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COMPLEXITY MEASURING APPROACHES TO ASSESSING OF ASSEMBLY SUPPLY CHAIN STRUCTURES

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ABSTRACT

Networked manufacturing systems are becoming increasingly complex. One of the major challenges at the early configuration design stage is to make a decision about a suitable networked manufacturing structure that will satisfy the production functional requirements and will make managerial tasks simpler and more cost effective. An experimental approach for assessing the structural complexity of supply chain networks is presented in this paper. Its main scope is to present a methodical approach to generate assembly supply chain structural models and subsequently to test and evaluate their structural complexity properties.

Keywords: supply chain networks, topological analysis, complexity indicators, classes of structure.

INTRODUCTION

In the present manufacturing environment, final producers and their suppliers must be able to process high variety of products while guaranteeing competitive prices and reasonable delivery times. Modular assembly supply chains have been recognized as major enablers to handle the increased variety of products against to so-called non-modular assembly supply chains. Assembly supply chain as a network of facilities often present complex engineering and logistical issue and brings for practitioners and investigators serious challenges including topological complexity metric for supply chains. Its main scope is to present a methodical approach to model assembly; this paper presents a new configuration complexity assessment to outline a working framework for measuring structural complexity of assembly supply chains (ASCs). This procedure is intended to be used at the early design stages when alternative structural model supply chain structures and subsequently to test and evaluate their topological complexity properties. The remainder of the paper is organized as follows. In Section 2, some of the most important related work is briefly presented. The next section outlines a classification of assembly supply chain structures that will be applied in this study. Methodological issues associated with sorting the assembly supply chain structures in order to create benchmark models for the purpose of complexity assessment are incorporated in section 4. A description and application of assembly SC complexity indicators under different scenarios are presented in section 5. In the same section, different approaches for assembly supply chain complexity metrics are compared. Subsequently, a testing of indices for optimal supply chain configuration is presented. In final section, the results are briefly discussed and summarized.

RELATED WORK

It is well-known that original equipment manufacturers are moving to improve their financial performance by outsourcing the production of the components and semi-finished products in order to reduce costs and increase production flexibility. For example, Toyota’s assembly plant uses the externally produced components to assemble final products when the orders of its customers arrive [1, 2].

The need to optimize material flows between facilities in a supply chain has often inspired researchers and practitioners across the world. The most important criterion of optimization has long been focused on reducing costs in each process from product development to market [3-4]. A typical feature of this approach has been the use of modern managerial tools with aim to ensure high product quality standards, volume and mix flexibility, and delivery speed and reliability [5-7].

Undoubtedly, new challenges related to the increasing complexities of global supply chains mean that new and different approaches have to be applied for managing the supply chain including measurement methods for the evaluation of supply chain complexity. In general, the complexity of supply chains can be characterized in terms of several interconnected aspects of the networked system. Some of these aspects that were described by, e.g. [8-13] are: product structure, uncertainty and variety by information and material flows based on entropy measure, number of elements or sub-systems, degree of order within the structure of elements or sub-systems, degree of connectivity between the elements, sub-systems and the environment and mutual relations between number of elements, links and tiers.

Research undertaken by Bozarth *et al*., [14], empirically explores SC complexity using plant-level data from 209 plants across several different countries. Three basic dimensions of SC complexity that linkage the uncertainty with performance were identified in the work presented by Milgate [15].

An innovative complexity measure for assembly supply chains has been proposed Hu *et al*., [16]. This complexity measure is based on Shannon's information entropy [17] and takes especially into consideration: the supply chain structure, product variety level of each node and the mix ratios of variants offered by each node. Their approach is the closest to the one proposed in this work.

STRUCTURING OF ASSEMBLY SUPPLY CHAINS

Supply chain can be defined in numerous ways. According to Christopher [18] a supply chain is the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer. Beamon and Chen [19] add that each functional level of this network is represented by numerous facilities that along with the structure of the material and information flows contribute to the complexity of the chain.

For the purposes of this work, the supply chain structure classification according to Figure-1 has been used. Convergent class of structure that represents assembly-type of supply chains is that one in which each node in the chain has at most one successor, but may have any number of predecessors. This class of SC structures is matter of interest in this study. Convergent supply chains can be divided into two basic groups; Modular SCs and Non-modular SCs [16]. In the modular structure, the intermediate sub-assemblers are understood as assembly modules, while the non-modular structure consists only from suppliers (initial nodes) and a final assembler (end node). Moreover, it is suggested here to divide the Modular SCs into two specific categories; Modular SCs with minimal number of echelons and Modular SCs with maximal number of echelons. This categorization is conditioned on the requirement that number of initial nodes is the same for these two altered structures. In the modular configuration, the final producer purchases subcomponents from intermediate sub-assemblers instead of doing all the assembly activities itself. Modular assembly is typical for many industries, such as automotive, agricultural equipment, aerospace and others.

Generating all possible combinations of structures brings enormous difficulties in order to optimize the design and operation of the assembly supply chains. In this context, it is proposed here to establish a framework for creating topological classes of assembly supply chains.

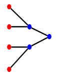
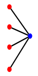
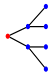
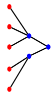
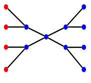
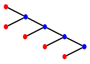
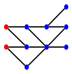
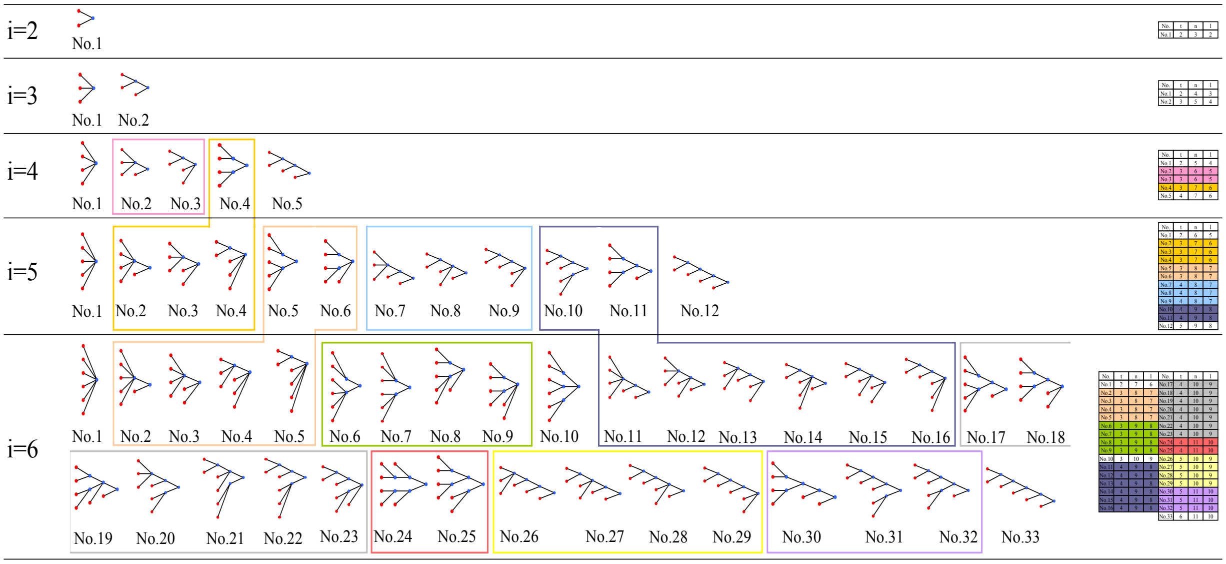
Classification of supply chain structures	Examples	Classification of assembly supply chain structures	Examples
Convergent (assembly) SC		Non-modular assembly SC	
Divergent SC		Modular assembly SC (minimal number of echelon)	
Conjoined SC		Modular assembly SC (maximal number of echelon)	
General SC			

Figure-1. Supply chain structure classification (adopted from [19, 20]).

CLASSES OF ASSEMBLY SUPPLY CHAIN STRUCTURES

The framework for creating topological classes of ASCs follows the work of Hu *et al*., [16] who outlined the way forward to model possible supply chain networks with four original suppliers. An intention in proposed framework is to determine classes of ASCs for Non-modular and Modular assembly supply chain networks based on number of initial nodes respecting the following rules:



No.	t	n	l
No.1	2	3	2

No.	t	n	l
No.1	2	4	3
No.2	3	5	4

No.	t	n	l
No.1	2	5	4
No.2	3	6	5
No.3	3	6	5
No.4	3	7	6
No.5	4	7	6

No.	t	n	l
No.1	2	6	5
No.2	3	7	6
No.3	3	7	6
No.4	3	7	6
No.5	3	8	7
No.6	3	8	7
No.7	4	8	7
No.8	4	8	7
No.9	4	8	7
No.10	4	9	8
No.11	4	9	8
No.12	5	9	8

No.	t	n	l	No.	t	n	l
No.1	2	7	6	No.17	4	10	9
No.2	3	8	7	No.18	4	10	9
No.3	3	8	7	No.19	4	10	9
No.4	3	8	7	No.20	4	10	9
No.5	3	8	7	No.21	4	10	9
No.6	3	9	8	No.22	4	10	9
No.7	3	9	8	No.23	4	10	9
No.8	3	9	8	No.24	4	11	10
No.9	3	9	8	No.25	4	11	10
No.10	3	10	9	No.26	5	10	9
No.11	4	9	8	No.27	5	10	9
No.12	4	9	8	No.28	5	10	9
No.13	4	9	8	No.29	5	10	9
No.14	4	9	8	No.30	5	11	10
No.15	4	9	8	No.31	5	11	10
No.16	4	9	8	No.32	5	11	10
				No.33	6	11	10

Figure-2. Graphical models and parameterized properties of the selected classes of ASC structures.

R1: The initial nodes in topological alternatives are allocated to possible tiers t_l $(l=1,..., m)$, except the tier t_m, in which is situated a final assembler.
R2: The minimal number of initial nodes in the first tier t_l equals 2.

Then, all possible structures for given number of initial nodes (classes) can be created. An example of generating the sets of all possible structures with numbers of initial nodes from 2 to 6 is shown in Figure-2 above.

Subsequently, it is purposeful to arrange decisive properties of these structures that are numbers of tiers *(t)*, numbers of nodes *(n)* and number of links *(l)* in a systematic order. The table arrangements of these properties for the selected classes (from i=2 to i=6) are depicted at the right part in Figure-2, where the structures with identical properties are boxed in equal color. As it is visible from these tables, there are occurred repeated properties of different ASC structures. It is suggested here to order the groups of properties of all possible structures for selected classes (from i=2 to i=10) with non-repeated ones based on t, n, l parameters (see Figure-3). Numbers for non-repeated ones of each class follow a classical sequence MSC 6858778 introduced by Munafo and used by Liu [21].

i=2	i=3	i=4	i=5	i=6	i=7	i=8	i=9	i=10
t;n;l	t;n;l	t;n;l	t;n;l	t;n;l	t;n;l	t;n;l	t;n;l	t;n;l
2;3;2	2;4;3	2;5;4	2;6;5	2;7;6	2;8;7	2;9;8	2;10;9	2;11;10
1	3;5;4	3;6;5	3;7;6	3;8;7	3;9;8	3;10;9	3;11;10	3;12;11
	②	3;7;6	3;8;7	3;9;8	3;10;9	3;11;10	3;12;11	3;13;12
		4;7;6	4;8;7	3;10;9	3;11;10	3;12;11	3;13;12	3;14;13
		④	4;9;8	4;9;8	4;10;9	3;13;12	3;14;13	3;15;14
			5;9;8	4;10;9	4;11;10	4;11;10	4;12;11	3;16;15
			⑥	4;11;10	4;12;11	4;12;11	4;13;12	4;13;12
				5;10;9	4;13;12	4;13;12	4;14;13	4;14;13
				5;11;10	5;11;10	4;14;13	4;15;14	4;15;14
				6;11;10	5;12;11	4;15;14	4;16;15	4;16;15
				⑩	5;13;12	5;12;11	4;17;16	4;17;16
					6;12;11	5;13;12	5;13;12	4;18;17
					6;13;12	5;14;13	5;14;13	4;19;18
					7;13;12	5;15;14	5;15;14	5;14;13
					⑭	6;13;12	5;16;15	5;15;14
						6;14;13	5;17;16	5;16;15
						6;15;14	6;14;13	5;17;16
						7;14;13	6;15;14	5;18;17
						7;15;14	6;16;15	5;19;18
						8;15;14	6;17;16	6;15;14
						⑳	7;15;14	6;16;15
							7;16;15	6;17;16
							7;17;16	6;18;17
							8;16;15	6;19;18
							8;17;16	7;16;15
							9;17;16	7;17;16
							㉖	7;18;17
								7;19;18
								8;17;16
								8;18;17
								8;19;18
								9;18;17
								9;19;18
								10;19;18
								㉞

Munafo classical sequence
2, 4, 6,...,26, 34, 42,..., 86, 100,

Figure-3. Size-based representatives of the selected classes of ASC structures based on t, n, l.

Generating of all possible ASC structures of higher classes (for instance i=11,…, n) based on t, n, l parameters, it offers more challenge. On the other hand the numbers of all possible ASC structures for arbitrary class of network can be easily determined by the following manner. Firstly we need to calculate the sum of non-repeated combinations for each class of ASC structures through the so called Cardinal Number [22]. The individual classes are determined by the number of initial nodes (inputs) denoted by 'i'. Then, for any integer i ≥ 2, we denote by S(i) the finite set consisting of all q-tuples $(i_1, . . . , i_q)$ of integers $i_1, . . . , i_q \geq 2$ with $i_1 + \cdots + i_q \leq i$, where q is a non-negative integer.

The Cardinal Number #S(i) of S(i) is equal to p(i)−1, where p(i) denotes the number of partition of 'i', which increases quite rapidly with 'i'. For instance, for i = 2, 3, 4, 5, 6, 7, 8, 9, 10, the cardinal numbers #S(i) are given respectively by 1, 2, 4, 6, 10, 14, 21, 29, 41 introduced by Chen [23].

Using structure decomposition of the number of initial nodes (see Figure-4), the non-repeated numerical combinations "K" for each ASC structures are allocated. Then, for each non-repeated numerical combination "K", a multiplication coefficient "M" is assigned (see Figure-5).

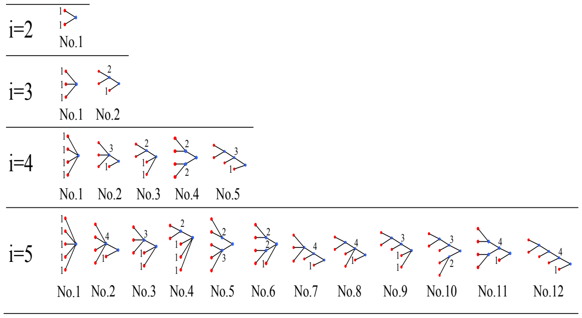


Figure-4. Example of numerical combinations of the ASC structure for selected classes.

i=2			i=3			i=4			i=5			i=6		
S(i)	K	M	S(i)	K	M	S(i)	K	M	S(i)	K	M	S(i)	K	M
1	1;1	1	1	2;1	1	1	3;1	2	1	4;1	5	1	5;1	12
	∑M	1	2	1;1;1	1	2	2;2	1	2	3;2	2	2	4;2	5
				∑M	2	3	2;1;1	1	3	3;1;1	2	3	4;1;1	5
						4	1;1;1;1	1	4	2;2;1	1	4	3;3	3
							∑M	5	5	2;1;1;1	1	5	3;2;1	2
									6	1;1;1;1;1	1	6	3;1;1;1	2
										∑M	12	7	2;2;2	1
												8	2;2;1;1	1
												9	2;1;1;1;1	1
												10	1;1;1;1;1;1	1
													∑M	33

Figure-5. Determination of total combinations of ASC networks related to the given classes.

The multiplication coefficients "M" is determined in accordance with a combinatorial arrangement corresponding with an integer sequence A000669 by Sloane [24] (see Table-1). Then, $\sum M$ - Total combinations for a given class of ASC structures can be obtained.

Table-1. Determination of all relevant alternatives for structural combinations of ASC networks.

The highest figure of a combinatorial set	Number of alternatives for the given combinations
2	1
3	2
4	5
5	12
6	33

APPROCHES TO ASC STRUCTURES COMPLEXITY ASSESSMENT

When studying complex assembly supply chain operations, we are interested in certain measurable quantities that we want to predict or control. In the proposed approach this problem is treated for two special scenarios defined by Wang *et al*., [20]:

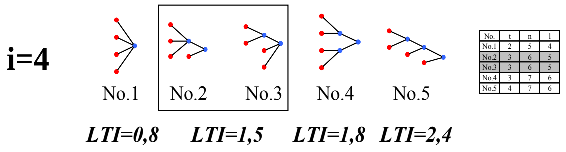
- there is only one dominant final product among all the variants determined by a final product portfolio,
- demand shares are equal across all variants a final product portfolio.

They also showed that in the first scenario where one variant significantly dominates the demand, the optimal assembly supply chain with smallest complexity should be non-modular. In the scenario of equal demand shares, the Modular assembly supply chains are more beneficial than Non-modular ones when the product variety is rather large than small.

The case when a dominant demand exists

Based on the previous premise for this scenario two propositions can be formulated:

a) For a given class of ASS structures the optimal structure is one with the smallest number of links.
b) When comparing two or more structures with the same number of links, nodes and modules but with different number of tiers (see, e.g., structures No. 4 and No. 5 in Figure-5), the following argument can be construct: The structure with the smallest number of tiers is topologically less complex than other one (s).



No.	t	n	l
No.1	2	5	4
No.2	3	6	5
No.3	3	6	5
No.4	3	7	6
No.5	4	7	6

Figure-5. Example of comparison of ASC structures by Links/Tiers Index.

Then it is proposed to measure structural complexity by formula *Links/Tiers Index* [25]:

$$LTI = \sum_{j=1}^{p}\sum_{l=1}^{m} l_j . t_l 0,1 \tag{1}$$

The case when a dominant demand doesn't exist

According to the assumption for this scenario Modular assembly supply chains are more beneficial than Non-modular ones. Authors [18] of this premise showed that, e.g., for the structures of in Figure-6a the following relation can be formulated:

$$\text{Complexity (I)} > \text{Complexity (II)} > \text{Complexity (III)} \tag{2}$$

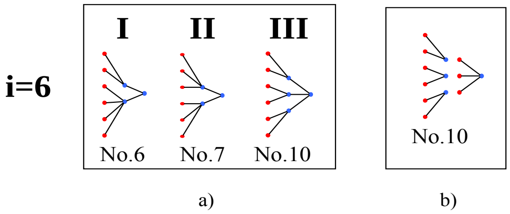


Figure-6. a) Example of Modular ASC structures, b) the substructures of the original structure

Considering this assumption, it is proposed the following parameterization with aim to obtain measures that allow comparing complexity of structures:

a) To split a given structure into substructures which are represented by Non-modular ones, the number of which is just equal to sum of the intermediate sub-assemblers plus one assembler of final products (see Figure-6b).
b) To calculate a structural complexity for each substructure of original structure.
c) To calculate a total structural complexity of an original structure.

For step 2, to measure sub-structure complexity, the following index of *Module degree* can be formulated:

$$\deg(m)_i = (i_m - 1)^2 , \tag{3}$$

where i_m presents number of module inputs (i_m=1,...,r) of given Non-modular structure.

For step-3, to measure the total structure complexity, the following formula is used [26]:

$$I_{md} = \sum_{s=1}^{q} \deg(m)_i , \tag{4}$$

where
s = number of substructures of an original structure.

Then, when we apply this procedure we obtain the following measures for the given structures depicted in Figure-5(a):

$$I_{md\,I} = \deg(m)_{2,1} + \deg(m)_{4,2} + \deg(m)_{2,3} = 1 + 9 + 1 = 11 ,$$

$$I_{md\,II} = \deg(m)_{3,1} + \deg(m)_{3,2} + \deg(m)_{2,3} = 4 + 4 + 1 = 9 \,,$$

$$I_{md\,III} = \deg(m)_{2,1} + \deg(m)_{2,2} + \deg(m)_{2,3} + \deg(m)_{3,4} \,.$$
$$I_{md\,III} = 1 + 1 + 1 + 4 = 7$$

Obtained complexity relation is the same as in the expression (2).

CONCLUSIONS

It's not a new thought that supply chain complexity has proved to be an elusive concept to find stable solutions. However, its topicality is unabated, as the increased level of manufacturing complexity brings risks associated with increasing the time of development and manufacturing of products. This paper extends above mentioned previous contributions to assembly supply chain complexity by the following two outputs. Its first focus was to propose the generic reference model for specifying the classes of assembly supply chain structures based on highly regarded modeling principles of these structures. Graphical representations of such ASC structures and parameterized properties of the selected classes of the networks are shown in Figure-2. Proposed framework allows exact determination of all relevant structure combinations that can be effectively used for benchmarking purposes. As the second contribution of this paper, it is showed that structural complexity of ASC networks can be dependable measured for the two different scenarios by using proposed final formulas (1) and (4). Potentially, these structural complexity measures can by used to find or create optimal assembly supply chain configurations according to one of the specific criteria.

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