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Supply Chain Complexity in the Semiconductor Industry: Assessment from System View and the Impact of Changes

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Abstract: The semiconductor industry is considered to be one of the most complex industries, not only due to more than 500 processing steps involved in the manufacturing and various products, but also the harsh environment it faces, e.g., the volatile electronic market and the unpredictable demand. On the one hand, companies have to adapt their behaviors to the changing environment; on the other hand, many changes inevitably bring in the complexities and challenges to the supply chain management. Our research strategy is to build a general model for complex systems first and then generate the supply chain instance model from it. A complex system can be decomposed into three levels: subsystem, component and part. The part level is the lowest level which defines four types of key elements (process, role, object and its states) and different relationships among each other. Various types of complexity are discussed, and changes and their potential impact on the system complexity are also analyzed. We use an instance model from the semiconductor supply chain to illustrate the system modeling, specify the features of each element on the part level and propose the metrics of complexity measurement. Consequently, two scenarios are compared by calculating the variation of their overall complexity. The intermediate results of doctoral research are presented and the future research is also planned.

Keywords: supply chain, complex system, complexity measurement, change management, semiconductor industry, system engineering

1. INTRODUCTION

1.1 Motivation

The supply chain in the high-technology semiconductor industry is characterized by long fabrication cycle times, high levels of stochasticity, and non-linearity in the manufacturing process (Wang 2008). These all lead to complexity to be managed in the supply chain. Add to that, recent trends in the semiconductor supply chain are towards greater speed, globalization, customization and flexibility (Chien 2007). However, to reach these goals certain degree of complexity would be increased too, e.g., the globalization resulted in more complex processes and organizational structures; customization and diversification increased the design complexity of products.

These trends also reflect the volatile characteristics of a semiconductor supply chain, which faces a consumer dominant market. Globalization results in very competitive product price for customers, whereas it pushes the companies to reduce cost by relocating manufacturing to low cost countries and keep looking for the even lower places. Correspondingly, the supply organizations are evolved from linear supply "chains" into broader and more complex supply "networks" (Marchese 2014). The product itself also becomes more complex than before. It is designed towards more sophisticated, integrated and specialized components and services. For example, the mobile phone has many more functions than 20 years ago and car manufactures could double the number of electronic components in 5 years. Besides that the product features are constantly changing due to the market demand and customer pressure. This requires companies to redesign their supply network and collaborate with numerous partners at different stage to achieve this integration, as it is almost impossible to do everything within one company (Chopra 2010).

From above analysis, we can state that global supply chain is complex and we must consider the influence of changes in the supply chain as it is a dynamic system.

Supply chain complexity is aware by leading firms. People could somehow observe and perceive the complexity and its orientation, but they can hardly judge whether the increased complexity is valuable to the business goals as it is difficult to measure it. People follow this strategy in principle: value-adding ("good") complexity offers ways to meet customer demands and creates a real competitive advantage; while value-destroying ("bad") complexity pushes the customer away and sends the company into chaos and confusion (Scheiter 2007, Etheredge 2009). After complexity is classified, we can take these actions: reduce non-value-added complexity; manage value-added and necessary complexity; and avoid non-value added complexity in the future.

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Besides this strategic way, people are keen to have some qualitative methods to evaluate complexity comprehensively. Only with the quantitative indicators, it could be more convincing for decision making and thus used as an operational guideline.

1.2 Research Objective and Questions

The main objective of this research is to develop a practical framework for managing complexity in the semiconductor supply chain. It should be able to identify and model the complexities as well as their changes in a systematic way. It should also provide certain instruments to assess the complexities and thus apply various strategies (reduce complexity, avoid complexity, etc.) based on the classification of value adding complexity. In the end, the results of complexity measurement should be validated and support decision-making.

To achieve this research objective, this paper aims to answer the following main research question: How to assess supply chain complexity from system view and the impact of changes in order to support decision-making in the semiconductor supply chain?

In order to reach the goal step-by-step, this research question can be broken down into a few sub-questions as below:

a) How can we evaluate a complex supply chain? Complexity metrics should be developed. The preliminary research is to understand the sources and characteristics of the complexities and their manifestations within a supply chain system.

b) How can we assess the complexities induced by changes of a system? We need to investigate the changes and their impact to the system complexity.

c) How to develop the implementation tools for complexity measurement? This research question aims to develop an assessment tool for the practical use to measure complexity.

d) How to verify the first three questions with industrials cases and thus reduce the non-value added complexity? This research question integrates the role of complexity evaluation into decision making.

1.3 Related Work

Our literature research on complexity measurement is mainly on these aspects: a) The drivers of supply chain complexity and their impact; b) The methodologies to measure complexity; c) The dynamic complexity caused by changes.

In the semiconductor industry, supply chain complexity arises from a number of sources: network complexity, market complexity, process complexity, product complexity, organizational complexity and information complexity (Christopher 2010, Lindemann 2007, Schuh 2008).

There are various measurement approaches available for the complexity measurement. We summarize several main approaches here: information theory including statistical and entropy-based approach (Schuh 2008, ElMaraghy 2012); single aspect of supply chain such as system, workflow and product complexity (Qusaibaty 2004, Cardoso 2006, Götzfried 2013); supply chain network with many nodes (Kandjani 2012); Agent-Based Modelling (ABM) for behaviours modelling (Shalizi 2006). The evaluation of approaches is based on three criteria: quantitative, practical, integrated. The first two are easy to understand, and integrated aspect means that all drivers of complexity should be considered from a holistic view.

The changes of complexity are also explored, many research studies are about the organization, process and design changes. For the measurement, most measurements are limited to the qualitative analysis. A few approaches, e.g., simulation techniques can be used to assess the impact of changes (Fernandes 2013).

In summary, complexity is generated from different parts of supply chain and they are interrelated to each other. However, the evaluation for the complexity is more on the single and static part while the integrated and dynamic analysis is missing; complexity measurement lacks practicality and its role for support decision making is not explicit; and the complexity caused by and changes and their impact on the whole supply chain are not much explored.

The rest of this paper is organized as follows: in Section 2 we introduce our research method and thus propose a general framework to model the complex systems; Section 3 focuses on the supply chain model and explains the details of measurements on a practical example. Section 4 presents the results achieved and future research plan; the expected contributions are highlighted in Section 5.

2. RESEARCH METHODOLOGY

There are commonalities among different complex models and our pre-study has showed supply chain can be viewed as a complex system (Sun 2015b). Therefore, we adopt the method of general-to-specific modelling and first study the general complex systems. The primary goal is to design a framework for the complex system on the abstract level, including the system modelling method, complexity analysis and influence of change. Under this framework, we can define a clear structure for the supply chain systems; meanwhile, the supply chain features can be integrated into the instance model at the bottom level.

2.1 A general model of complex system

System engineering methodology can be used to model a complex system. A preliminary step is required to define the problem scope. We employ a system delimitation technique to define the relevant parts of system, which can be demarcated into three areas: environment, intervention system, area of solution (Haberfellner 2002). Environment covers all external factors (outside of the intervention system) which are relevant to the system complexity. Intervention system includes the area where all interventions and modifications related to the problem can be made. It acts as an interface between the internal system and external environment. Area of solution is the core part to find problem solutions. This step is helpful to define the working area and boundary when we detect the impact of changes.

2.1.1 Definition of terms

Some key terminologies are defined in order to avoid ambiguity in this paper.

A *System* can be broadly defined as an integrated set of elements (activities, subsystems) cooperating together in order to accomplish a defined objective (INCOSE handbook 2000). A *subsystem* can be viewed as a system only except it cannot fulfil a goal completely on its own, it must be integrated with other subsystems as a whole (Beale). A *component* is a clearly identified subset of the products being designed or produced and it contains many parts. Normally, *part* is identified as the basic or inseparable item of a system (Carson 2012).

2.1.2 System decomposition

System decomposition is a common used technique in the area of software engineering and system engineering. It can decompose the system into two or three layers or even more. A widely used two-layer structure is the subsystems-components (Jennings 2001, Kim 2003); if the system is very complex a 3-layer architecture, e.g., the subsystems-components-parts (Carlson 2012) is exploited and even can be extended to four-layer: subsystem-components-subcomponents-parts (Beale). Carlson states that the definition of system hierarchy depends on the objective. Since we would like to model a complex supply chain, a three-layer architecture should be appropriate to capture the details within a complex system. The break-down of System is shown on Fig. 1.

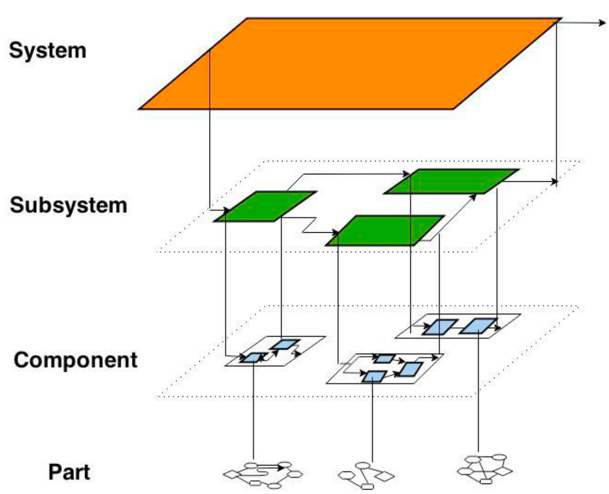

Fig. 1. System decomposition into three layers (relationships are not depicted due to visibility) (adapted from Haberfellner 2002 and ETH 2015)

2.1.3 System attributes and relationships

For each level, the attributes of basic elements and their interfaces are defined. The basic element for the *subsystem* layer is the subsystem, similarly for the layer of *component* and *part*. In our model, the interface part can be described as the relationships among all the elements. These relationships are illustrated in Fig. 2.

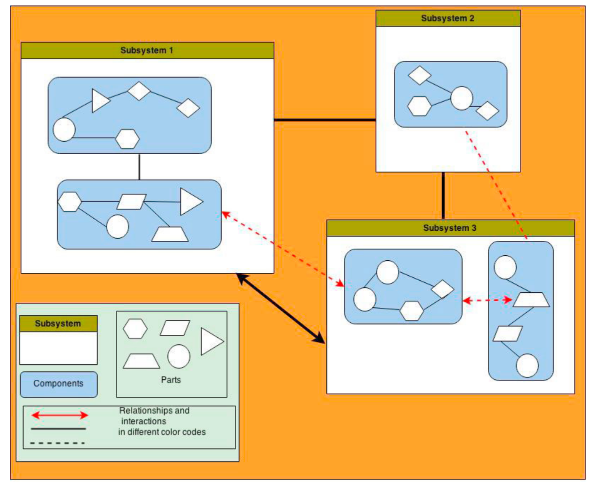

Fig. 2. A hierarchical model of various relationships in a complex system (adapted from Jennings 2001)

The relationship includes dependencies and interactions among all the elements from different levels. The former relationship is about the static interdependencies and the latter one refers to the dynamic connection. In Fig. 2, the lines between any two elements without arrows stand for dependencies, while lines with arrows mean the interactions.

The relationships can also be categorized as the local or external ones according to the position of the two elements. If they are within the same level or under the same element, the relationship is local, otherwise it is external. In Fig. 2, the black line means the local relationship while the red line means the external one. We can also distinguish the relationships by strength. For example, the solid line represents the pair is strong related and the dashed line is the weak related pair.

Besides the multiple types of relationships, a constraint set should also be given. E.g., a *part* within one *subsystem* is not allowed to be directly related to another *subsystem*.

2.1.4 The part layer- PROS analysis

At the lowest level of this abstract model, the *part* layer, it defines the basic types of elements (parts) with distinct features, a group of which under certain rules constitutes the *component* on the upper layer.

We employ a conceptual model including four elements: **p**rocess, **r**ole, **o**bject and its **s**tates (PROS) to describe a complex system. It also defines the six types of relationships among these elements; the constraints are given too (Sun 2015a). For example, the process can be related to any other elements. A simple PROS model is sketched in Fig. 3.

This model could cover most key features in a system and keep it simple, thus we consider using these four types of "pieces" on the *part* layer. The specification of relationships can also be taken from PROS.

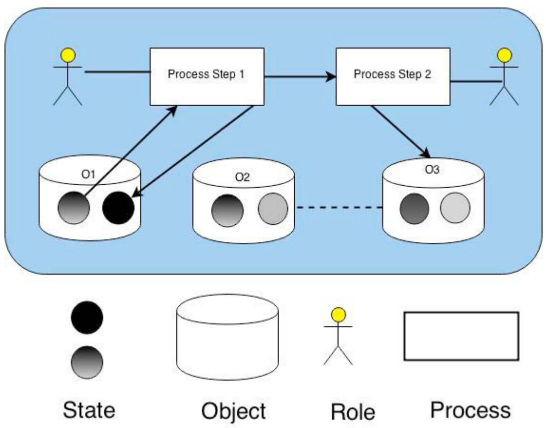

Fig. 3. A simple system described by PROS approach

2.2 Complexity analysis on different types

Complexity analysis is based on the hierarchical model built in Section 2.1. We can address the complexities from different views:

a) The element and relationship complexity. The element complexity is related to the attributes and type of each element; relationship complexity is about the dependencies and interactions among all elements. For the overall complexity, the quantity and impact factors of elements and relationships should also be considered (Sun2015b).

b) The structural complexity, functional complexity, and organizational complexity. This corresponds to the different layers of our model respectively: *part*, *component* and *subsystem* layer (Schuh 2013, Salado 2014).

c) The internal and external complexity. The complexity within the solution area of a system belongs to the internal complexity, and the external one means the complexity caused by any environmental factors (ETH 2015, Sun2015b).

d) The dynamic and static complexity. The static complexity is related to the inherent interdependencies while the dynamic one is influenced by the interactions and changes.

2.3 Changes of system and their impacts

Changes lead to the dynamics of system and complexity is generated accordingly. There are many types of changes in a system. Below we list some categories of them and also analyse their potential impacts on the system complexity.

a) Internal changes and external changes. The changes could be generated from the local internal system or stimulated by the environment. External changes might affect more parts than the internal ones.

b) Passive changes or active changes. Passive changes refer to the physical components, while the active changes are more initiated by humans, which have more uncertainty and thus increase complexity.

c) Changes on the different levels: *subsystem*, *component* or *part*. Changes occurred at the higher layer have more influence on the whole system than at the lower layer.

3. SUPPLY CHAIN INSTANCE MODEL

Based on the framework developed in Section 2, we can build a supply chain instance model, which inherits the properties from the general model and highlights the specific features of each type of elements at the *part* level and below. In this section we take a simplified semiconductor supply chain as an example, to illustrate the system modelling, metrics formulation and scenarios comparison.

3.1 A model of semiconductor supply chain

A typical semiconductor supply chain has five stages: customer, Original Equipment Manufacturer (OEM), tier 1, tier 2 and raw material supplier. Two flows run in the supply chain, one up and one down. For the order flow, the customer orders products from the OEM and the OEM sends the order to its upstream - the tier 1 until the final order is received by the upstream end of the chain- the raw material supplier. Vice versa is the delivery flow: the raw material supplier produces units and delivers them to other downstream stages until the final products reach the end customer.

This supply chain can be mapped into the three-layer model introduced in Section 2.1.

- The *subsystem* layer: it has five subsystems: customer, OEM, tier 1, tier 2 and raw material supplier.
- The *component* layer: it varies according to the subsystems. It may include the module of production, order management, delivery service, etc.
- The *part* layer: it defines the key elements for the modules on the *component* layer. It includes processes such as order request, delivery and their responsible entities; the objects like orders, products and their varied states, etc.

To get an easy identification of the elements on each layer, we employ the reference models for process and data management in the supply chain management field. One widely accepted framework is the Supply-Chain Operations Reference (SCOR) model, with the scope from suppliers' supplier to customers' customer, which defines the main abstract processes in a hierarchical way. For the data model, Entity-Relationship (ER) model is one popular method to describe the information structure, which is usually defined by individual companies. Based on these reference models, it is easy to extract the elements and their features, especially helpful for us to get more details on the lower levels.

3.2 Complexity measurement on the supply chain system

Our measurement aims to reflect the features of complex systems comprehensively. Besides the quantity of elements and relationships in a system, we are more interested in these aspects: the variety of elements and their individual contributions to the system complexity; the collaborationism of them acting together in order to reach the system goals; the dynamic dependencies among elements. For example, a process could match the objective of a system at different degrees. The better it meets the goal, the less complexity it contributes to the system.

Hence, we can list all factors which influence the system complexity, for each of them we assign different values or value scales. The quantitative measurement can be applied to each type of complexity mentioned in Section 2.2 after analysis of all possible influence factors for a system.

3.3 The scenario of changes: from non-collaboration to the collaboration

The complexity measurement serves for decision-making support. Using the supply chain in Section 3.1 as an example, we can view it as a system with the goal that each supply chain partner has to fulfil the incoming orders and minimize the inventory cost. Two scenarios are drawn out: the first one requires that each partner makes decisions separately without communication with others; while the second one uses the collaboration mechanism and thus each stage can get better overview about the whole supply chain.

We assume that the non-collaboration scenario is less complex than the collaborative one, but has higher cost. This can be validated with an experiment. By collecting the results we can calculate the complexities based on the measurement approaches proposed in Section 3.2. Instead of comparing the whole system complexity of two scenarios, we can also only consider their difference, or the changed part from scenario 1 to scenario 2, which is limited to the area of intervention system. By checking the affected elements and involved relationships in this area we can evaluate the changes and thus calculate the complexity and cost.

4. RESULTS ACHIEVED

Towards answering the research questions in Section 1, we summarize the intermediate results of this research, some of which have been published.

The first stage research is about the complexity management theory, which includes: understanding the complex system with the support of a general framework for the system modelling; presenting the key drivers in the supply chain through a conceptual model called PROS; demonstrating the complexity analysis with an industrial example from the semiconductor manufacturing (Sun 2015a).

Based on the general model of complex systems, the measurement methods are investigated; and the key influence factors of the system complexity and their impact are identified. A few preliminary measurement metrics and key parameters have been proposed, e.g., system collaboration, satisfaction of goals, etc. The system complexity can be calculated based on these basic formulas (Sun 2015b). These measures are partly validated by a practical example, for some input lacking of real data we simply use assumptions.

The change analysis for supported decision making is also investigated to compare two technology solutions (Sun 2015a), or two business scenarios (Sun 2015b).

5. THE FUTURE RESEARCH PLAN

The future research focus on these aspects: the full definition of the general complex model including various relationships should be described in details. Based on this fundamental model, dynamic changes and their impact on the system within the space-time domain should be distinguished. Afterwards, a thorough list of the influence factors with their potential impacts on the system complexity will also be provided and thus analysed.

The features for each element on the *part* level, e.g., the diversity, coupling, influence should be investigated. Among these features, it is worth noting that one type of element, the agents, is a main driver to increase complexity as the human's decision making could lead to huge uncertainty. A state-of-the-art method is the Agent Based Modelling (ABM), which can be used to analyse the humans' behaviour in a Complex Adaptive System (CAS) (Aelker 2013).

Other simulation techniques such as discrete event modelling are also helpful to analyse the influence factors, e.g. tracking one or more variables at the same time, or tuning the values of input parameters, an implementation tool should be developed too.

The proposed metrics and formulas can be validated and calibrated through the industrial cases. The required input values for some parameters can be obtained from the real data in the semiconductor supply chain.

The established metrics of complexity measurement can not only be applied to one tier-2 company, but also be able to benchmark the whole semiconductor supply chain. The comparison with other tier 2 companies will be also taken into account.

6. EXPECTED CONTRIBUTIONS

In this doctoral proposal we aim to set up a framework for complex system modelling and develop metrics for complexity measurement in a supply chain. The uniqueness and scientific contribution are highlighted below:

- Analyse the complexity from a holistic system view instead of on certain aspect
- Build a general complex system model using system thinking and combine the techniques from software engineering and system engineering

- Consider the overall complexity not only from the static part but also the changes and their impact on the system complexity
- Develop practical metrics and formulas to measure complexity and benchmark industry practices
- Emphasize the uncertainty and complexity oriented from the humans' behaviour and model it through the simulation technique
- Support decision making with complexity metrics and cost & benefits analysis

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