# Modularity Metric in Reconfigurable Supply Chain

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**Abstract.** Confronted with an increasingly uncertain and fluctuating economic environment characterized by a technological evolution driven by industry 4.0 concepts, companies have to adapt their supply chains in order to improve its competitiveness. They must also implement strategies that allows them to deal with these new challenges. Supply chain modularity offers the opportunity to change and reorganize the structure of the supply chain to meet changing market needs. In this paper, we propose a new framework to design a modular supply chain using Design Structure Matrix and a modularity measurement in Reconfigurable Supply Chain. We also show the importance of integrating the direction of flows, i.e. inbound and outbound flows in the calculation of modularity and, in particular, its impact on lead time. Finally, an illustrative example is developed to validate the proposed measurement.

**Keywords:** Modularity, Assessment, Reconfigurable Supply Chain, Design Structure Matrix.

## 1 Introduction

Manufacturing systems face numerous challenges and changes due to the excessive production capability and economic globalization. Thus, companies start implementing manufacturing and logistics systems that are more flexible and more agile by several actions of reconfiguration. They are also looking for technical and organizational strategies, such as reconfigurability, to improve the design of their supply chains [1]. In fact, reconfigurability can be defined as the ability to change the supply chain structure and functions at the lowest cost. Reconfigurable Supply Chain (RSC) is a supply chain that is flexible to alter its configuration with relatively minor resource requirements and without losing its operational efficiency in response to the changing customer demands and operating environment [2, 3]. RSC, also called the collaborative network, is defined as the process of modifying the structure of the agile supply chain or virtual enterprise. Reconfigurability in supply chain has five characteristics extended from those of Reconfigurable Manufacturing Systems (RMS): modularity, integrability, convertibility, diagnosability and customization [4]. Recently, authors, in [5], have defined the RSC as a network capable of adapting to structural changes by rearranging, reallocating or changing its components in order to quickly adjust its capabilities, structure and functionalities using modularity to respond to market requirements.

Supply chain complexity requires a high degree of independence between the elements of the supply chain in order to reduce the overall lead time and ensure high responsiveness to customer requests. [6] considered modularity as an effect strategy applied to meet the demand for increasing variety in the market. According to [7], modularity is not a binary measure. In other words, the product or system cannot be either modular or integral, but there is a definite degree of modularity. In the literature, the assessment of modularity of products or systems was given great attention. In production systems and product-related architectures, modularity affects productivity, development time and product manufacturing cost [6]. In supply chain, the interactions between modules represent inbound or outbound physical, informational and functional flows. Modularity has also a direct impact on lead time because the control of flows allows improving the performance of the supply chain, especially in terms of time.

The objective of this research work is to propose a modularity measurement in RSC based on a modular design using the DSM matrix.

The paper is organized as follows. In section 2, a definition of supply chain modularity is provided and review papers focusing on a modularity measurement are presented. Section 3 proposes a methodology for modularity design and assessment in RSC. Section 4 shows an illustrative example. The experimental results are discussed in Section 5. Conclusion and perspectives are given in the last section of the paper.

## 2 Literature review

### 2.1 Supply chain modularity

[8] defined the supply chain modularity as the degree of non-proximity of the elements of the supply chain. This degree is measured according to four dimensions: geographic proximity, organizational proximity, cultural proximity and electronic proximity. Indeed, modularity in RSC refers to the degree to which all product, process and resource entities at all levels of enterprises of supply network are modular [4].

According to [9], it is not limited to the process and product, but also concerns the supply chain, which allows generating different configurations with a variety of functionalities. [10] showed that modularity has gone beyond the technical dimension (product modularity) to achieve organizational modularity (modularity of the logistics chain). Standardization of interfaces facilitate the flow exchange between modules with the same interface. In addition, it ensures modules independence and facilitates its recombination. For supply chains and processes, interfaces can be in the form of contracts, transaction protocols and operational procedures [9]. A modular supply chain has low geographic, organizational, cultural and electronic proximity.

Several methods were used for designing a modular architecture or system namely Design Structure Matrix (DSM), Modular Function Deployment (MFD), Function Structure Heuristic (FSH), Variant Mode and Effects Analysis (VMEA) and Axiomatic Design (AD). Indeed, each method is deployed according to the application level of modularity (product, process, manufacturing system, supply chain). Each method has advantages and limitations related to its characteristics and implementation aspects. [11] presented a comparative study between three modular design methods to determine which method is the most appropriate to meet a specific objective [12]. For example, the MFD is more suitable for determining design variants and for make-buy decisions [11], which is more management-oriented than engineering-oriented [12]. On the other hand, DA and FSH are more oriented towards modularization of products and their transformation into a set of functional requirements. In this same context, the VMEA is used to describe the impact of product variants in all units of the company while evaluating the cost [13]. For complex systems with too many interactions, DSM is the most appropriate method for a better modular design [11].

A system is considered modular when it consists of a set of independent and autonomous components coupled to each other and having well-defined relationships with their functions. Although the interfaces between the components are standardized and require a low level of coordination, modularity cannot be reduced to the notion of proximity. Several measures were proposed to evaluate the degree of modularity that depends basically on the number of modules and the number of interactions between modules.

### 2.2 Modularity assessment

[7] conducted a comparative study of 13 modularity metrics for product and system architecture. These metrics were classified into three essential parameters, namely similarity, combination and coupling. Moreover, [6] proposed a modularity metric to maximize the cohesion degree and minimize the coupling degree.

Several measures were also suggested to evaluate the degree of modularity in RMS. To assess the degree of reconfigurability of RMS, [14–16] used several indicators including modularity. In fact, the essential utilized parameters are the similarity and the degree of independence. [15] applied the formula given by [17] which proposed a modularity index based on the degree of independence between product modules. In the same context, [6] introduced a reconfigurability measure including modularity based on the determination of reconfiguration ease and cohesion. In [16], a measure of modularity in the reconfigurability assessment was also developed based on the degree of module independency and the number of modules that corresponds to the optimum module granularity. Besides, [18] presented an index for modularity system assessment by taking into account five aspects such as machine module relationship, number of shared modules, product module relationship, process plan machine and product family module relationship.

In the supply chain, interactions correspond to physical and information flows whose direction affects considerably the lead-time. Indeed, if the number of inbound flows is high for a module, it means that its lead-time is high and vice versa. In this study, the degree of influence of each module, which allows assigning an importance weight to each module, is integrated.

# 3 The proposed approach

Our approach aims to at designing a modular supply chain and evaluating its degree of modularity, as shown in Fig. 1. Its first step is to break down the supply chain processes into a set of activities. However, the second step consists in identifying the interactions between the determined activities that allow grouping the activities with strong interactions into a module. The third step is to build clusters of activities having strong interactions with the DSM clustering. Then, to evaluate the degree of the supply chain modularity, the fourth step, which consists in determining the degrees of intra- and inter-modules, is applied. Then, the degrees of influence of each module from the number of incoming flows and the number of outgoing flows is calculated in the fifth step in order to better analyze the modules interactions. Based on these parameters, the degree of supply chain modularity is evaluated.

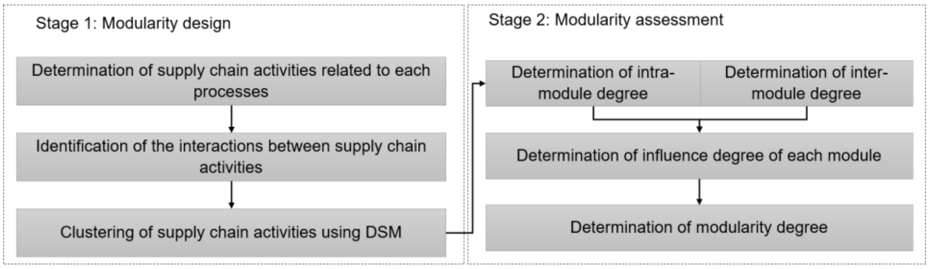


**Fig. 1.** Proposed methodology of modularity assessment in RSC

## 3.1 Modularity design

Supply chain is a set of processes involved in providing products to meet the needs of end-customers. These processes consist of a set of activities that convert inputs into outputs using the necessary resources. The determination of supply chain activities related to each processes gives a more detailed view about flows. Indeed, the modular design of the supply chain is based on analyzing the interaction between supply chain. These interactions correspond to the physical flows that mainly concern the internal and external transport of materials or products and to the information flows that coordinate all activities. For determining the impact of one activity over the other, the scale proposed by [19] in a range between 0 and 1 is used.

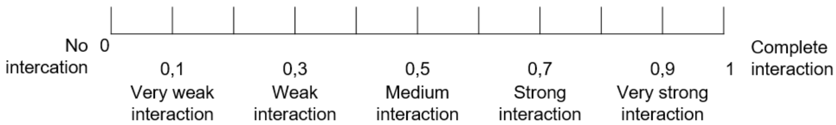


**Fig. 2.** The scale used for the activities interactions strengths [19]

According to [19], the identification of the intercations consists in making three matrices according to the three types of flows. Then, in order to obtain the final matrix of interactions, the three identified matrices must be aggregated with the following weights: the matrix of information flows, physical flows and functional flows are multiplied respectively by 0,5; 0,3 and 0,2.

The DSM is a matrix that allows reorganizing the system elements that are in the rows and columns of the matrix. Then, the identified interactions placed in the matrix allows grouping the matrix elements by applying clustering algorithms. The main objective of the latter is to reorder the rows and columns so that all marks will be as close to the diagonal as possible or will form a tight cluster with other marks [11]. In our approach, the elements of the DSM matrix correspond to the activities related to the supply chain processes identified in the first step. In order to cluster the activities, increase interactions within modules and decrease interactions between modules, the Euclidean distance is used.

### 3.2 Modularity assessment

The measurement of the degree of modularity is based on the numbers of intra-modules and inter-modules interactions. The module with the greatest number of inputs is the module that takes the longest time to function, which indicates that this module will increase the supply chain lead-time [1]. Therefore, the decrease of output numbers will reduce the total time of this module and consequently the lead time of the supply chain. The degree of modularity depends on both the type of interaction (inbound or outbound) of each module and the degree of independence of modules [1]. For this reason, it is important to take into account the degree of influence of the module on the modularity measurement. This degree noted *DI* of module *i* is defined as the direction of interactions between the elements of the supply chain, which is the difference between $D_i$ and $R_i$. Indeed, if the flows are incoming, then the value of will be negative. Otherwise, in the case of outgoing flows, it will be positive. The most influenced module *i* (the one that receives the most interaction/flows) takes the longer time of execution. Moreover, this module affects the total operating time of the supply chain, i.e. the lead-time that decreases the degree of modularity.

$$M = \frac{Ia + (1 - Ie)}{2} \tag{1}$$

$$Ia = \frac{1}{NM} \sum_{i \in NM} \frac{A_i}{TA_i} \tag{2}$$

$$Ie = \frac{1}{NM} \sum_{i \in NM} \frac{E_i}{TE_i} PI_i \tag{3}$$

$$PI_i = \frac{(DI_i + X)}{\sum_{i \in NM} (DI_i + X)} \tag{4}$$

$$X = Min(|DI_1|, |DI_2|, \ldots, |DI_{NM}|) \tag{5}$$

where:

- $M$ is the degree of modularity
- $Ia$ is the degree of intra-relations
- $Ie$ is the degree of inter-relations
- $A_i$ is the number of interactions within the same module
- $TA_i$ is the total of interactions within the same module
- $E_i$ is the number of interactions between modules
- $TE_i$ is the total of interactions between modules
- $PI_i$ is the weight assigned to each module
- $D_i$ is the sum of the rows corresponding to module $i$
- $R_i$ is the sum of the columns related to module $i$
- $DI_i$ is the degree of influence of each module
- $X$ is the minimum value of the absolute values of $DI_i$
- $NM$ is the number of modules

## 4 Illustrative example

In this section, the proposed approach is illustrated based on the example taken from [19] representing a multi-echelon supply chain with of a manufacturing organization with its own warehouse and distribution system, composed of 7 processes: plan, source, make, deliver return, warehouse and order process. Two partners are interacting with the company: suppliers and customers. Each process is decomposed into a set of activities to determine the interactions between them. This example is given to reorganize all the activities of the supply chain in order to maximize the intra-modules relationships and minimize the inter-modules relationships using DSM, as shown in Fig. 3 and Fig. 4 [19].

For highly interdependent elements, decision makers can group them into the same functional department by changing the physical layout of the supply chain. Indeed, some activities can be restructured by moving them from one department to another (from one process to another) for better communication and coordination. Although research has shown that the size of the teams must be reduced to ensure effective communication, the results of the modular design have shown that this reconfiguration is more manageable, so that personnel can work in collaboration with personnel from the same module (sub-group).

Each activity has two types of flows: the inbound flows that are necessary for the realization of the activity and the outbound flows of the activity that are necessary for the execution of other activities in relation with it. For example, the flow entries 0.2, 0.5, 0.3 and 0.1 in row X18 represent the information and material needs inputs from the elements X1, X2, X15 and X16. On the other hand, the three entries 0.7, 1 and 1 in the column X18 represent the needs of information and material outputs for the elements X16, X19 and X20 from the element X18.

| | | X1 | X2 | X3 | X4 | X5 | X6 | X7 | X8 | X9 | X10 | X11 | X12 | X13 | X14 | X15 | X16 | X17 | X18 | X19 | X20 | X21 | X22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plan: Business Strategy | X1 | | 0.2 | | | | | 0.1 | | | | | | | | 0.1 | | | | | | | |
| Plan: Resource Allocation | X2 | 0.4 | | 0.5 | | | | | | | | | | | 0.1 | | | | | | | | |
| Plan: Coordination and communication | X3 | 0.1 | 0.8 | | | | | | | | | | | | | | | | | | | | |
| Source: Delivery scheduling | X4 | | 0.5 | 0.5 | | 0.8 | 0.9 | | 0.1 | | | | | | | | | | | | | | |
| Source: Supplier selection | X5 | 0.5 | 0.2 | | 0.9 | | | 0.7 | 0.2 | | | | | | | | | | | | | | |
| Source: Inv management | X6 | | 0.9 | | 0.8 | | | | | | 0.5 | | | | | | | | | | | | |
| Produce: Production design | X7 | 0.4 | 0.8 | | | 0.2 | | | 0.1 | | | | | | | | | | | | | | |
| Produce: Individual parts of processing | X8 | | 0.8 | | 0.3 | | 0.5 | 0.1 | | 0.5 | 0.1 | | | | | | | | | | | | |
| Produce: Sub system coordination | X9 | | 0.8 | 0.8 | | | | 0.8 | 0.3 | | 0.8 | | | | | | | | | | | | |
| Produce: WIP/ FG Inv Mgmt | X10 | | 0.8 | | | | | 0.6 | 0.5 | | | 0.1 | 0.3 | | 0.2 | | | | | | | | |
| Warehouse: Inventory control | X11 | 0.8 | 0.4 | | | | | | | | 0.5 | | 0.2 | 0.2 | 0.3 | | | | | | | | |
| Warehouse: Procurement | X12 | 0.8 | 0.4 | 0.5 | | | | | | | 0.2 | 0.8 | | | 0.1 | | | | | | | | |
| Warehouse: Carrier selection | X13 | 0.5 | 0.2 | | | | | | | | | 0.2 | 0.5 | | 0.1 | | | | | | | | |
| Warehouse: Capacity and operation | X14 | 0.7 | 0.3 | | | | | | | | | 0.9 | 0.1 | | | | | | | | | | |
| Deliver: Distribution channel | X15 | 1 | 0.3 | | | | | | | | | | | 0.5 | | | | | | | | | |
| Deliver: Schedule and routing | X16 | | 0.1 | | | | | | | | | | | 0.5 | | | | | 0.7 | | | | |
| Order: Quotes | X17 | 0.2 | 0.3 | | | | | | | | | | | | | 0.5 | 0.1 | | | | | | |
| Order: Processing orders | X18 | 0.2 | 0.5 | | | | | | | | | | | | | 0.3 | 0.1 | | | | | | |
| Order: Back Orders | X19 | 0.2 | 0.5 | | | | | | | | | | | | | 0.3 | 0.1 | | 1 | | | | |
| Order: Invoice | X20 | | | | | | | | | | | | | | | | | | 1 | 0.5 | | | |
| Return: Receive and verify | X21 | 0.5 | | | | | | | | | | | | | | | | | | | | | |
| Return: Defective rework/ Dispose | X22 | | 0.7 | | | | | | | | | | | | | | | | | | | 0.9 | |

**Fig. 3.** The DSM before clustering

| | | X1 | X11 | X12 | X13 | X14 | X15 | X4 | X5 | X6 | X2 | X3 | X7 | X8 | X9 | X10 | X16 | X18 | X21 | X17 | X19 | X22 | X20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plan: Business Strategy | X1 | | | | | | 0.1 | | | | 0.2 | | 0.1 | | | | | | | | | | |
| Warehouse: Inventory control | X11 | 0.8 | | 0.2 | 0.2 | 0.3 | | | | | 0.4 | | | | | 0.5 | | | | | | | |
| Warehouse: Procurement | X12 | 0.8 | 0.8 | | | 0.1 | | | | | 0.4 | 0.5 | | | | 0.2 | | | | | | | |
| Warehouse: Carrier selection | X13 | 0.5 | 0.2 | 0.5 | | 0.1 | | | | | 0.2 | | | | | | | | | | | | |
| Warehouse: Capacity and operation | X14 | 0.7 | 0.9 | 0.1 | | | | | | | 0.3 | | | | | | | | | | | | |
| Deliver: Distribution channel | X15 | 1 | | | 0.5 | | | | | | 0.3 | | | | | | | | | | | | |
| Source: Delivery scheduling | X4 | | | | | | | | 0.8 | 0.9 | 0.5 | 0.5 | | 0.1 | | | | | | | | | |
| Source: Supplier selection | X5 | 0.5 | | | | | | 0.9 | | | 0.2 | | 0.7 | 0.2 | | | | | | | | | |
| Source: Inv management | X6 | | | | | | | 0.8 | | | 0.9 | | | | | 0.5 | | | | | | | |
| Plan: Resource Allocation | X2 | 0.4 | | | | 0.1 | | | | | | 0.5 | | | | | | | | | | | |
| Plan: Coordination and communication | X3 | 0.1 | | | | | | | | | 0.8 | | | | | | | | | | | | |
| Produce: Production design | X7 | 0.4 | | | | | | | 0.2 | | 0.8 | | | 0.1 | | | | | | | | | |
| Produce: Individual parts of processing | X8 | | | | | | | 0.3 | | 0.5 | 0.8 | | 0.1 | | 0.5 | 0.1 | | | | | | | |
| Produce: Sub system coordination | X9 | | | | | | | | | | 0.8 | 0.8 | 0.8 | 0.3 | | 0.8 | | | | | | | |
| Produce: WIP/ FG Inv Mgmt | X10 | | 0.1 | 0.3 | | 0.2 | | | | | 0.8 | | 0.6 | 0.5 | | | | | | | | | |
| Deliver: Schedule and routing | X16 | | | | 0.5 | | | | | | 0.1 | | | | | | | 0.7 | | | | | |
| Order: Processing orders | X18 | 0.2 | | | | | 0.3 | | | | 0.5 | | | | | | 0.1 | | | | | | |
| Return: Receive and verify | X21 | 0.5 | | | | | | | | | | | | | | | | | | | | | |
| Order: Quotes | X17 | 0.2 | | | | | 0.5 | | | | 0.3 | | | | | | 0.1 | | | | | | |
| Order: Back Orders | X19 | 0.2 | | | | | 0.3 | | | | 0.5 | | | | | | 0.1 | 1 | | | | | |
| Return: Defective rework/ Dispose | X22 | | | | | | | | | | 0.7 | | | | | | | | 0.9 | | | | |
| Order: Invoice | X20 | | | | | | | | | | | | | | | | | 1 | | | 0.5 | | |

**Fig. 4.** Clustering of activities using DSM [19]

To measure the degree of modularity of this supply chain, the degrees of intra- and inter-modules were calculated based on the numbers of interactions within the modules and between the modules. The degree of influence of each module was also computed in order to assign a weight of importance to each module. The obtained results are shown in Table 1.

**Table 1.** The obtained results for the 9 modules

| | *Ri* | *Di* | *DIi* | *DIi + X* | *PIi* | *Ai* | *Ei* |
|---|---|---|---|---|---|---|---|
| Module 1 | 4.8 | 3.10 | -1.70 | 4.50 | 0.08 | 17 | 26 |
| Module 2 | 1 | 4.10 | 3.10 | 9.30 | 0.17 | 4 | 12 |
| Module 3 | 8.8 | 2.60 | -6.20 | 0 | 0 | 16 | 33 |
| Module 4 | 2.2 | 1.60 | -0.60 | 5.60 | 0.10 | 2 | 9 |
| Module 5 | 0.9 | 0.50 | -0.40 | 5.80 | 0.10 | 0 | 2 |
| Module 6 | 0 | 1.10 | 1.10 | 7.30 | 0.13 | 0 | 4 |
| Module 7 | 0.5 | 2.10 | 1.60 | 7.80 | 0.14 | 0 | 6 |
| Module 8 | 0 | 1.60 | 1.60 | 7.80 | 0.14 | 0 | 2 |
| Module 9 | 0 | 1.50 | 1.50 | 7.70 | 0.14 | 0 | 2 |

The results were used to calculate the degree of modularity of this supply chain. In this example, the modular design of the supply chain shows, on the one hand, that the degree of intra-modules is low with a value of 0.31 due to the weak values of the weights of the interactions within the modules. On the other hand, the degree of inter-modules is very weak with a value equal to 0.01, which reveals that this clustering using DSM matrix allowed obtaining a high degree of independence between the different modules. Thus, the degree of modularity is 0.64, as demonstrated in Table 2.

**Table 2.** The calculation of the degree of modularity

| | *Ai/ Tai* | *Ei/ TEi* | *Ei/(TEi * PIi)* | *Ia* | *Ie* | *M* |
|---|---|---|---|---|---|---|
| Module 1 | 0.56 | 0.135 | 0.0109 | | | |
| Module 2 | 0.66 | 0.105 | 0.0175 | | | |
| Module 3 | 0.53 | 0.171 | 0 | | | |
| Module 4 | 1 | 0.112 | 0.01129 | | | |
| Module 5 | 0 | 0.047 | 0.00495 | 0.307 | 0.01004 | 0.64 |
| Module 6 | 0 | 0.095 | 0.01246 | | | |
| Module 7 | 0 | 0.142 | 0.01997 | | | |
| Module 8 | 0 | 0.047 | 0.00666 | | | |
| Module 9 | 0 | 0.047 | 0.00657 | | | |

The results indicate that the supply chain has a high degree of modularity due to the proposed modular decomposition. By considering the degree of influence of the intercations (inbound or outbound flows) it was possible to assign a weight of importance to each degree of inter-modules in order to understand the impact of the module on the lead time of the supply chain. Indeed, with a low number of inbound flows, the lead time was low and vice versa. The proposed measure of modularity shows the impact of the degree of influence of the different modules, especially lead time, on the performance of the supply chain.

## 5 Conclusion

Modularity is a key factor of RSC that allows reducing lead time by ensuring independence between the modules formed using the DSM matrix. Interactions between supply chain activities correspond to physical, information and functional flows. Therefore, it is important to take into account the direction of the flows, whether incoming or outgoing, to determine its impact on lead time. In this article, an approach of supply chain modularity assessment was introduced. Most of the proposed modularity measures rely on the degree of coupling, the degree of cohesion and the number of modules, especially for modular product architectures.

The main contribution of this approach is that it takes into account the degree of influence of the interactions between modules in order to reduce the lead time of the supply chain. It was concluded that, if the number of incoming flows of a module is high, the lead time of this module ~~is~~ will be high and vice versa. It is, therefore, important to increase the degree of intra-module in order to reduce the degree of inter-module and, consequently, the degree of influence of each module. It was also proven that lead time is a fundamental parameter that allows improving the performance of RSC.

The proposed approach has two main limitations. First, the model does not consider the cost of the modular design in the evaluation of the degree of modularity. It is recommended to integrate this parameter to improve the selection of the best modular configuration. Second, conceptually, it is recommended to improve the scale of determination of interactions between activities and to integrate objective criteria to improve clustering and to achieve a highly modular configuration.

For future research work, we may focus on the impact on the six characteristics of RSC on the improvement of the degree of reconfigurability.

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