Fuzzy Entropy Method for Quantifying Supply Chain Networks Complexity*

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Abstract. Supply chain is a special kind of complex network. Its complexity and uncertainty makes it very difficult to control and manage. Supply chains are faced with a rising complexity of products, structures, and processes. Because of the strong link between a supply chain's complexity and its efficiency the supply chain complexity management becomes a major challenge of today's business management. The aim of this paper is to quantify the complexity and organization level of an industrial network working towards the development of a 'Supply Chain Network Analysis' (SCNA). By measuring flows of goods and interaction costs between different sectors of activity within the supply chain borders, a network of flows is built and successively investigated by network analysis. The result of this study shows that our approach can provide an interesting conceptual perspective in which the modern supply network can be framed, and that network analysis can handle these issues in practice.

Keywords: supply network, complexity, complex network, network analysis, entropy, fuzzy variable.

1 Introduction

In today's business environment, where the pressure is on providing accuracy and flexibility to partners, while at the same time reducing costs, the only way to achieve these goals is by improving processes both internally and externally. At the same time, the walls of the enterprise continue to move out; there is outsourcing with more and more partnerships and organizations reaching out to one another. Companies are outsourcing what is not attached to their core competencies, so the bottom line is flexibility. At the same time, the bottom line is also agility; many researches focus on the ability of an organization to adapt to change and also to seize opportunities that become available due to change [2,3].

A supply chain (SC) may be defined as an integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw

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materials into specified final products, and (3) deliver these final products to retailers. This chain is traditionally characterized by a forward flow of materials and a backward flow of information [1]. In most cases, a supply chain, however, is not a simple linear sequence of connections, but rather, an intricate web-like structure, therefore a supply chain is also called a supply network (SCN).

Supply Chain Management (SCM) is deputy to the coordination of all these distinct processes in the most efficient way. Supply Chain Management means transforming a company's supply chain into an optimally efficient, customer-satisfying process, where the effectiveness of the whole supply chain is more important than the effectiveness of any individual department. We are therefore operating with a complex network of relations and connections between different partners. On the one hand, market globalization and products variety required by customers are trends from which no company can ignore but, on the other hand, the increased mix of products and the increased suppliers and customers stock, the fragmentation of orders and the consequent supply chain expansion demands continuing and increasingly complex control and managing systems. Modern enterprises must break barriers to the creation of connections with partners to maintain competitiveness, but, at the same time, they need more sophisticated methods to study and control how they are linked in their global network. If the number of partners increases, then production might increase, but system entropy and its indirect costs will increase as well. Managers' decisions and external resources and business can amplify or attenuate effects of such complexity on the Supply Chain. These and other considerations should warn us of the urgency for effective management strategies to preserve competitiveness, increase organization and control complexity of the industrial supply chain. Understanding and improving this integrated network is slightly more complicated. System analysis can contribute to overcome this short-sightedness because it allows the examination of elements and linkages in an interacting group as a whole. Now, "*we are close to know just about everything there is to know about the pieces: but we are as far as we have ever been from understanding nature as a whole*" [4].

Today supply chains are suffering from a high complexity, which is due to several causes, such as customer tailored and elaborate products, global procurement and distribution, or technological innovations. Besides a raising complexity in the structures and processes of the manufacturer itself, also the whole supply chain is infected by this complexness. Because of the direct link between the efficiency and the complexity of a supply chain, complexity management becomes a major task of today's business management.

The PRTM research[5] shows that the success of world-class companies stems from their ability to reduce the complexity of their supply chain architecture. All aspects of the supply chain contribute to the complexity: physical breadth and configuration, management, relationships with suppliers and customers, organizational structure, and information technology capabilities.

These aspects become complex for several reasons. Competitive pressures constantly drive businesses to expand their capabilities. In addition, most people in large organizations continue to wear functional hats and, as one might expect, strive for functional excellence: As each function does what is in the best interests of its customers or internal stakeholders, it places demands on other functions, which in turn introduces greater complexity. Finally, complexity simply evolves over time from the cumulative outcome of many seemingly unrelated functional decisions. These decisions leave in their wake supply chain artifacts that service a need that may no longer exist.

This work applies network analysis paradigms to supply chains in order to compute the complexity and organization level of an industrial network. The main objectives of this study are two folded: (1) to provide new criteria for assessing organization and measuring complexity of SCN; (2) to provide a potential approach for supply chain improvement to reduce complexity and increase efficiency and competitiveness of companies.

2 Related Research

Complexity reduction as a strategic goal for the operation has been investigated and measured by previous works in this field. A number of specific simplification techniques can be applied to the supply chain. The key is to identify those that will improve the different performance levers for each supply chain process element. Literature dealing with this topic can be classified on the basis of:

- *Introductory and/or general studies.* This research activity presents the whole problem of Supply Chain Performance Management and Control, underlines the special features of the modern supply network and introduces a large set of supply chain performance indices [6].
- *Statistical approaches.* Analysis of correlations existing between qualitative measures of complexity and general supply chain performance indices [7,8].
- *Analytical approaches* to measure the complexity of supply chains and manufacturing systems[9].

The main approaches towards measuring system complexity are based on entropy measures: information-theoretic modelling of manufacturing organizations has led to the development of an entropic method to compute the static and dynamic complexity measure of a single manufacturing system [10,11,12].

Researchers gradually focused on supply chain complexity too during the past several years. One of the most notable examples of quantification of the complexity of a supply chain is the one introduced by Sivadasan et al. [13], in which a single customer-supplier relationship is analyzed by the use of the information entropy measure.

Choi et al [14]. proposed that many SCNs emerge rather than result from purposeful design by a singular entity. The emergent patterns in a SCN can much better be managed through positive feedback, which allows for autonomous action. Imposing too much control detracts from innovation and flexibility; conversely, allowing too much emergence can undermine managerial predictability and work routines. Therefore, when managing SCNs, managers must appropriately balance how much to control and how much to let emerge.

Sharon et al.[15] studied the connection between product complexity and vertical integration using original empirical evidence from the auto industry. Their research shown that complexity in product design and vertical integration of production are complements: that in-house production is more attractive when product complexity is high, as firms seek to capture the benefits of their investment in the skills needed to coordinate development of complex designs. And they found a significant and positive relationship between product complexity and vertical integration.

Richard's "Supply chain complexity triangle" [16] describes the interaction of deterministic chaos, parallel interactions and demand amplification. It provides a useful framework for understanding the generation of uncertainty within supply chains.

Bozarth et al. [17] proposed a model of SC complexity and empirically tested it using plant-level data from 209 plants across several different countries. Their results shown that upstream complexity, internal manufacturing complexity, and downstream complexity all have a negative impact on manufacturing plant performance. Furthermore, SC characters that drive dynamic complexity are shown to have a greater impact on SC performance than that drive only detail complexity.

In a summary, SC complexity has great impact on its whole systematic performance, but current research on SC complexity is not enough, so it is meaningful to study it deeply.

3 A Framework

SCs can be described as networks, constructions made of boxes and arrows; the former identify the components and the latter describe flows of various nature. Flows can be divided in four classes: (1) inputs from outside the system; (2) flows between components; (3) exports to other systems; and (4) dissipation. losses.

We can sketch the flows of goods and materials (in pieces or money value per time period) inside a SCN or single production plant using a matrix, T, of flows which represents fluxes from compartment i to compartment j, that is, from row to column. If there are N compartments in the network, the matrix T will be composed of an $N \times N$ sub-matrix accommodating flows between compartments and rows and columns accounting for the inputs and outputs coming into and leaving the system. The 0th row and column, labelled IM, represents Imports of goods (or materials) into the system, the $(N + 1)$th row and column, labelled EXP., will account for Exports from the system (usable goods/materials), while the $(N + 2)$th row and column, labelled DISS., will stand for Dissipations. Total System Throughput (TST) is simply the sum of all coefficients, that is,

$$TST = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \triangleq t_{..}. \tag{1}$$

In what follows we will often use contractions to shorten the formulae and $t_{..}$ will stand for sum across all rows (first dot) and columns (second dot). In the same way, $t_{i.}$ will be the sum of the ith row and $t_{.j}$ the sum of the jth column.

3.1 Entropy and Joint Entropy

We depict a SCN as a collection of transition probabilities (i.e., the probability of finding a ‘quantum’ of the exchanged goods in a certain box at any time), and we compute the entropy ($p\log(p)$) of the system considering inputs to any node and outputs from any node. In particular, we represent the network as a weighted adjacency matrix, and we compute the entropy associated with row sums (probabilities of leaving the boxes) and columns sums (probabilities of entering the boxes). If, at a given time, we mark a particle at random that is travelling in the system, we will find the probability associated with the event “the particle is moving from compartment i to compartment j” and we will call this quantity the probability associated with the arrow from i to j.

Shannon introduced a measure of the entropy associated with the process X equal to the sum of the probabilities of each possible outcome i times the logarithm of the probabilities.

$$H_X = -\sum_{i \in X} p(i) \log P(i) \tag{2}$$

The entropy associated with the events like “a particle is leaving compartment i and entering compartment j”is usually called the joint entropy $H_{O,I}$

$$H_{O,I} = -\sum_{i=0}^{N+2} \sum_{j=0}^{N+2} p_{O,I}(i,j) \log p_{O,I}(i,j) = -\sum_{i=0}^{N+2} \sum_{j=0}^{N+2} \frac{t_{ij}}{t_{..}} \log \frac{t_{ij}}{t_{..}} \tag{3}$$

The entropy associated with outputs from compartments will therefore be

$$H_O = -\sum_{i=0}^{N+2} p_O(i) \log p_O(i) = -\sum_{i=0}^{N+2} \frac{t_{i.}}{t_{..}} \log \frac{t_{i.}}{t_{..}} \tag{4}$$

and the entropy associated with inputs to compartments:

$$H_I = -\sum_{j=0}^{N+2} p_I(j) \log p_I(j) = -\sum_{j=0}^{N+2} \frac{t_{.j}}{t_{..}} \log \frac{t_{.j}}{t_{..}} \tag{5}$$

3.2 Conditional Entropies

The conditional entropy is:

$$H_{I|O} = -\sum_{i=0}^{N+2} p_{I|O}(j|i) \log p_{I|O}(j|i) = -\sum i = 0^{N+2} \sum_{j=0}^{N+2} \frac{t_{ij}}{t_{..}} \log \frac{t_{ij}}{t_{..}} \tag{6}$$

In the same way we can define the conditional entropy $H_{O|I}$. Then the following identity holds:

$$H_{I,O} = H_I + H_{O|I} = H_O + H_{I|O}. \tag{7}$$

3.3 Average Mutual Information (AMI) Index

Average Mutual Information (AMI) is defined as

$$AMI = H_O - H_{I|O} = H_O + H_I - H_{I,O} \tag{8}$$

This formula explicitly states that the information is equal to the decrease in entropy associated with inflows once we know the outflows (or the decrease in outflows entropy once we know the inflows), and that AMI possesses symmetry. In a network of exchanges many configurations are compatible with the same Throughput level (TST). More constrained topologies are those in which a restricted number of flows exists, so that the medium is forced to move along a limited number of pathways. This occurs when compartments are more functionally specialized in the system. The AMI index measures such degrees of specialization or amount of constraints on the medium. If the flows are constrained to follow a given path, then knowing that a particle is leaving compartment i also tells us that it will enter compartment j, leading, therefore, to the maximum possible AMI: this configuration is usually associated with a linear flow exchange. Obviously, $0 \leq AMI \leq H_{I,0}$.

3.4 Principal Steps of the Methodology

(1) Measure flows of goods, money and interactions between different sectors of activity within the supply chain borders
(2) Build a network of flows
  (2.1) Input from outside
  (2.2) Flows between components
  (2.3) Export to other systems
  (2.4) Dissipation losses
(3) Build a matrix of flows and calculate total system throughput
(4) Depict the network as a collection of transition probabilities
(5) Calculate network indices (i.e., Average Mutual Information (AMI) index)
(6) Compare results and identify critical parts (bottleneck)
(7) Improve and control supply network improvements

4 Model with Fuzzy Information

In most real applications, the matrix T is difficult to obtain, but we can get some inaccurate information by some kind of methods such as forecasting and experts estimation, therefore, it is more reasonable to use fuzzy data to represent this. Suppose that the information of matrix T comes from n different experts' estimation. Each expert gives an estimation with form of a triangle fuzzy number $A = (\alpha, a, \beta)$. The information would be accurate if $\alpha = \beta = 0$. The expectation of a triangle fuzzy number is defined as [18]

$$\mathrm{E}(A) = a + \frac{\beta - \alpha}{4}. \tag{9}$$

Suppose that each entry of the matrix T comes from judgements of n experts' on p attributes of the corresponding objects such as price, capability, flexibility etc. Each judgement is presented by a triangle fuzzy number $[a_{ij}, b_{ij}, c_{ij}]$, i.e. the conservative, the most possible and the optimism estimation respectively. Let $\alpha_{ij} = b_{ij} - a_{ij}$, $\beta_{ij} = b_{ij} - c_{ij}$ and $r_{ij} = b_{ij} + \frac{\beta_{ij}-\alpha_{ij}}{4}$ $(i = 1, \cdots, p; j = 1, \cdots, n)$, then the initial estimation matrix $R = (r_{ij})_{n\times p}$ for this entry is obtained. Suppose the weight matrix of different experts is $e = [e_1, \cdots, e_n]$, then the integrated weight matrix is

$$W = e \times R, \tag{10}$$

where, $W = [t_1^*, \cdots, t_p^*]$ and $t_i^* = \sum_{j=1}^{n} e_j \times r_{ij}$. After normalization, the fuzzy weight matrix is $W_F = [t_1, \cdots, t_p]$ where

$$t_i = \frac{t_i^*}{\sum_{i=1}^{p} t_i^*}. \tag{11}$$

After this treating, we can evaluate the current SC configuration performance or give some improvement suggestion to the current SC by the method present in section 3.4.

5 Example

In this section, the supply chain configuration problem is used as an example to show how the potential complexity of a supply chain should be considered in the phase of configuration. The supply chain configuration problem (SCCP), introduced by Graves and Willems [19], is the problem of determining the configuration of a supply chain, i.e., what suppliers, parts, processes and transportation options (modes) to select at each stage in the supply chain. It arises after the logistics network of the supply chain and product design have been determined. There are various ways to conduct each stage of a supply chain. For example, raw material can be procured from different suppliers; products can be manufactured or assembled on different machines; finished goods can be shipped through different modes. Each option differs in lead time and cost reflecting the time-cost trade-off. The goal of SCCP is to select the options and thus the configuration of supply chain so that some supply chain metric is minimized. In addition, supply chain complexity should be considered in the configuration stage. This is our start point.

Research on network design focuses on developing the optimal manufacturing and distribution network for a company's entire product line. Geoffrion and Powers [20] describe the evolution and primary assumptions in this field. These approaches generally formulate large-scale integer linear programs that capture the relevant fixed and variable operating costs for each facility; these variable costs go beyond manufacturing costs to include tariffs and taxes. This stream of research (for instance, Geoffrion and Graves [21], Arntzen *et al.* [22]) differs from this paper in its level of detail and scope. Network design focuses on the design of two or three echelons in the supply chain for multiple products; the supply chain configuration problem focuses on a single product family at the supply chain level, allowing it to model all the echelons in the supply chain and to explicitly capture the impact of variability on the supply chain.

During recent years, much research on SCCP have been made. Li [23] studied SCCP under resource constraints. A new modeling framework based on multi-mode resource-constrained project scheduling for configuring the supply chain subject to explicit resource constraints was proposed. Their model was able to handle additional practical issues such as quality level requirements and general temporal constraints, which are often encountered in the real world. A constraint programming based solution approach was proposed and implemented.

In [24], Wang and Shu modeled supply chain uncertainties by fuzzy sets and developed a possibilistic supply chain configuration model for new products with

Table 1. Options for Notebook Computer

component description	option	lead time	cost-added
Parts w/4-week lead time	1	35,40,42	145,130.00,120
	2	15,20,24	134.2,133.25,130
	3	9,10,12	135,134.91,133.2
	4	0,0,3	138.10,136.95,134.23
Parts w/3-week lead time	1	15,20,24	210,200.00,180.00
	2	8,10,12	210,202.50,200
	3	0,0,1	208,205.03,200
Parts w/2-week lead time	1	6,10,12	158,155.00,145
	2	0,0,2	162,156.93,150
Parts on consignment	1	0,0,1	210,200.00,190
Circuit board assembly	1	18,20,22	115,120.00,128
	2	4,5,6	145,150.00,158
LCD display	1	50,60,65	312,300.00,268
	2	4,5,6	360,350.00,330
Miscellaneous components	1	25,30,32	213,200.00,187
Metal housing	1	65,70,72	230,225.00,220
	2	23,30,34	265,240.00,220
Battery	1	50,60,65	43,40.00,32
	2	18,20,22	55,45.00,40
Notebook assembly	1	4,5,6	130,120.00,100
	2	1,2,4	138,132.00,130
Gray cover	1	35,40,45	6,5.00,4
	2	12,15,18	6.5,5.50,5
Blue cover	1	35,40,45	6,5.00,4.5
	2	13,15,17	6.5,5.50,5
Gray assembly	1	0,1,2	40,30.00,25
Blue assembly	1	0,1,3	35,30.00,24
US demand-gray	1	4,5,6	15,12.00,10
	2	0,1,3	30,20.00,15
Export demand-gray	1	12,15,18	20,15.00,12
	2	1,2,3	35,30.00,26
US demand-blue	1	4,5,6	15,12.00,10
	2	0,1,2	30,20.00,15

unreliable or unavailable statistical data. The supply chain was modeled as a network of stages. Each stage may have one or more options characterized by the cost and lead-time required to fulfill required functions and may hold safety stock to prevent an inventory shortage. The objective was to determine the option and inventory policy for each stage to minimize the total supply chain cost and maximize the possibility of fulfilling the target service level. A fuzzy supply chain model was developed to evaluate the performance of the entire supply chain and a genetic algorithm approach was applied to determine near-optimal solutions. The proposed approach allows decision makers to perform trade-off analysis among customer service levels, product cost, and inventory investment depending on their risk attitude. It also provided an alternative tool to evaluate and improve supply chain configuration decisions in an uncertain environment.

Wang and Che [25] presented an integrated model for modelling the change behavior of product parts, and for evaluating alternative suppliers for each part by applying fuzzy theory, T transformation technology, and genetic algorithms. The proposed model was based on the concepts of part change requirements, fuzzy performance indicators, and the integration of different attributes, to allow the part supplier selection of a specific commercial product to be explored and modelled.

Wang [26] examined the problem of assessing the configuration change of engineering products with complex structure through the observation of actual case. An analysis model was proposed and applied to a production system, where the parts of products are manifold and any part is available with several suppliers, so as to establish an efficient scheme to select eligible suppliers in case that certain parts need to be replaced. Four steps were involved in the analysis model. In addition to the analysis of component parts with association graph, fuzzy theory and data T transfer were also employed, meanwhile, taking such assessment attributes as cost, quality and time into consideration, in order to effectively assess the efficiency of configuration change schemes.

The example is from [19]. A notebook computer consists of three major subassemblies: the liquid crystal display (LCD), the circuit boards, and the housing.

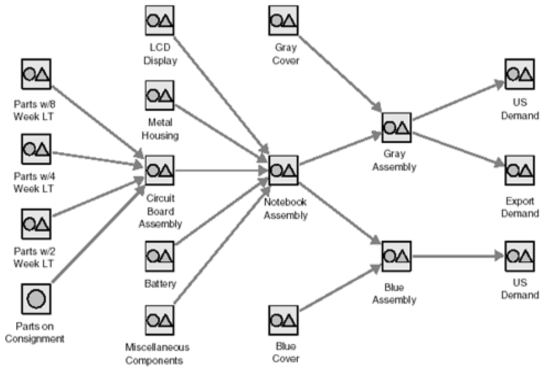

Fig. 1. A Notebook Computer Supply Chain Configuration

The LCD is a standard component that is purchased from an external vendor. The housing is a custom-designed product that is also sourced from an external vendor. To create the circuit boards, components are purchased from external vendors and assembled by a contract manufacturer. The assembly process involves assembly of the components and quality testing and creates a generic notebook computer. Some important data are listed in Table 1. Using our method, we can get a satisfactory configuration as shown in Fig. 1.

6 Conclusions

Supply chains are often described as complex and extended networks. The great number of connections within partners, system integration and product variety increase the complexity of the supply chain and, as a consequence, its connected indirect costs. Many supply chains designed to be flexible and agile are constrained by their structural complexity to be inflexible. This interdisciplinary work tries to bring in a new methodology for measuring how much fluxes inside the supply chain are constrained. The method in this paper appears to identify the dynamical bottlenecks in supply chain connections and provide consideration of supply chain improvement in an organization. When the network is very large, the computation is huge, this is a drawback of this method and it would be our further research.

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