A System Framework for Complexity Measurement and Evaluation on the Example of Supply Chain

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***Abstract*—The complexity of a system is generated by a lot of interactive and interdependent components with dynamic behaviors working together as a whole system. However, the quantitative analysis of the complexity generated by these components and their behaviors and its impact on the system still lacks practical methodology. This paper aims to design a framework to measure the complexity of complex supply chain. The first step is to understand and represent the complexity using an extended conceptual model. Due to the similarity between system and process complexity, we can thus develop the formulas to measure system complexity based on the metrics of process complexity as well as the properties of complex system. The validation is done through a classical supply chain phenomenon – the bullwhip effect, which can be demonstrated using a serious game called beer distribution game. We set two scenarios in the game and compare their complexity values. This framework can also be applied to evaluate the impact and complexity of changes in a system.**

Keywords-complex system; process complexity; complexity measurement; supply chain; bullwhip effect

I. INTRODUCTION

What is complex? Some intuitive understanding is that complex is “not easy to understand or analyze” [1] or complexity is “something difficult to replace”. There are many definitions of complex system from different fields and aspects. The consensus is that a complex system has “enormous elements interact with one another and with the environment” [2].

From a scientific view, even though the complexity of various systems manifests in diverse ways, there is certain commonality among them. Bar-Yam [1] summarizes some universal properties of complex system:

- Elements (and their number)
- Interactions (and their strength)
- Environment (and its demands)
- Activities (and their objectives)
- Diversity/Variability
- Formation/Operation (and their time scales)

Supply chain is viewed as a complex system [3] consisting of a set of activities, agents, technological and physical infrastructures which interact with each other through information exchange and material flows in order to reach business goals. It is also highly influenced by the environment, e.g., the policies and external markets, and the requests for customization of products and services. The formation of supply chain refers to the emergence, e.g., a global supply network emerges with not single one firm deliberately organizing and controlling it [4].

Before measuring complexity, the first step is to understand the system, as the quantitative knowledge arises from this qualitative understanding [5].

As noticed, the difference between simple and complex system is that the latter one focuses on the “interconnected” or “interwoven” part. This requires that one must understand not only the behavior of the underlying parts but also how they act together to form the behavior of the whole complex system [1]. Experiments indicate that experts can have deeper understanding on a domain system by integrated thinking from the perspective of structural (elements of a system), behavioral (mechanisms), and functional aspects of a system; while the novices tend to focus on perceptually available, static components of the system. This can be explained by a framework called Structure–Behavior–Function (SBF) theory, which focuses on causal understandings of the relationships among different aspects of the system [6]. Therefore, it is necessary to align the common understanding that the system needs to be understood from both aspects of components and their interrelationships.

There are two basic strategies to model a general complex system: analytic tools dealing with elements and interactions and computer simulation handling descriptions and information [1]. Some researchers argue that the analytic thinking has limitations on processing human and organization elements in system design and less support to mathematical modeling for unstructured problems [5] comparing with the simulation techniques, which can be used to model the behaviors of agents.

The application area of our research is the supply chain system and we can try to take the strong points of both analytic and simulation methods on it. The first step is to build a conceptual model via identification and description of the parts as well as their interactions in supply chain. After the key information is captured, we could go for the quantitative analysis using simulation approaches.

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The objective of this paper is 1) To extend a conceptual model based on an existing one to represent the key information of the supply chain complex system 2) To set a framework with metrics to measure system complexity 3) To validate these metrics using an industrial example.

This rest of this paper is structured as follows: in Section 2, a conceptual model based on PROS is elaborated; the relevant factors to the system complexity and their value assignment are discussed; the complexity metrics of the whole system are formulated and demonstrated. In Section 3, the findings are summarized and further research is outlined.

II. Approach

Previous research proposed a conceptual model called Process, Role, Object and State (PROS) to extract the key elements and their various relationships of a supply chain [7]. It is used to describe a change management process.

The quantity (size) of the elements and the relationships in a system can be easily calculated via this approach. However, this is not sufficient to reflect the "diversity" of each element, nor the various relationships among them. For example, there is only one type of serial relationship between two processes. And current description for each element is still on the abstract level, without more details to distinguish them. When evaluating their impacts on the whole system, more precise information is needed.

In this section, the conception of PROS idea is enriched and thus can be used to quantify the complex system.

A. Basic definitions

Since many terms have been defined in previous research [7], in this subsection we only focus on the new content and the parts which may cause ambiguity.

1) Goals of the system

A system usually has a definable objective or function [1]. From the supply chain view, the activities of a system are either directly related to cost reduction, turnover increase or have indirect benefits in general, e.g., quality (higher flexibility and better forecast accuracy), speed (shorter committable lead time), cost (enabler for cost reduction), customer service (better delivery reliability or delivery performance). By using these criteria as Key Performance Indicators (KPI) we have indication whether the activities in a system is valuable or not.

2) Business system and boundary

A business system has dynamic (processes) and static (objects) aspects. A business system refers to the value-added chain, which describes the value-added process. The system has boundaries and interacts with other surrounding systems via interfaces [8][9].

3) Process and activities

The supply chain process is recognized as one type of the business process. A process is made up of multiple steps, also referred to as activities, and has to be completed in a predetermined order. An atomic activity consists of a single process step or action and cannot be subdivided. There is interdependency among the activities within one process. A business process also has goals and can be viewed as a system [8][9].

4) Objects and states

Two types of objects can be distinguished: an information object and a business object. An information object is described via a data structure in an IT system and a business object presents physical objects in real-world [8][10].

5) Roles (Agents)

Roles can be replaced by the term agent in many situations. From the simulation view, agents are usually autonomous or intelligent, representing a human being, an organization or an autonomous machine [4].

6) Relationships and others

For this part please refer to our previous research [7].

The conception model can be illustrated by a serious game called beer distribution game, which was firstly invented by Jay Forrester at MIT in the 1960s to explain the bullwhip effect [11]. The purpose of this game is to understand the dynamics of a multi-roles supply chain and how demand fluctuates in the different distribution stages.

A widely-accepted beer game setup usually has five stages: customer, retailer, wholesaler, distributor and factory. Two flows run in the supply chain, one up and one down. For the order flow, the customer orders units of beer from the retailer and the retailer sends its order to its upstream - the wholesaler until the final order is received by the upstream end of the chain- the factory. Vice versa is the delivery flow: the factory produces beers and delivers to other three downstream stages until it reaches the end customer. It is noticed that, there are possible delays in the flow between each stage considering the shipping and information time.

The task for each supply chain partner is to fulfill incoming orders and keep the inventory/backorder cost at the minimum level.

We thus identify all the key components in this beer supply chain system: five roles, two main processes (*order flow*, *delivery flow*) with time delay on different stages, one main object *order* and its two states (*inventory*, *backorder*).

B. Complexity attributes and impact on system

As mentioned in Subsection A.3, a process can also be viewed as a system. Similar to the system complexity, the process complexity has the "difficulty to describe and execute a process" [12]. Therefore, we assume the methodology to measure process complexity can be learned and adapted to the system complexity measurement.

Based on the metrics and formulas to measure process complexity [12], in addition to the specific properties of complex system, we list the factors which affect the complexity of a system. The overall complexity of a system is represented as **C*s***.

- Environment: the part interacts with the internal components of a system. Environment E may have one of several variables. Let Z = number of external variables $E_1, E_2 \dots E_z$ interacting with system.

- Components: let N = quantity (size) of all components in a system; let M be the quantity of all (static) relationships among components.
- Diversity: the more diverse a system is, the higher the complexity it contains. Let d be the value of diversity, for each component i, its diverse value d_1, d_2… d_i… d_N; $d_i \in (0, 1]$ with 1 being very diverse, and 0 not diverse.
- Emergence: this property depends on the entire system and reflects its relationships L, $L \in (0, 1]$ with 1 the system being very cooperative, and 0 not cooperative at all.
- Interactions: complexity R_E is interactions related to the environment and complexity R_I is interactions within internal components. For each component *i*, $R_{i,z}$ is the interaction with one environment factor z, R_{iE} ($R_{iE} = \sum_{z=1}^{Z} R_{i,z}$) is the total interactions with all factors in environment; $R_{i,j}$ is the interaction with one internal component *j* and R_{iN} ($R_{iN} = \sum_{j=1}^{N} R_{i,j}$) is the total interactions within the remaining part of the system. R value depends on the different types of interactions and the rules predefined (if there are any). For the types of interaction, if component *i* and *j* belongs to the same category of components, $R_{i,j}$ has smaller value than if they belong to the different ones. For the rules, e.g., the value of interaction with outside system is assumed to be much higher than internal ones, $R_{i,z} >> R_{i,j}$.
- Activities and Goals: each activity and involved components have certain impact on the goals. The better the activity matches the goal, the less complexity the system has. This attribute can be subdivided into 3 factors: for each component, 1) its commitment to the overall goal 2) the importance (comparing with other components) to the goal 3) the collaboration with other components.
- Commitment to the intention (goal): let G be the numeric value of intention fulfillment, for each component i, G_1, G_2… G_i… G_N; $G_i \in (0, 1]$ with 1 satisfying the intention perfectly, and 0 does not meet the goal at all.
- Order of importance to satisfy the intention: let α be the weight value of importance, for each component *i*, $\alpha_1, \alpha_2 \ldots \alpha_i \ldots \alpha_N$, $\alpha_i \in (0,1]$ with 1 being most important, and 0 not important to the goal,
- Collaboration with other components: or conflicts. Let β be the weight value for collaboration, for each component *i*, $\beta_1, \beta_2 \ldots \beta_i \ldots \beta_N$, $\beta_i \in (0, 1]$ with 1 being very collaborative, and 0 not collaborative to others at all.

Above analysis doesn't differentiate the categories of components for each C_i, in this step we need to include the individual features for each type of element in PROS. To make the analysis easier, we can simply add one coefficient γ for each type, γ_p, γ_r, γ_o, γ_s stands for the coefficient of process, role, object and state. Accordingly, for each component *i*, its complexity $C_i = \{C_p, C_r, C_o, C_s\}$.

For the role element, some additional features need to be highlighted. In this paper, we only give some qualitative analysis:

- Intelligence: If Agent is intelligent, the influence is higher than non-intelligent ones on the system.
- Influence to the system: some agents have more power than others in the organization or system.
- Level of convergence: decided by skills, experiences, knowledge, etc. A higher level of convergence correlates to a lower level of complexity in the system.

C. Formulation

Based on the attributes listed in Subsection B, we can define some formulas to measure the system complexity $\mathbf{C}_{\boldsymbol{s}}$.

$$\mathbf{C_i = \prod_1^N \gamma_i \cdot d_i \cdot \frac{1}{\alpha_i} \cdot \frac{1}{\beta_i} \cdot \frac{1}{G_i}} \quad \forall \mathbf{i} \in \{\mathbf{1, 2, \ldots, N}\} \tag{1}$$

$$\mathbf{R_i} = \sum_{z=1}^{Z} \mathbf{R_{iz}} \cdot \sum_{j=1}^{N} \mathbf{R_{ij}} \quad \forall \mathbf{i} \in \{\mathbf{1, 2, \ldots, N}\} \ \mathbf{and\ i \neq j} \tag{2}$$

$$\mathbf{C}_S = \frac{\mathbf{1}}{\mathbf{L}} \cdot \mathbf{N} \cdot \mathbf{M} \cdot \prod_{i=1}^{N} \mathbf{C_i} \prod_{i}^{N} \mathbf{R_i} \tag{3}$$

Equation (1) addresses the impact of one single component to the whole system; (2) focus on the interaction between one single component to the other components within and outside of system; and (3) is about the overall complexity.

We also need to know how to set the values of variables in these formulas. Based on the data sources and methods to obtain them, we can divide these variables into three types:

- N, M - the natural number, which can be acquired from the physical world directly from the statistic tools or the enumeration method.
- $R_{i,z}$, $R_{i,j}$ – the values can be perceived from the physical world on a certain degree, for example, it is easy to observe which types of relationships they are, however, for more precise weights for each relationships type, some predefined measures need to be done, which can be based on the empirical results. For example, Gruhn and Laue defined a table which summarizes all possible relationships as well as their cognitive weight values [13]. These rules are easy to understand, e.g., the weight of sequential relationship type is 1, and for the iterative type it is 4. It is obvious that the latter one is more complex than the former one.
- For these values α, β, γ, d, L and G – these values cannot be observed from the physical world directly. An easy way is to assign their values

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based on the domain experience, e.g., set three scales: low, medium and high. For calculation, the scales can be assigned value with, e.g., 0.2, 0.5, and 0.8. These values can be easily tuned within the simulation environment. A more accurate but complicated way is to collect the data via certain experiments and do statistical analysis. There are some other indirect approaches, e.g., we can subdivide one factor into several more detailed sub factors and thus get an accumulated value. Just like the γ for the agent element, it needs to consider the humans skills and influence, etc.

III. VALIDATION

We continue our validation with the beer game. It is played online via the platform provided by University of Houston and we choose the game "SCM_1409_24" for our analysis [14]. In this game, the participants were divided into two groups and each group performed one scenario.

Scenario 1 with communication (S1): supply chain partners are allowed to exchange and share information with each other in order to get better forecasting about the order quantity and thus reduce the cost of inventory/backorder.

Scenario 2 without communication (S2): supply chain players are not allowed to communicate and collaborate with each other. If the order from customer is not visible for the whole chain, the upstream stage has to forecast the demand by itself. In this game, the cost of one inventory unit is configured as 0.5, while one backorder unit costs 1. Hence the players tend to order more than necessary in order to have a safety stock. The deviations are accumulated and thus the overall supply chain cost is increased.

Table I shows the results for each supply chain partner in two scenarios, including the order quantity per week and inventory/backorder cost.

TABLE I. BEER GAME RESULTS

Roles	Scenario 1		Scenario 2	
	Order quantity/week	*Cost in 26 weeks*	*Order quantity/week*	*Cost in 26 weeks*
Customer	7	0	7	0
Retailer	7	80.5	9	483
Wholesaler	9	157	37	1039
Distributor	6	285	17	2923.5
Factory	7	324	14	226.5

We would like to compare the complexity of these two supply chain scenarios. For the simplicity, we only consider the changeable parts which have impact on the complexity. Some assumptions are given below:

- The external factors have the same impact for the two scenarios
- Diversity factor is the same for two scenarios
- The size of system components and their interrelationships (static part) are the same
- The role complexity of customer is the same; while the other 4 roles have different behaviors
- The order flow process execution time increased 33% in S1 ($\gamma_{p1} = 1.33$, $\gamma_{p2} = 1$)

From above analysis, we only need to extract the relevant factors: α, β, G, R and L.

The values of α and G (see Table II) can be calculated from the results in Table I. The α value is decided by its cost percentage in the overall supply chain. E.g., the retailor in S1 has the lowest cost, so it contributes the most importance value to the goals (to reduce the overall cost). The G value is used to evaluate the demand forecast accuracy. The closer to the end customer demand, the higher value it has.

TABLE II. COMPLEXITY FACTORS (ALPHA, G) FOR TWO SCENARIOS

Scenario	α				G			
	α_{r1}	α_{r2}	α_{r3}	α_{r4}	G_{r1}	G_{r2}	G_{r3}	G_{r4}
S1	0.90	0.81	0.66	0.62	1	0.78	0.88	1
S2	0.90	0.78	0.37	0.95	0.78	0.19	0.41	0.5

And the values of β, R (see Table III) can be acquired from the system configuration. For one single stage, β counts the total number of roles it collaborates with. R stands for the number of interactions, which is much higher in S1 than in S2.

TABLE III. COMPLEXITY FACTORS (BETA, R) FOR TWO SCENARIOS

Scenario	β				R			
	β_{r1}	β_{r2}	β_{r3}	β_{r4}	R_{r1}	R_{r2}	R_{r3}	R_{r4}
S1	1	1	1	1	3	3	3	3
S2	0.5	0.75	0.75	0.5	1	2	2	1

The L value is difficult to obtain from above data; therefore we simply set three scales for it: low, medium and high. From the observation in the game, the collaboration of S1 can be considered as the medium level. Because the highest value of L is 1, which means the total supply chain cost should be 0. In our case the total cost of S1 is 846 so we set L = 0.5; for S2 we choose L = 0.2.

By using the equations in Subsection C, we get the ratio of complexity of S2 to S1 is 5.39, which is very close to the cost ratio of S2 to S1, 5.52. Although it is too early to conclude that there is some causal relationship between supply chain cost and complexity, we can at least state that: 1) the supply chain complexity and cost have the same trend. 2) The communication and collaboration could reduce the overall supply chain complexity via information sharing.

IV. CONCLUSION AND NEXT STEP

This work-in-progress paper has proposed a framework to understand and measure the system complexity by capturing its key information. It analyzes the complexity influence factors and their impact on the system. Based on the process complexity and complex system attributes, the metrics to measure complexity for both individual components and the entire system are formulated. A supply chain example is used to demonstrate this framework.

So far, our work is mainly built on the hypothesis of complexity measurement. In the next step, our research will focus on the fine tuning of these metrics and further validation.

A. *Value assignment for influence factors*

Part of the variables, e.g., “L” is assigned based on the cognitive experience. To obtain more accurate values, we can employ survey, e.g., having interviews with experts from industry; and investigate more empirical results for similar problems.

B. *The spatiotemporal features*

Current measurement only considers the execution time of process, which is not sufficient to reflect a complex system. Other features, e.g., objects with lifecycles; processes in different locations should also be included.

The dynamic complexity is highly dependent on the time and space changes. Therefore, the quantitative impact of time and space need to be included in the future research.

C. *The complexity of system changes*

As soon as the spatiotemporal feature is considered, we could evaluate the impact of changes on system.

By using the differentiation operation on (3), we can get the ΔC_s, which stands for the complexity of changes.

D. *Simulation and validation*

Simulation techniques have been widely used in the complex systems. Discrete-event simulation and agent-based modeling are two popular methods.

To validate our hypothesis, we can use the simulation tool because it could support batch data processing and track many parameters in one model. By setting different values for the input parameters, we can analyze the impact of each variable to the complexity of the entire system.

The changes of system and their impact on the system can also be modeled. Fernandes, Arlindo and Henriques proposed a modeling framework to assess the impact of changes in a process, in which attributes are defined as variables and behaviors (process steps) are treated as the functions of variables [15]. This idea is worth considering for the further research on the change management of supply chain.

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