4-7	Rather low
3	8-11	Moderate
4	12-14	Rather high
5	15-16	High

With reference to Table 11, the main tasks composing the assembly process of a water pump were identified. Average times include pick and place times of each part and related assembly time.

Table 11 - CXB assessment of a water pump assembly

Tasks	Average time	Number of HC criteria fulfilled	Range
Screwing EB and RF	53 s	1	Low
Screwing D and F1	79 s	8	Moderate
Screwing C and F2	53 s	5	Rather low
Screwing pump head and EB	67 s	5	Rather low
Screwing PS and C	68 s	5	Rather low
Screwing FI, FA1 and FA2	25 s	2	Low

Results showed that the assembly of diaphragm and flange 1 was the most critical. The strong influence of the subjective judgements of the experts is undoubtedly the main weakness of this method. Even though some guidelines to make an objective assessment are provided, assessments will be inevitably influenced by experts' experiences. One of the main contributes of this work is the attempt to include different dimensions that may affect the complexity of a task, without only focusing on product features.

4. ASSEMBLY COMPLEXITY IN COLLABORATIVE TASKS

The practical case study (section 3) shed more light on which are the main variables defining complexity in the three different approaches. The methods analyzed focused heavily on product and information-based complexity, neglecting interactions between agents that are also part of the assembly process, and thus potential cause of defects. In a collaborative assembly, this new dimension of interaction complexity becomes crucial. Malik and Bilberg (2019) identified three main causes for HRC complexity: parts, process and workspace. Regarding workspace, they considered HRC safety as the only variable influencing task complexity. Many other studies though, proved that human robot collaboration should be evaluated using also other dimensions, i.e., autonomy, information, team organization, adaptivity, task, human factors, ethics and cybersecurity (Gervasi *et al.*, 2020). A new vision of complexity in a collaborative assembly process is therefore proposed (Figure 4).

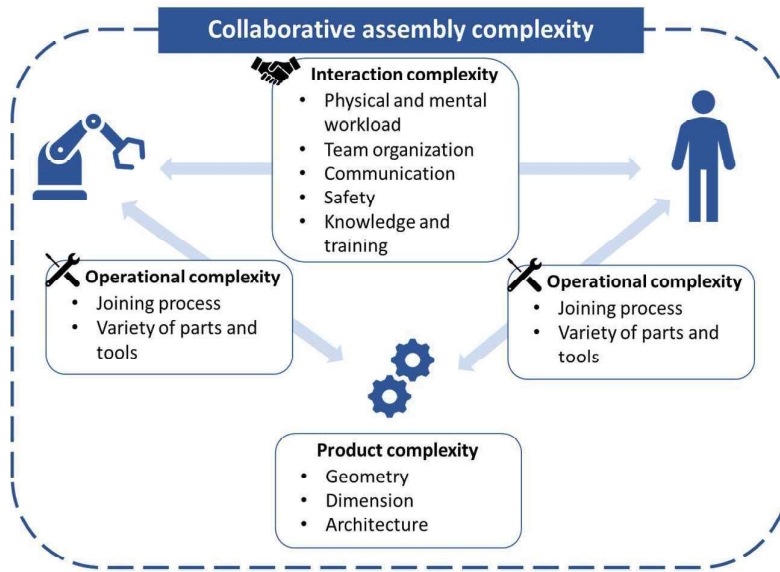


Figure 4 - Complexity framework for collaborative assembly

The complexity of an assembly process with collaborative robotics can be reduced to three main categories:

- **Product complexity:** it derives from intrinsic physical features of single parts (Malik and Bilberg, 2019). This type of complexity depends mainly on number of parts composing products, their architectures, geometrical and dimensional characteristics.
- **Operational complexity:** it is related to difficulties of assembly, such as insertion resistance, type of joining, etc. (Malik and Bilberg, 2019). In addition to these elements, sources of operational complexity may also include variety of product demanded and of tools needed.
- **Interaction complexity:** it includes all those variables that may influence an assembly task when it is carried out by several agents, i.e., humans and robots. Most studies in the field have only focused on safety as crucial variable (Malik and Bilberg, 2019), but in evaluating human robot collaboration a multidimensional approach should be followed.

While first two types of complexity were widely investigated across literature, assessing interaction complexity represents a new challenge in manufacturing control. Interaction complexity aims to describe the dynamics by which multiple agents interact with each other. When describing interaction complexity in an assembly process, all those variables that are typical of the interaction between multiple agents (e.g., human and robot) should be considered, as they may have an impact on the success of the process itself. To this purpose, the HRC evaluation framework proposed by Gervasi et al. (2020) was used to highlight main dimensions that may influence the complexity of interaction in an assembly process. Variables, such as communication, team organization, safety, mental workload, physical ergonomics and knowledge and

training were considered crucial also in assessing manual assembly complexity, while cybersecurity, ethics, autonomy and adaptivity were specifically related to the introduction of cobots in production workstations and thus were neglected in this preliminary comparison. The main dimensions adapted from Gervasi et al. (2020) on which both manual and human-robot assembly could be assessed are as follows:

- Communication

Communication is a crucial element in interaction between agents (Goodrich and Schultz, 2008). An appropriate and well-designed exchange of information influences success and efficiency of the task. Operators' awareness of procedures to be followed impacts positively on task performances, especially in terms of product and process defects.

- Team organization

Team organization aims to assess the organization of agents involved in a task, focusing mainly on balance between members and their role in pursuing a specific goal. Roles of each agent must be well assigned in order to successfully complete the task (Goodrich and Schultz, 2008).

- Safety

Safety in manufacturing processes has been extensively studied over the years. Many regulations have been introduced to quantify and reduce risks for workers in human-robot collaboration. From this perspective, it can be assumed that the riskiness of HRC operations is directly related to their complexity (Malik and Bilberg, 2019).

- Mental workload

Mental workload refers to the mental effort of operators during the execution of a task. Complex and stressful actions may generate fatigue and alienation. This condition of mental distress can affect performances and subsequently the quality of outputs and processes (Arai *et al.*, 2010).

- Physical ergonomics

Physical ergonomics encompasses all those measures taken to ensure that worker movements and postures are safe and correct. The amount of physical effort required impacts on the complexity of the assembly activity, leading to a deterioration in product and process quality due to exhausting and alienating actions (Zare *et al.*, 2016).

- Knowledge and training

In a successful human-robot collaboration, the skills of the operators and the related training required to interface with the robot are critical (Gervasi et al., 2020). Even in a manual assembly, however, the level of knowledge and experience of the operators involved has an impact on the complexity and success of the assembly process.

Complexity assessment methods were analyzed with a view to their future possible implementation in collaborative assembly. Tables 12, 13 and 14 show, for each approach, the methods obtained through literature review and their coverage of HRC typical dimensions. Some interesting results emerge from the analysis:

- Product-centered methods mainly focus on defining objective parameters that consider the architecture of products and the corresponding time required to handle them. The physical characteristics of the components and the corresponding product architecture, however, remains a key aspect in the complexity assessment, since the geometry of the components influences task complexity, even in a collaborative task. On the other hand, the assumption that cycle time is the only measure of task complexity in a collaborative approach loses some of its significance. In fact, the cycle time in a human-robot task is influenced both by the design of the task itself and by the technological and safety limits of the machine. These methods are obviously the least suitable for evaluating collaborative assemblies as they fail to cover any of the dimensions needed to assess human-machine interaction.

Table 12 -HRC Complexity vs product-centered approaches in literature. The table highlights HRC dimensions covered or not covered by the models

		HRC assembly complexity								
		Task			Interaction					
Year	Authors	Product	Operational	Communication	Team organization	Safety	Mental Workload	Physical ergonomics	Knowledge and training	
1993	Hinckley M.	x	x							
1994	Ben-Arieh, D.	x	x							
2002	Shibata, H.	x	x							
2010	Su Q., et al.	x	x							
2012	Mathieson J.L., et al.	x	x							
2014	Sinha, K.	x								
2017	Alkan B., et al.	x	x							
2018	Genta et al.	x	x							
2019	Alkan B.	x	x							
2021	Verna et al.	x	x							

- Information-centered approach begins to shift the focus to the operator. Methods belonging to this approach assume that the complexity of a task depends on the variety of choices an operator is led to make. A greater variety of components, of tools to be used, of different assembly sequences increase the complexity of the assembly task. The operator is forced to choose between various configurations, and this generates more mental effort. It is worth noting that the amount of information an operator manages in a collaborative task may be partially mitigated by the presence of a robot. It is possible to design the task in such a way that the robot provides the parts to the operator in the order in which they are to be assembled, thus considerably reducing the choices left to the human operator. From this perspective, it can be stated that methods belonging to this approach are more suitable to be adapted for the assessment of a collaborative assembly task, since they also investigate mental load. However, many other fundamental dimensions in collaborative interaction complexity remain uncovered.

Table 13 – HRC complexity vs information-centered approaches in the literature. The table highlights HRC dimensions covered or not covered by the models

HRC assembly complexity									
Year	Authors	Task		Interaction					
		Product	Operational	Communication	Team organization	Safety	Mental Workload	Physical ergonomics	Knowledge and training
2003	ElMaraghy W.H. and Urbanic R.J.	x	x						
2003	Fujimoto H., et al.	x	x						
2004	ElMaraghy W.H. and Urbanic R.J.	x	x				x	x	
2008	Ameri F., et al.	x	x						
2008	Zhu X., et al.	x	x				x		
2010	Samy S.N. and ElMaraghy H.	x	x						
2010	Wang H. and Hu S.J.	x	x				x		
2012	Samy S.N. and Elmaraghy H.A.	x	x				x		
2013	Wang H., et al.		x						
2014	Modrak V., et al.	x	x						
2015	Park K. and Okudan Kremer G.E.	x	x						

- Methods that attempt to capture system complexity seem to be best suited to describe interaction complexity as well. The main strength of methods belonging to this approach is that they share a multidimensional view of complexity. Unlike the previous two approaches, however, they do not always succeed in defining an objective and quantifiable measure of complexity due to the large number of variables to be considered. Some of them rely heavily on questionnaires and expert judgements which, while providing a holistic view of the problem, also introduce subjectivity in expert assessments.

Table 14 - HRC complexity vs system-centered approaches in the literature. The table highlights HRC dimensions covered or not covered by the models

		HRC assembly complexity							
		Task		Interaction					
Year	Authors	Product	Operational	Communication	Team organization	Safety	Workload	Physical ergonomics	Knowledge and training
2009	Zaeh M.F., et al.	x	x				x	x	x
2010	Jenab K. and Liu D.	x	x		x				x
2011	Abad A.G. and Jin J.	x	x	x					
2012	Samy S.N. and ElMaraghy H.	x	x						
2013	Al-Zuheri A.	x	x				x	x	x
2013	Chrysosolouris G., et al.	x	x						
2014	Elmaraghy H., et al.	x	x						
2016	Mattsson S., et al.	x	x		x	x	x	x	x
2017	Falck A.-C., et al.	x	x			x	x	x	x
2018	Modrak V. and Soltysova Z.	x	x						
2019	Busogi M., et al.	x	x					x	
2020	Martínez-Olvera C.	x	x						

5. CONCLUSIONS

In this preliminary investigation, the aim was to identify the most suitable approach for the assessment of assembly complexity in collaborative tasks, starting from the methods available in the literature. Unlike manual assembly, in a collaborative task the co-presence of humans and robots and the simultaneity of their actions can generate a significant impact on the operator's well-being, thus influencing the quality of the interaction. In this context, the approach considered most suitable for modelling complexity in collaborative assembly is the system-centered approach, as it tends to provide a holistic view of complexity. None of these methods, however, directly introduces multi-agent interaction as a variable that can influence the complexity of an assembly process. Despite its exploratory nature, this study offers some insights into the definition of a new concept of complexity for collaborative assembly, which cannot focus only on the product, but also on the complexity of interaction among the agents involved. Future developments will involve the analysis of the relationship between interaction complexity and observable defects in collaborative tasks and thus their contextual effects on product and process quality.

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APPENDIX A: High and low complexity criteria (Falck, A. et al., 2017)

n	High complexity criteria	Low complexity criteria
1	Many different ways of doing the task	Standardized way to do the task
2	Many individual details and parts operations	Few details to mount; pre-assembly; module solution
3	Time demanding operations	Solution that are easy and quick to assemble
4	No clear mounting position of parts and components	Clear mounting position of parts and components
5	Poor accessibility	Good accessibility
6	Hidden operations	Visible operations
7	Poor ergonomics conditions implying risk of harmful impact on operator	Good ergonomics conditions implying no harmful impact on operators
8	Operator dependent task requiring expert knowledge to be properly done	Non operator dependent operations not requiring much experience to be properly done
9	Operations must be done in a certain order/sequence	Independence of assembly order
10	Visual inspection of fitting and tolerance is required, i.e., careful subjective assessment of the quality output	Standardized assembly. Careful subjective assessment of fitting/tolerances is not needed
11	Accuracy/precision demanding task	No precision-demanding task, no careful fitting is necessary
12	Need of adjustment	No adjustment needed
13	The geometric environment has a lot of variation (“tolerances”) meaning the level of fitting and adjustment varies between the products	Easy fitting, self-positioning parts/components that can be controlled in 3 dimensions x,y, and z
14	Need to have in detail described work instructions	Self-evident operations that do not need clearly written instructions
15	Soft and flexible material	Form resistant material that does not change shape or form during assembly
16	Lack of immediate feedback of properly done work, e.g., by a clear click sound and/or compliance with reference point	Immediate feedback of proper installation e.g., by a clear click sound and/or compliance with reference points