Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

A New Perspective on Measuring of Manufacturing Modularity

Pascale Mekazi[1], Antoine Tahan[1], Lucas A. Hof[1]
[1]Mechanical Engineering Department, École de technologie supérieure, Montréal, Canada

Abstract—Modularity is perceived as an interesting solution to manage products and manufacturing complexity. Indeed, it allows for great variety while promoting product flexibility and respecting the environment. This concept has been already introduced, albeit imperfectly, in the automotive industry due to the strong interdependence of subsystems. As a result, several researchers have proposed definitions tailored to their fields of interest. Consequently, the design of a module can vary depending on designers and manufacturers, making modularity metrics applicable only in specific cases. In this context, we propose a new methodology to measure manufacturing modularity by introducing the notion of module aggregation levels, a key element of this approach. Our starting point is the use of metrics found in literature, which have been tested. As these results do not meet industrial standards and expectations, we developed an index that captures several modularity criteria in a second step. Thirdly, fictitious assembly process structures were created and then ranked by experts from industry and by the developed index according to the obtained values. Finally, the correlation between the two (2) rankings was studied. Applied to our case studies, good correlations were obtained; 97.3% and 90% respectively for our simple and complex use cases with the experts' rankings.

Keywords-Manufacturing modularity; module; complexity; metric; assembly process structure.

I. INTRODUCTION

The concept of modular products is far from new. Still, it has lately gained actuality due to the increased need for shortened lead times, differentiated products, environmentally friendly products [1] The concept of product modularity is becoming increasingly popular among manufacturing companies. It is an interesting solution for mastering manufacturing complexity in order to meet the needs of ever-growing customers in a process of mass customization and personalization [2]. Some companies that have embarked on this process of modularization evaluate manufacturing modularity intuitively and according to their own definition of it. However, an indicator of the level of modularity is needed to help decision-making on an objective, quantifiable basis.

It was worth tackling because most of the modularity metrics found in the literature do not meet our expectations in terms of modularity following the various tests carried out on product assembly sequences. The integration of the module aggregation level is therefore the new element that we are bringing to the measurement of manufacturing modularity.

II. BACKGROUND

A. *Product Modularity vs Manufacturing Modularity*

This study focuses on manufacturing modularity. It is therefore essential to highlight how this differs from product modularity. A modular architecture refers to the diagram describing how a product's functional elements are implemented in modules, and how these modules interact with each other while a manufacturing system architecture is defined by production platforms, which are a set of production equipment, interfaces, processes and knowledge from which production systems and their constituent elements can be efficiently derived and developed [10]. Product modularity therefore implies manufacturing modularity, and not the other way around. So, if a product is modular, the manufacturing process will be modular also. However, if the product is not modular, the process can not be modular [11]. Hence the need for companies embarking on the modularization process to develop not only a modular product architecture, but also a modular manufacturing system architecture.

Throughout the literature there is much said, and neglects to usefully define modules [3]. originally, a module was define as an autonomous and functional set of components linked to other modules by stable and well-defined interfaces [4], [5], [6], [7]. The field of computer science perfectly illustrates this definition. However, over time, this definition has proven unsuitable for other sectors due to the strong interdependence of subsystems. As a result, several researchers or experts have proposed definitions tailored to their fields of interest.

Modularization of the manufacturing system involves designing operational value chains that maximize separability and

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combinability. Here, we talk about the operational modules. This modularization also means designing, manufacturing and assembling in such a way as to reduce the complexity of the primary process, by prioritizing the maturity of subassemblies before grafting them on to the main line [8].So an assembly or subassembly or manufacturing assembly is a module from a manufacturing perspective or viewpoint [3]. The output of each line is considered as a manufacturing assembly until the finished product (output) is obtained at the end of the process [9].

B. *Modularity Metrics*

The literature presents a considerable amount of modular design measures. These measures have been categorized into eight groups on Fig.1. Each of these groups of modular design measures is divided into subgroups to clarify their composition [12].

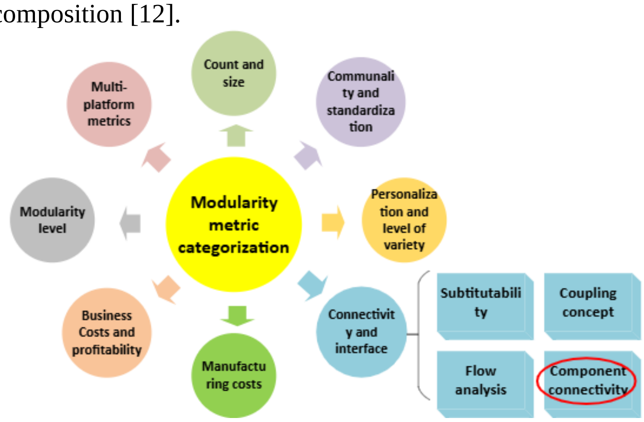

Figure 1. Positioning of the modularity measurements adapted from [12].

Group connectivity and interfaces gather measures that assess the level of interaction between components and the level of connectivity of interfaces by the number of interfaces between parts within modules, coupling between modules, or the level of exchange between modules [12].

These modularity indices are applied to Assembly Process Structure (APS), which can be represented in a simplified way as shown in Fig.2:

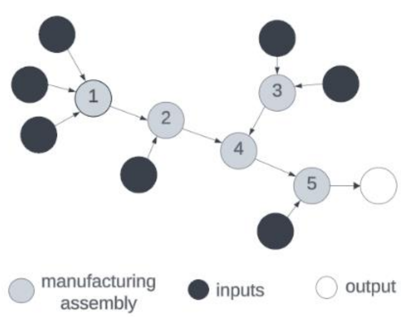

Figure 2. Assembly process structure simplified, adapted from [13].

Current metrics are insufficient to consistently return useful optimized analysis. It's suggests using a situational approach to choosing the metrics [3], [9].

TABLE I. A FEW CONNECTIVITY INDEXES ARE SHOWN INTO THE TABLE I EXISTING MODULARITY METRICS.

Measure	Table Column Head		
	inputs	*formula*	*Source*
Singular Value Modularity (*SMI*)	N the number of system components; σi represents the singular values obtained by diagonalization of the design structure matrix	$= 1 - \frac{1}{N.\sigma_1}\sum_{i=1}^{N-1}\sigma_i\,(\sigma_i - \sigma_{i+1})$	[13], [14]
Module independence index (IM)	Ri the number of internal connections to the assembly module i; T the total number of connections in the system and n the number of assembly modules	$= \sum_{i=1}^{n}\frac{R_i}{T}$	[1], [15]
Network Modularity Index (NMI)	w_s the amount of input and output edges of the individual assembly module s; w the total number of interactions or edges in the network; w_s^{in} the amount of input edges of the individual assembly module s and w_s^{out} the amount of output edges of the individual assembly module s	$= \sum_{i=1}^{M}\frac{w_s}{w} - \frac{w_s^{in} + w_s^{out}}{w^2}$	[13], [14]
Optimal modularity measure (Q)	n the number of assembly modules; l_s the number of edges between nodes in module s; L the number of edges in the network and ds the sum of the degrees of the nodes in module s	$= \sum_{S=1}^{n}\frac{l_s}{L}\left(\frac{ds}{2L}\right)^2$	[13], [14]

III. METHODOLOGY FRAMEWORK

The development of the new modularity indicator employs a mixed strategy, incorporating both qualitative and quantitative methods (Fig. 3). Initially, experts perform a subjective analysis of the case studies based on their definition of modularity, resulting in a ranking that reflects expected outcomes. This is subsequently compared to an objective ranking generated using the new modularity index.

Descriptive statistical methods are applied to analyze the data, including scatterplots to examine the dispersion between the subjective and objective rankings of the case studies. Furthermore, the correlation between these rankings is assessed using Pearson's correlation coefficient with a 95% confidence level.

To be able to rely on this new index, we tested its validity by studying its behavior on the simple cases study in Fig. 7. On the other hand, we created more complex fictitious cases to ensure that the index works.

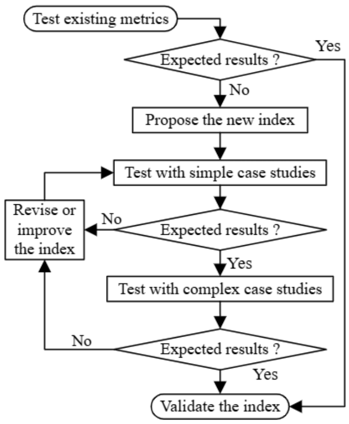

Figure 3. Process development of modularity index.

IV. DESCRIPTION OF THE PROPOSED MODULARITY INDICATOR

A. Empirical Data Set

To better understand the various equations proposed below, we thought it wise to present the variables involved and their significance in Table II.

TABLE II. VARIABLE DRIVING MANUFACTURING MODULARITY.

Variable	Table Column Head	
	Description	***Value/unit***
IM_p	Weighted modularity index	$\mathbb{R}$
n	Number of APS levels counted from first to last assembly module	$\mathbb{Z}$
i	Level index	$\mathbb{Z}$
k_i	Number of inputs/primary parts making up the product at level i	$\mathbb{Z}$
k'_i	Number of inputs/primary parts in subassembly at level i	$\mathbb{Z}$
m_i	Number of components (assembly modules and primary parts) at level i	$\mathbb{Z}$
S_i	Number of assembly modules on the level i	$\mathbb{Z}$
S'_i	Number of modules in subassembly at level i	$\mathbb{Z}$
p_i	Level weights, $\sum_{i=o}^{n} p_i = 1$	$\mathbb{R}$
q_i	Weight associated with sub-assembled primary parts at the level i, $\sum_{i=o}^{n} q_i = 1$	$\mathbb{R}$
γ	Weight of all sub-assembled modules	$\mathbb{R}$
$(\alpha_i)^i$	Geometric sequence such that $(\alpha_i)^i : \alpha_i = \alpha_1 . r^{i-1}$ with first term $\alpha_1 = 2$, $\alpha_0 = 0$ and the common ratio $r = 2$	
α_i	i^{th} term of the geometric sequence $(\alpha_i)^i$	$\mathbb{Z}$
β_i	Ratio between the number of modules in sub-assembly of a level i and the number of inputs in sub-assembly of the previous level $i-1$.	$\mathbb{R}$

B. Measurement Model

The new metric is inspired by the module independence index of the Table 1 developed by [1] is suggested to measure the goodness of the modular structure. Indeed, the latter demonstrates that the more manufacturing assemblies are created within a product's assembly process, the more modular that process becomes. However, this conclusion is not always relevant, and may even be insufficient, as the rankings of the case studies according to this index are completely disparate from the results expected by the experts.

So, we're going to try to improve the behavior of this index by integrating the notion of module aggregation level, by assigning weights by levels. This leads us to modify the initial representation of Assembly Process Structure (APS) from Fig. 2 into Fig. 4.

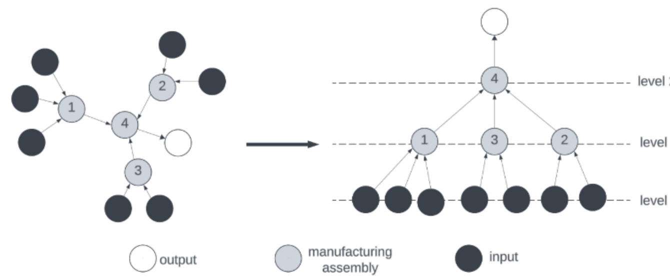

Figure 4. Integreting of aggregation levels.

The application of this modularity index requires a certain number of prerequisites. It is therefore essential to distinguish between the different components of the APS, as illustrated in Fig.5. We consider as independent inputs any elementary component or part of the system. Fasteners (e.g., flanges, nuts, rivets, rings, washers, etc.), tie raps, tapes, fluids and decals are excluded, because they have little impact on modularity. Moreover, taking them into account would artificially inflate the number of components, which could skew the index.

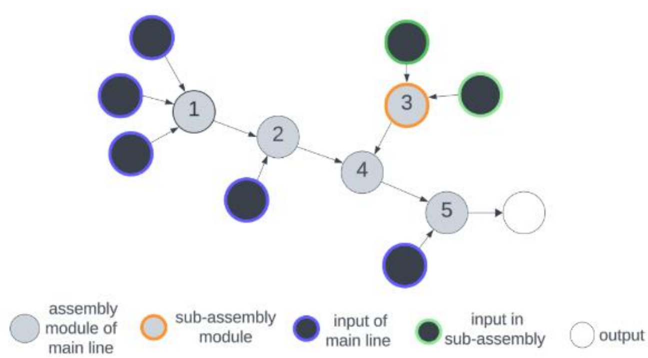

Figure 5. The difference between APS components.

The weight assigned to the input or assembly module depends on the level on which it is located. In this way, modularity is improved by reducing as many inputs as possible to the lowest levels.

From there, we weighed all the connections of the APS. This leads to (1):

$$IM_p = \gamma \left[1 - \frac{\sum_{i=0}^{n} p_i q_i k_i}{\sum_{i=0}^{n} p_i q_i m_i} \right]. \quad (1)$$

Where γ is a weight obtained by dividing the total number of modules in subassembly by the total number of modules whether in subassembly or on the main assembly line.
According to (2), the fewer the modules in the assembly, the less modular the system.

$$\gamma = \frac{\sum_0^n s_i' + 1}{\sum_{i=0}^n s_i}. \quad (2)$$

So, the closer the index value is to 1, the more modular we are. On the other hand, if it approaches 0, then it tends towards an integral structure.
The weights p_i are obtained from a geometric sequence such that $(\alpha_i)^i : \alpha_i = \alpha_1 . r^{i-1}$ with first term $\alpha_1 = 2$, $\alpha_0 = 0$ and the common ratio $r = 2$. So, to keep the normalization, i.e. $\sum p_i = 1$, we divide all $\alpha_i . \sum \alpha_i$ Hence (3).

$$p_i = \frac{\alpha_i}{\sum_{i=0}^n \alpha_i}. \quad (3)$$

with $\alpha_0 = 0$, $p_0 = 0$ and $\sum_{i=0}^n p_i = 1$. Using the previous example, $\sum \alpha_i = 2 + 4 + 8 + 16 = 30$. We obtain the weighting shown in *Table III*.

TABLE III. EXAMPLE OF WEIGHTING ACCORDING TO LEVEL i.

i	α_i	p_i
0	0	$\frac{0}{30}$
1	2	$\frac{2}{30}$
2	4	$\frac{4}{30}$
3	8	$\frac{3}{30}$
4	16	$\frac{16}{30}$

From a manufacturing perspective, [16] argue that a system is deemed modular if the equipment units that comprise it form clusters (modules) of dense connectivity. The weights q_i and γ include the criterion of grouping inputs into subassembly modules. The more subassembly modules we have, the more modularity is.
The weight q_i is obtained from β_i, which is the ratio between the number of modules in sub-assembly of a level i and the number of inputs in sub-assembly of the previous level $i - 1$ given by (4). With $\beta_0 = 1$. Because there is no module and no previous inputs neither in the main line nor in the sub-assembly lines in level 0.

$$\beta_i = \sqrt{\frac{s_i' + 1}{k_{i-1}' + 1}}. \quad (4)$$

Hence, we have q_i in (5):

$$q_i = 1 - \frac{\beta_i}{\sum_0^n \beta_i}. \quad (5)$$

The sum of total network connections is obtained by (6) below.

$$m_i = \sum_{i=0}^n k_i + \sum_{i=1}^n s_i. \quad (6)$$

V. CASE STUDIES

To evaluate the modularity index, we first analyzed its behavior in simple scenarios (Fig. 6) derived from the APS depicted in Fig. 2. These scenarios were constructed by varying the number of assembly modules and the positions of the inputs, while maintaining a constant number of inputs.
Subsequently, we extended our analysis to more complex cases (Fig. 7) involving a larger number of inputs, up to 31, adhering to the same principles applied in the simpler cases. *Table IV* summarizes the key data extracted from these case studies, which account for inputs in the main line, subassembly inputs, modules for manufacturing assembly, and subassembly modules.

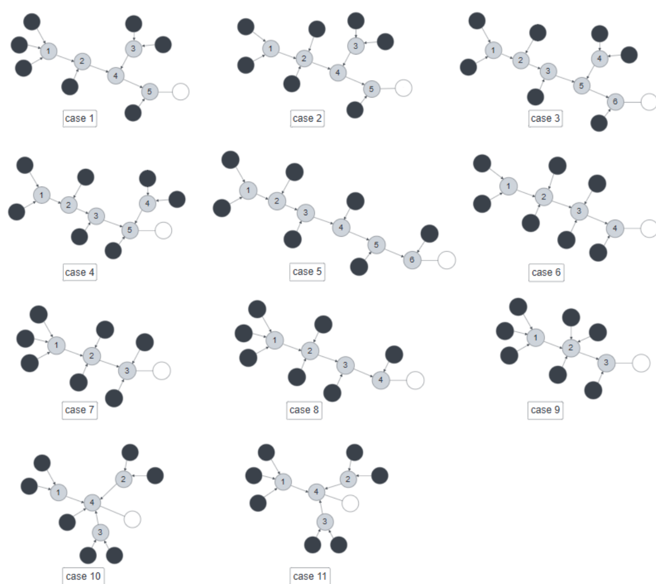

Figure 6. Simples study cases.

Figure 7. Complex study cases.

TABLE IV. DATA REQUIRED TO CALCULATE THE MODULARITY INDEX FOR CASE STUDIES.

i	***Main line inputs***	***subassembly Inputs***	***modules***	***subassembly module***
Simple use cases				
Case 1	5	2	5	1
Case 2	5	2	5	1
Case 3	5	2	6	1
Case 4	5	2	5	1
Case 5	7	0	6	0
Case 6	7	0	4	0
Case 7	7	0	3	0
Case 8	7	0	4	0
Case 9	7	0	3	0
Case 10	3	4	4	2
Case 11	3	4	4	4
Complex use cases				
Case A	31	0	15	0
Case B	3	28	29	14
Case C	4	27	15	9
Case D	4	27	14	9
Case E	11	20	14	7
Case F	6	25	13	9
Case G	5	26	7	5
Case H	8	13	7	5
Case I	4	27	12	7

VI. RESULTS AND DISCUSSION

TABLE V. RESULTS OF MODULARITY INDEXES AND RANKINGS OF SIMPLE STUDY CASES.

Cases	**Index value**		**Ranking**		
	IM	IM_p	IM	IM_p	***Experts***
Case 1	36.36%	28.43%	3	3	3
Case 2	36.36%	27.30%	3	4	5
Case 3	41.67%	23.39%	2	6	4
Case 4	36.36%	25.36%	3	5	6
Case 5	41.67%	11.17%	1	11	11
Case 6	30.00%	15.00%	8	10	10
Case 7	22.22%	17.95%	11	8	8
Case 8	30.00%	16.30%	6	9	9
Case 9	22.22%	19.44%	10	7	7
Case 10	30.00%	62.01%	8	2	2
Case 11	30.00%	75.00%	6	1	1

Based on the line plot, we can see that the ranking according to the module independence index IM is completely disparate from the ranking of IM_P and that of the experts. This disparity can be justified by the fact that modularity measures are specific to the point of view of the experts and the phenomena we are trying to capture [3]. The behavior of IM suggests that by increasing the number of manufacturing assemblies required or not, the process becomes more modular. However, the number of assembly modules is not a sufficient condition for modularity.

On the other hand, the line plots of the IM_p and experts show the same trend, with a few exceptions. Case 5 has the lowest modularity index, while case 11 is the most modular. However, cases 2, 3 and 4 alternate in rank. These are very similar APSs that differs very little. They are far from the linear regression line, while the other cases are perfectly aligned, giving a high correlation of 97.3% with the expected ranking.

Following this interesting correlation index, let's evaluate the behavior of the index on the complex cases.

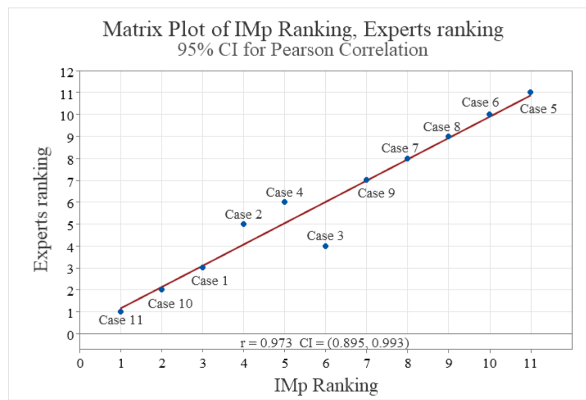

Figure 8. Correlation between Imp ranking and experts ranking for simple cases study.

TABLE VI. RESULTS OF MODULARITY INDEXES AND RANKINGS OF COMPLEX STUDY CASES.

Cases	IM	**Ranking**	
		IM_p	***Experts***
Case A	3.33%	9	9
Case B	38.75%	5	8
Case C	38.41%	6	5
Case D	42.50%	4	4
Case E	30.27%	8	7
Case F	54.35%	3	3
Case G	85.71%	1	1
Case H	61.22%	2	2
Case I	37.74%	7	6

From the outset, case B, according to the index, is placed in fifth position, whereas for the experts it is literally one of the worst cases. We can also see that, because of its position by the index, it will shift the position of the other cases by one rank in relation to the experts' ranking.

Looking at the line plot for the complex cases, we see that the first 4 rankings are identical, both those of the experts and those of the index. However, case B shifts the others by one rank. The scatterplot formed by our different rankings is distributed on either side of the linear regression line, with all points aligned along this axis, whereas case B is far removed. This gives a correlation rate of 90%. In view of these results, if we exclude the case B from our study, we could conclude that the rankings are perfectly correlated. Thus, by studying the case B rigorously, we can identify the limits of our index.

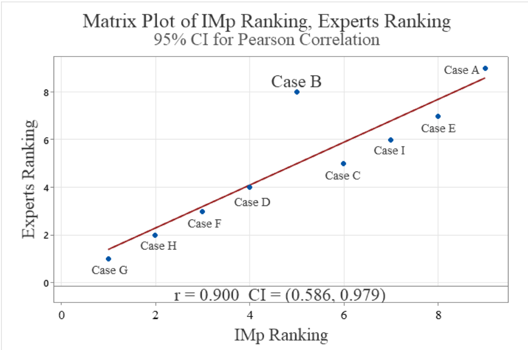

Figure 9. Correlation between IM_p ranking and experts ranking for complex cases study.

VII. Conclusion

The modularity measurements found in the literature are applied specifically depending on the point of view of modularity. The module independence index was not conclusive. Based on this, we developed an index that captures several modularity criteria. We firstly test on our simple assembly process structures with few inputs and then on complex assembly Process structure with much more inputs to validate the methodology. we obtained very good correlation from the study cases, 97.3% and 90% respectively for our simple and complex use cases with the experts' rankings. A rigorous analysis of the exceptions, particularly the alternation of ranks between cases 2, 3 and 4, and the reason for the ranking of the case B, will enable us in future work to gain a better understanding of the index's behaviour, to identify its limitations and even to consider its improvement.

Acknowledgment

The authors would like to express their sincere gratitude to the industrial partner for their valuable support and collaboration throughout this research. Additionally, this work was supported by BRP and MITACS through the Accelerate program which provided funding and resources essential to the successful completion of this project. The guidance and contributions from all parties involved have been instrumental in achieving the objectives of this study.

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