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Perspectives of Complexity and Intelligence on Logistics and Supply Chain Management

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Perspectives of Complexity and Intelligence on Logistics and Supply Chain Management

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"If I have seen a little further, it is by standing on the shoulders of Giants". (Isaac Newton)

Although the cover page of this thesis holds only my name, there are several people who have contributed to accomplishment of the work both directly and indirectly. I would like to thank them all.

In the family area, I dedicate this work to my glorious parents who have supported and motivated me all during my life. I learn upon their kindness, patience, management and philanthropy. They actually taught me 'when there is a will, there is a way'. They have been my best friends during all seasons!

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Abstract

In recent decades, millions of articles, books and journals have been written and thousands seminars and conferences have been held to present increasing importance of supply chain management both in practice and theory. Undoubtedly, nowadays, success is not tied-up just in processes of a focal company but in processes of all its value chain and network. In order to survive in highly competitive markets, it sounds essential that all processes and entities of the supply and demand network be analyzed and value-adding ones be separated from those which are not.

One of the origins of non-value adding processes is non-value adding complexity. So, a systematic study and analysis of supply chain complexity and rendering remedies for simplicity are essential.

In this thesis, at first, some definitions as well as causes of supply chain complexity based on its complication and complexity are mentioned. In the next step, embodiments of some themes of complexity science in discipline of supply chains are explained. Later, a recipe for studying complexity is offered. Ingredients of this recipe are identification, classification, measurement, modeling, and simplification. Finally, implementation of intelligent agents as assured tools for simplification of supply chains complexity is described.

Keywords
Supply chain, Logistics, Complexity, Simplification, Management, Intelligent agents.

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1. INTRODUCTION

"Straws tell which way the wind blows". (Oxford dictionary of proverbs)

This chapter presents background and frame of the thesis. In this regard, an overview of supply chain complexity, questions of the thesis as well as its purpose and scope are introduced. Furthermore, structures of different chapters are explained.

1.1. Background and Problem definition

Supply chain is not a novel phenomenon. Story of Adam and Eve evinces its antiquity:
It is narrated that after creation of Adam, God planted him in the Garden of Eden and gave him total dominion over everything in it - including all of the fish, the birds and every living thing that moved on the earth at that time. After a certain period of time, God then saw that it is not good that Adam continue to remain alone - so He then created the first woman; Eve (The story is continued by description of forbidden tree, banishment from the Garden of Eden, procreation and …).
This story obviously shows that supply and demand chain has occurred since creation of Adam. As Adam had not been able to exist without his demands (Food, Shelter, Love and so on), God had supplied his demands (dominion over foods and shelter, creation of Eve and so on).
Counterpart of this story happens exactly in business. It is non-negotiable that a human, company, firm, institute or organization can not survive solely. In order to fulfill its demands as well as demands of its customers and as a result earning money (revenue) and survive, it must be connected to some suppliers of resources and services. This connection of supply and demand creates a supply and demand chain (network).
In recent decades, millions of articles, books and journals have been written and thousands seminars and conferences have been held to present increasing importance of supply chain management both in practice and theory. Undoubtedly, nowadays, success is not tied-up just in processes of a focal company but in processes of all its value chain and network. In order to survive in highly competitive markets, it sounds essential that all processes and entities of the supply and demand network be analyzed and value-adding ones be separated from those which are not.
One of the origins of non-value adding processes is non-value adding complexity. So, a systematic study and analysis of supply chain complexity and rendering remedies for simplicity are essential.

As yet, in most literature, complexity of supply chains has been considered just as complication of the system. In this thesis, complexity is referred to complication as well as intangible complexity of the system. These two categories of complexity form problems of supply chain complexity.

1.1.1. Problem of complication

Since the Industrial Revolution in the late 18th and early 19th centuries, all industries have fairly entered in an era of progress. In recent decades, Informational Revolution has accelerated this progress, tremendously.
Apparently, knacks of doing business in an industry have been also revolutionized in recent years. In many cases, such changes have led to complicated products and relationships as well as supply and demand chains.

For example, a customer who considered purchasing a car from Ford Company in 1920 was confined to a black model T ("You can have the Model T in any color so long it is black"). Nowadays, a customer connects to online website of the company and configures its desired model, color, accessories and so on from a multitude of configurable products.
Such mass configuration and customer orientation make supply and demand network of the company fairly complicated. In a simple case, diverse parts from diverse suppliers and locations should be supplied with diverse transportation modes to diverse Ford assembly lines and then the final products should be transferred to diverse locations of dealers and customers. In this list of diversity, other issues such as diversity of functions, after sale services, recycling, standards, flows, rules and laws, markets, cultures and so on and so forth should also be added.

Another source of supply chain complication is market expansion. Expansion, which is not essentially a vicious phenomenon, brings complicated and complex products, relationships, schedules and functions to the system.
According to Amaral & Cargille (2005), in 2004, HP generated $80 billion in revenue and $3.5 billion in profit, and offered more than 90 different product lines for sale in 160 countries. To a company of this size, the impact of successfully managing product line complexity, or the cost of its mismanagement, can easily reach into the hundreds of millions of dollars.
As an example, consider HP's product line of consumer desktop PCs. In 1998, HP and Compaq combined offered a total of 88 unique desktop PC systems to North American consumers. In 2002, after the companies merged, this total had reached 110 systems. By 2004, the number had grown to 170 unique systems, with a complete set of new models introduced every three months. The proliferating number of products also triggered corresponding increases in unique and custom parts. While a broader product line allows HP to offer a larger selection — ranging from no-frills low-cost PCs to "gaming" PCs offering enhanced video and audio — the managerial, marketing and supply-chain costs of adding this variety can amount to tens of millions of dollars per year.

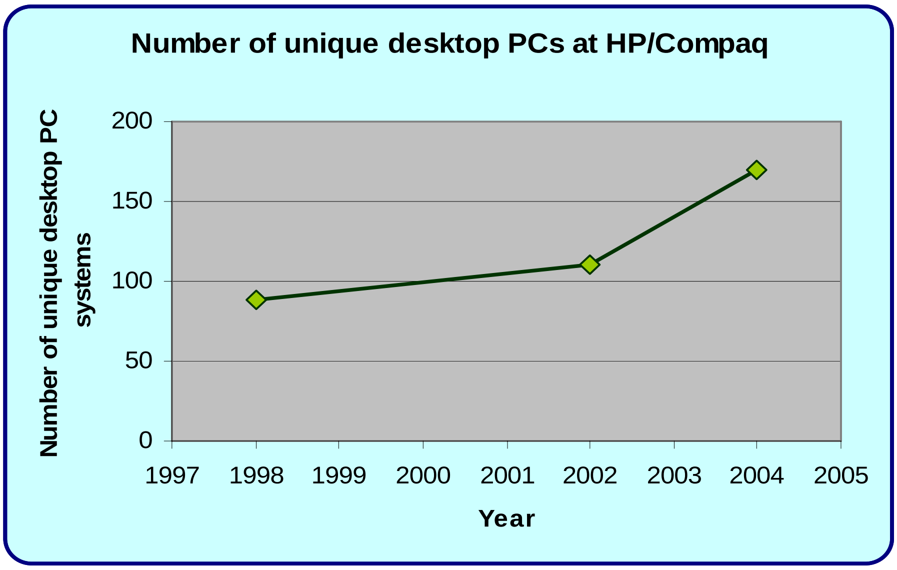


Figure 1.1- Number of unique desktop PCs at HP/Compaq (Source: Amaral & Cargille 2005)

Globalization and off-shoring are other sources of supply chain complication; although in some occasions they are prerequisite.
Clearly, global supply chains are faced up to more variables, risk and complication than domestic ones (Table 1.1).

Variables	**Supply Chain**	
	Domestic	***Global***
Cycle Time	Days	Weeks
3 rd Party Touch-points	1-2	5-10
Government Involvement	None	Significant
Time Zones	1-3	8+
Transport Modes	1	3-5
Transportation Costs	Low	High
Languages & Currencies	1	Multiple
Document Reqs	Low	Significant

Table 1.1- Challenges of global logistics (Source: Farrell 2007)

Time restrictions and short time-frames are also significant causes of complication and complexity in supply chains. One feature of this issue is reduced product life cycle. Less product business life cycle entails more design, competition and processes' speed in the system.
In order to compete with rivals, frequent introduction and modification of products are essential. The outcome of this play is more complicated supply chains. (Figure 1.2)

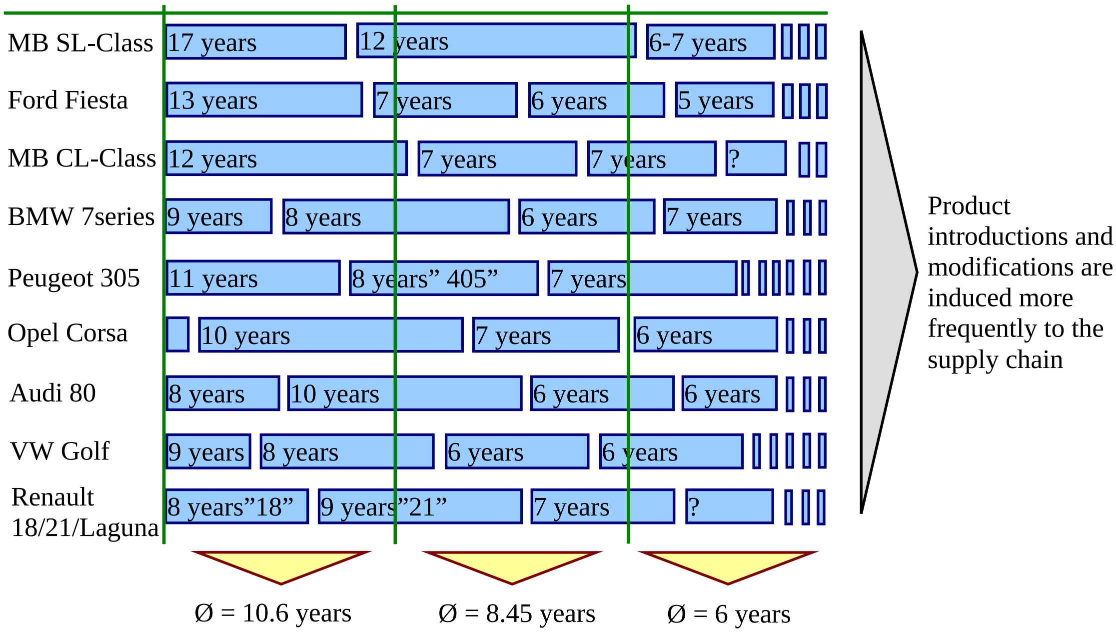


Figure 1.2 - Development of product life cycle over time (Juerging & Milling 2006 cited in Hellingrath 2007)

Figure 1.3 indicates decrease of product life cycle for automotive industry from1990 to 2004.

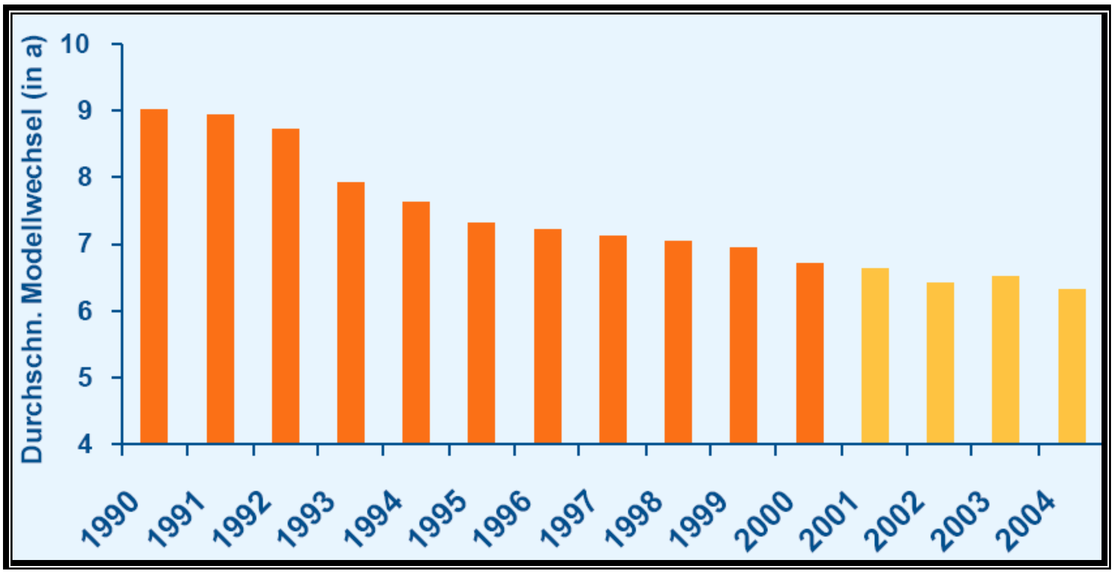


Figure 1.3 - Decrease of product life cycle in automotive industry from 1990 to 2004 (Source: Hellingrath 2007)

On the increase transportation has also made the supply chains complicated. According to a survey done by Airbus and Boeing, the global air traffic flow is expected to averagely grow 5% per year to 2025. Hunt (2005) states that air cargos are anticipated to grow 6.4% per year to 2021.

1.1.2. Problem of intangible complexity

Supply chain is a nonlinear system. Here, agents and entities of the system always self-organize and adapt with their environments. In fact, based on different circumstances, strategies and markets, they do co-adaptation and co-evolution. Furthermore, all the times, new patterns of agents of the system are emerged.
Another important issue is chaos. As supply chains are chaotic systems, just a tiny change or problem in the system can lead to catastrophic consequences and different emerged patterns of the system.
Demarcation of the supply chain and network is another part of the problem. As the chain is tied to different other chains of different networks, depicting borders of the system sounds impossible. The scenario even becomes worse when a chain enters a new market and becomes engaged with several new actors, agents and so on.
All the mentioned problems make thorough management of supply chains, impossible.

Complexity has a major impact on supply chain performance. It is one of the key drivers of excess cost as well as inventory in the system. Furthermore, it impacts flexibility, resilience and responsiveness of the supply chains.
According to Hoole (2006), complexity makes a supply chain inflexible and inefficient. It also hampers on-time delivery and creates problems for product quality. The more complex the supply chain, the greater the possibility it will fail in one or more of its functions, and failures jeopardize a company’s relationships with customers.
Hellingrath (2007) demonstrates effects of variant complexity as a vicious cycle. Vicious cycle of complexity causes increase of complexity in the entire chain. (Figure 1.4)

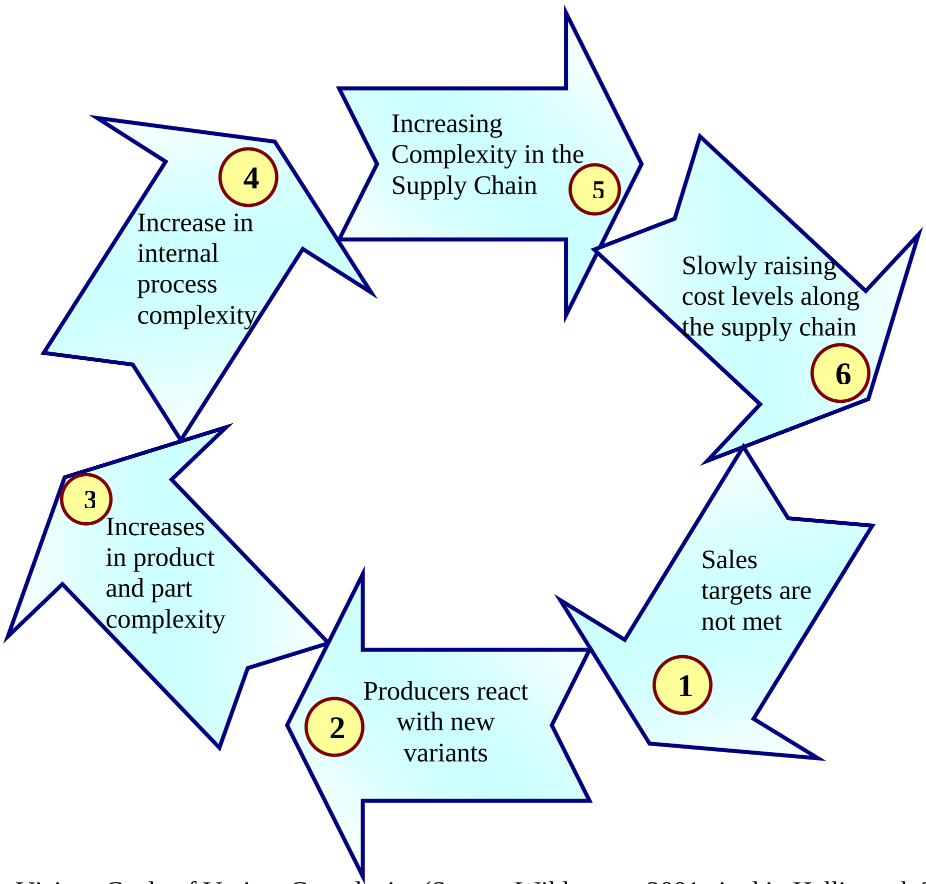


Figure 1.4 -Vicious Cycle of Variant Complexity (Source: Wildemann 2001 cited in Hellingrath 2007)

It is important to bear in mind that like different phenomena and stuffs in the world such as wind, fire and so on that have both positive and negative aspects, complexity is not essentially and always an unpleasant phenomenon.

As complexity is the edge of chaos, some amounts of it are requisite in the system. The value-adding complexity would lead to innovation in the system as well as a tool for competing with competitors. That is why the amount of complexity in the system should always be validated.

According to Ratliff (2004), there is a gap between supply chain complexity and optimization which is called *Complexity Gap*. Large complexity gaps are bad as they induce increased cost, risk and inefficiencies. On the other hand, small complexity gaps are not necessarily good (Figure 1.5).

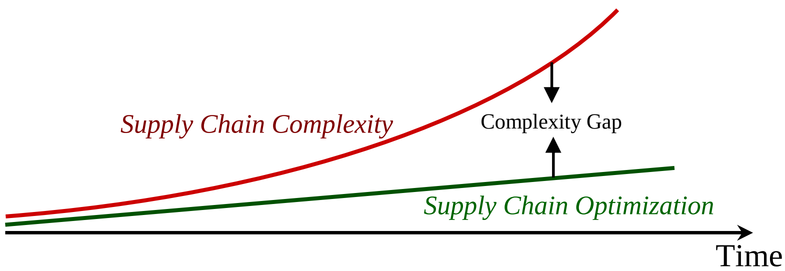


Figure 1.5 - Complexity Gap (Source: Ratliff 2004)

A critical characteristic of supply chain complexity is that reducing complexity in one part of the system may increase complexity in another. Reducing complexity gaps often results in new complexity gaps. Transforming complexity and/or complexity gaps may itself be complex.

The holly grail of complexity reduction is determining the optimum amount of complexity in the system and finding patterns of its management.

Effectively managing supply chain complexity can result in a powerful operational competitive advantage, lower costs, increased revenue, sales efficiency as well as higher customer satisfaction (Figure 1.6). According to Hunt (2005), *"A 1% increase in customer satisfaction can produce a 3% increase in market capitalization"!*

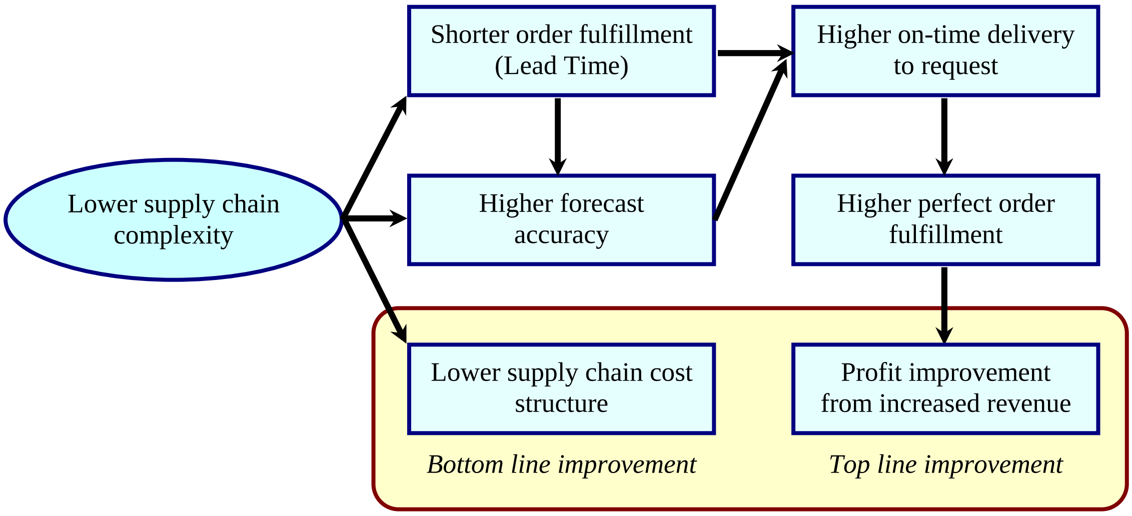


Figure 1.6 – Results of lower supply chain complexity (Source: LogicTools 2006)

1.2. Purpose and questions of the thesis

Purpose of this thesis is academic contribution to scientific research. It provides a theoretical study of supply chain complexity from different angles.
This thesis struggles to answer the following questions:

Q1: What are embodiment and counterparts of themes of complexity science in context of supply chains?

In different literature of supply chain management, complexity has been interpreted as complicated. It is important to bear in mind that a complicated system is not essentially complex.
A system is complicated if it can be given a complete and accurate description in terms of its individual constituents, no matter how many, such as a computer. Complication is a quantitative escalation of that which is theoretically reducible. A system is said to be complex when the whole cannot be fully understood by analyzing its components (Reitsma 2001).
To figure out science of complexity, its main themes and issues should be reviewed. Furthermore, embodiment and counterparts of such themes in a complex system like supply chains should be explicated.

Q2: What are remedies for non-value added complexity?

Complexity is not essentially vicious. Like many phenomena of the universe such as fire, water, wind, dynamite and so on which have some positive aspects as well as negative ones, there is non-value adding and value-adding complexity. Value-adding complexity is prerequisite; it leads to innovation in the system. On the other hand, non-value adding complexity is waste and must be amended as far as possible.
In this thesis, some solutions for simplification of non-value adding complexity and complicatedness should be presented. Furthermore, some remedies for getting rid of undesired complexity should be suggested.

Q3: How can intelligent agents simplify supply chain complexity?

This question is a derivative of question number two. Intelligent agents which capture both dynamic and static characteristics of supply chain complexity are significant tools of supply chain simplification. Such intelligent agent-based supply chains should be investigated thoroughly.

1.3. Scope and demarcation

Scope of this thesis is a priori study of logistics and supply chain management in context of complexity science as well as intelligent agent-based systems.

- Complexity science in this study is limited to some general themes and subjects of complexity and chaos like Self-organization, Adaptation, Emergence, Evolution, Butterfly effect and so on.
- Agent-based systems in this thesis are confined to agent-based modeling of complex dynamic systems like supply chains.
- Supply chain is here restricted to its complication, complexity, risk and intelligence.

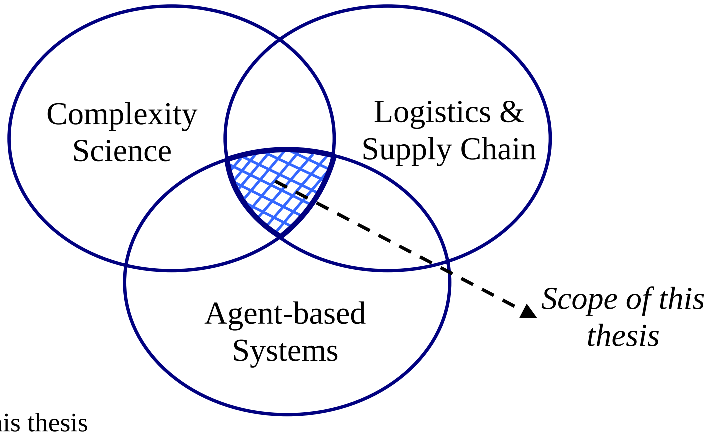


Figure 1.7 – Scope of this thesis

1.4. Target readers

This final thesis is submitted for the degree of Master of Science (MSc); so the main readers are its supervisor, examiner and interested students. Skim of this work is recommended to researchers, scientists and students who are eager to supply chain management, risk management, science of complexity and organizational as well as operational management.

1.5. Outline (Chapters review)

This thesis is constituted of eight chapters and some derivative articles. Summaries of the chapters are as follow:

Chapter 1 provides background and preface. It includes definition of the problem, questions of the thesis as well as its purpose, scope, demarcation and structure.

Chapter 2 presents implemented methodologies. It discusses nature and characteristics of rendered frames, diagrams, models and methods of the thesis. Methods of data collection, validity and reliability of data and information as well as time line of the work are also included in this chapter.

Chapter 3 is allocated to terminologies, definitions, themes and brief history of complexity as well as chaos. Reasons of ubiquitousness of complexity in different sciences are also discussed in this chapter. Furthermore, some descriptions of logistics, supply chain and value chain are reviewed.

Chapter 4 is frame of reference of the thesis. It is composed of a novel systematic approach to context of supply chain complexity and reflection of soaring complexity of supply chain based on introduced systematic approach. Ultimately, counterparts and embodiment of complexity and chaos themes (which were introduced in chapter 3) in context of supply chains are clarified. This chapter is accomplished by reviewing several articles and literature.

Chapter 5 introduces structure of (a recipe for) studying supply chain complexity. It includes some instructions of complexity identification, classification, measurement, modeling and simplification. The main ingredients of this recipe, in this thesis, are complexity classification and simplification. To develop these elements thoroughly, numerous articles have been analyzed and some interviews have been executed.

Chapter 6 considers intelligent agent-based systems as powerful tools for simplification and modeling of supply chain complexity. It embraces definition of agents, their structures, types, classifications, ancestors as well as modeling. Furthermore, characteristics of multi-agent systems especially supply chains are expounded. Lastly, latent abilities of agents and agencies in future supply chains are elaborated.

Chapter 7 is allocated to conclusion and analysis of this thesis.

Chapter 8 suggests some hints for further research in the area of supply chain complexity and intelligence.

In the follow, connections of the eight chapters with research questions are depicted.

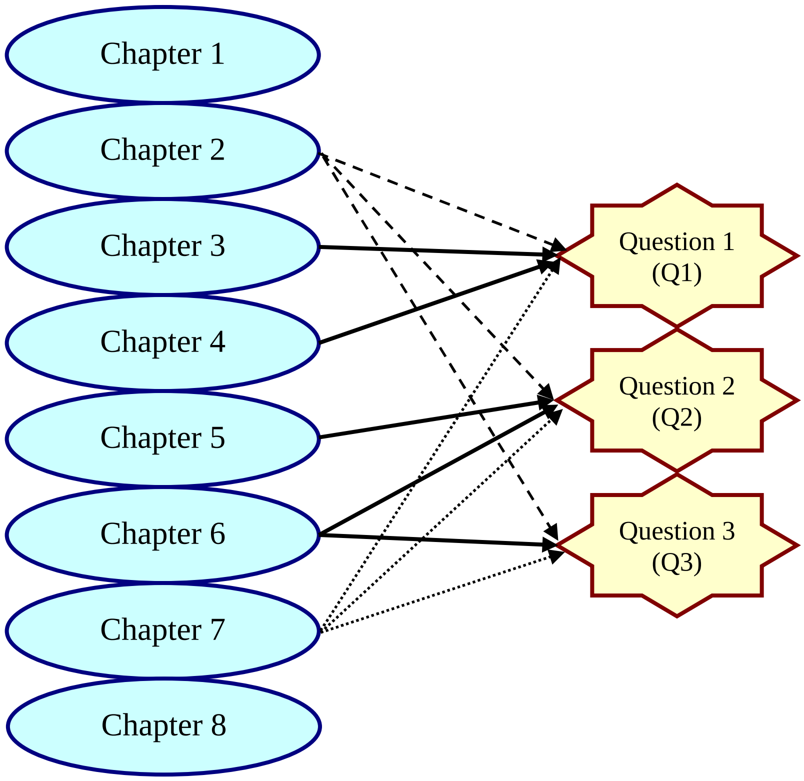


Figure 1.8 – Connections of different chapters with questions of the thesis

1.6. Structure of the thesis

In the following diagram, structure of this thesis and some implemented tools are depicted. The word 'literature' mentioned below is related to books, articles, journals, magazines, PowerPoint files as well as doctorate, licentiate and master theses.

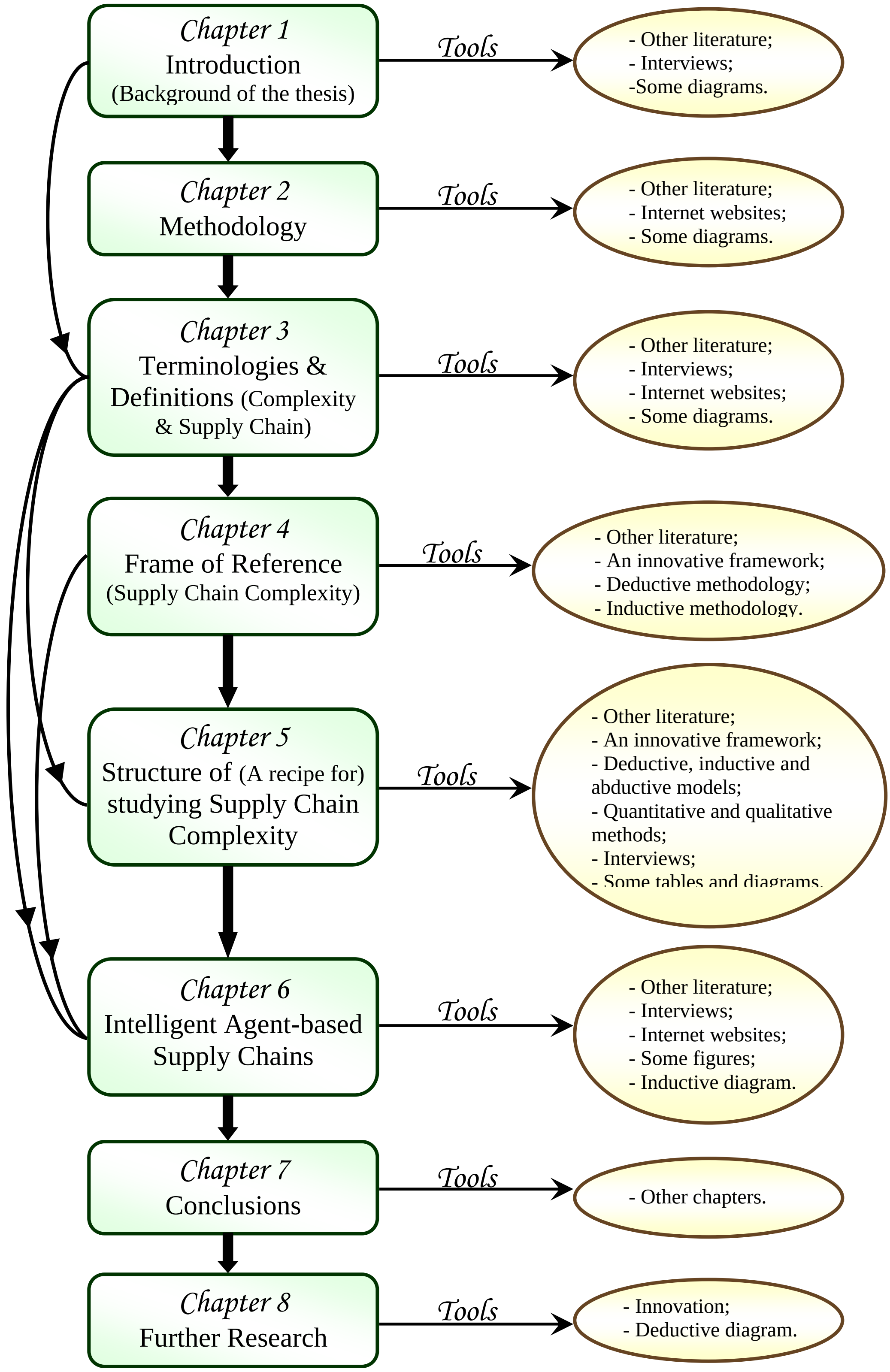


Figure 1.9 – Structure of the thesis

2. METHODOLOGY

“Models without practice are dangerous; Practice without models is fatal”. (Brewis)

This chapter presents implemented methodologies. It discusses nature and characteristics of rendered frames, diagrams, models and methods of the thesis. Methods of data collection, validity and reliability of data and information as well as time line of the work are also included in this chapter.

2.1. Scientific method

A given scientific argument may be good or bad, and its conclusion may be true or false. But in any case, the first step in assessing a scientific conclusion is merely to disclose the argument fully.

In order to present a scientific conclusion with full disclosure, Hugh & Gauch (2003) have developed a basic model of scientific method which is named the ‘PEL’ model. The PEL model combines presuppositions (P), evidence (E), and logic (L) to support scientific conclusions. In essence, scientific method amounts to provide the presuppositions, evidence, and logic needed to support a given scientific conclusion.

Presuppositions + Evidence + Logic → Conclusions

- ***Presuppositions*** are beliefs that are absolutely necessary in order for any of the hypotheses under consideration to be meaningful and true but that are completely non-differential regarding the credibility of the individual hypotheses. Science requires several common-sense presuppositions, including that the physical world exists and that our sense perceptions are generally reliable.
- ***Evidence*** is data that bear differentially on the credibility of the hypotheses under consideration. Evidence must be admissible, being meaningful in view of the available presuppositions, and it must also be relevant, bearing differentially on the hypotheses.
- ***Logic*** combines the pre-suppositional and evidential premises, using valid reasoning, to reach a conclusion. Science uses deductive and inductive logic.

Figure 2.1 summarizes inquiry using the PEL model, from starting question to final conclusion.

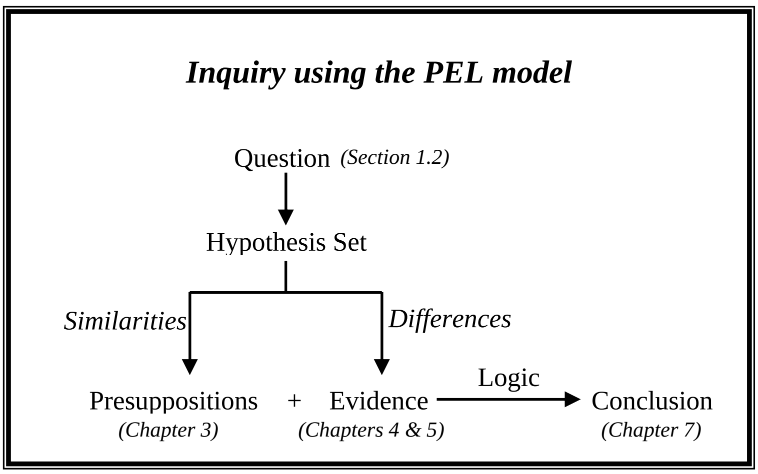


Figure 2.1- Scientific inquiry using the PEL model (Source: Hugh & Gauch 2003)

In this thesis, presuppositions are explained in chapter 3. They are, in fact, pre-defined definitions and terminologies. In order to prove this hypothesis that supply chains are complex systems, chapters 4 and 5 struggle to bring enough evidences. The implemented logics are explained in section 2.3.

2.2. Research approach

Research is defined as human activity based on intellectual application in the investigation of matter. The primary aim for applied research is discovering, interpreting, and the development of methods and systems for the advancement of human knowledge on a wide variety of scientific matters of our world and the universe (Wikipedia).
According to Livesey (2003), the purposes of research can be categorized as:

- Description (*fact finding*)
- Exploration (*looking for patterns*)
- Analysis (*explaining why or how*)
- Prediction (*forecasting the likelihood of particular events*)
- Problem Solving (*improvement of current practice*)

In table 2.1, purpose and approach of research in different sections of this thesis are mentioned:

Chapter		Research approach
Chapter 3		Description, Analysis
Chapter 4	Section 4.1	Description, Exploration
	Section 4.2	Description, Exploration, Analysis
	Section 4.3	Description, Exploration, Analysis
Chapter 5	Section 5.1	Description
	Section 5.2	Exploration, Analysis
	Section 5.3	Description, Analysis
	Section 5.4	Description, Analysis
	Section 5.5	Description, Exploration, Analysis, Problem solving
Chapter 6		Description, Exploration, Analysis, Prediction, Problem solving

Table 2.1 – Research approach in different sections of the thesis

2.3. Theory and model

A theory may be viewed as a system of constructs and variables in which constructs are related to each other by propositions and the variables are related to each other by hypotheses. Without theory, it is impossible to make meaningful sense of empirically-generated data; it is impossible to distinguish positive from negative results, and empirical research merely becomes data-dredging (Voss et al 2002).

According to Hugh & Gauch (2003), in order to make any observations at all, scientists must be driven by a theoretical framework that raises specific questions and generates specific interests.

Second, what may appear to be a simple observation statement, put to work to advance one hypothesis or to deny another hypothesis, actually has meaning and force only within an involved context of theory.

Third, theory choice involves numerous criteria that entail subtle trade-offs and subjective judgments. For example, scientists want theories to fit the observational data accurately and also want theories to be simple or parsimonious.

A model in science is a physical, mathematical, or logical representation of a system of entities, phenomena, or processes.

Figure 2.2 represents relations between theory (model) and system (reality).

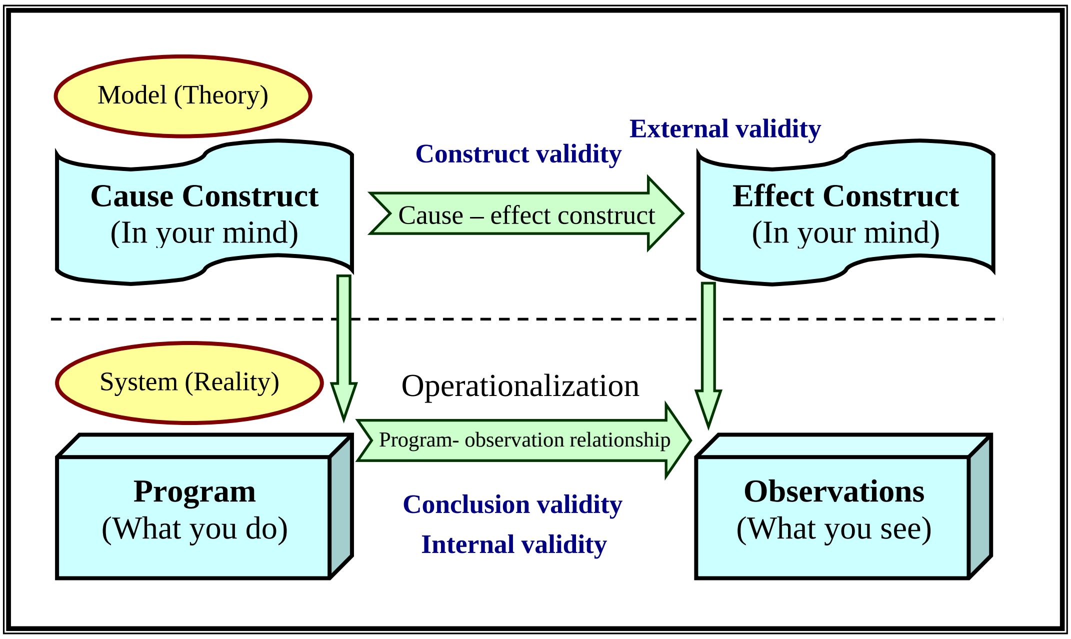


Figure 2.2- Modeling in social science (Source: www.socialresearchmethods.net)

The aim of this thesis is review of pre-defined models as well as establishment of novel models for studying supply chains in perspectives of complexity and intelligence.

2.4. Inductive and deductive logic

Logic is the science of correct reasoning and proof, distinguishing good reasoning from bad. Logic sorts out the relationships that are fundamental in science, the relationships between hypotheses and evidence, between premises and conclusions (Hugh & Gauch 2003).

There are two basic kinds of logic: deductive and inductive. According to Hugh & Gauch (ibid), the distinction between deduction and induction can be explained in terms of three interrelated differences:

(1) The conclusion of a deductive argument is already contained, usually implicitly, in its premises, whereas the conclusion of an inductive argument goes beyond the information present, even implicitly, in its premises.

(2) Given the truth of all its premises, the conclusion of a valid deductive argument is true with certainty, whereas even given the truth of all its premises, the conclusion of an inductive argument is true with, at most, high probability, but not absolute certainty.

(3) Typically, deduction reasons from the general to the specific, whereas induction reasons in the opposite direction, from specific cases to general conclusions.

As encountered in typical scientific reasoning, the "generals" and "particulars" of deduction and induction have different natures and locations. The general principles exist in models or theories in a scientist's mind, whereas the particular instances pertain to physical objects or events that have been observed.

From observations, induction provides general principles, and with those principles serving as premises, deduction predicts or explains observed phenomena (Figure 2.3)

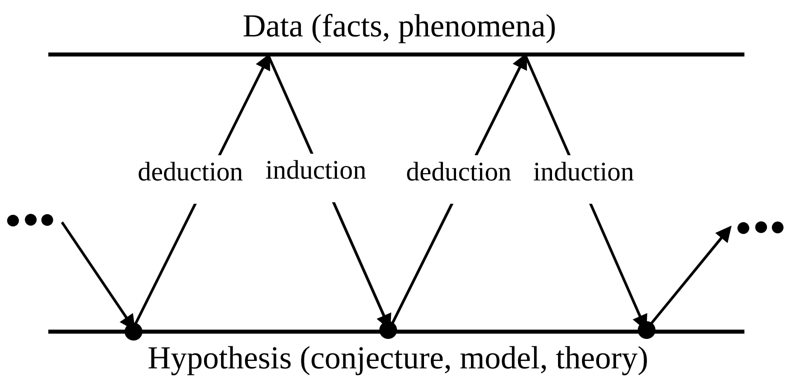


Figure 2.3 – Deduction and induction (Source: Hugh & Gauch 2003)

The research carried out in this thesis can be characterized as abductive which is a combination of deductive and inductive. Most of the innovative frames in this thesis, like figures 4.1.2, 4.1.2 as well as 5.2.2 have inductive natures which involve deductive examples.

2.5. Qualitative and quantitative methods

Research methods are generally categorized as being either quantitative or qualitative. In general, quantitative methods result in numeric information, which is usually machine-readable and can be analyzed by accepted statistical tests and models.
On the other hand, Qualitative methods result in textual or narrative information that is either descriptive, or subject to other forms of analysis (Maxwell 1998).

In this thesis, both qualitative and quantitative approaches are considered (Table 2.2) without arguing that one is more appropriate than the other.

Chapter		**Research method**	
		Qualitative	***Quantitative***
Chapter 3		●	
Chapter 4	Section 4.1	●	●
	Section 4.2	●	●
	Section 4.3	●	
Chapter 5	Section 5.1	●	
	Section 5.2	●	●
	Section 5.3	●	●
	Section 5.4	●	●
	Section 5.5	●	●
Chapter 6		●	

Table 2.2 – Qualitative and quantitative considerations in this thesis

2.6. Research strategy

According to Whetten (1989), a complete theory contains four elements: (1) what, (2) why, (3) how, and (4) who, where, when.
According to Yin (2003 cited in Sternberg 2008), the choice of a research strategy depends on three conditions: type of research question posed, the extent of control an investigator has over actual behavioral events, and the degree of focus on contemporary as opposed to historical events.
Table 2.3 shows how the different research strategies relate to these conditions:

Strategy	*Form of research question*	*Requires control over behavioral events?*	*Focuses on contemporary events?*
Experiment	How, Why	Yes	Yes
Survey	Who, What, Where, How many, How much	No	Yes
Archival analysis	Who, What, Where, How many, How much	No	Yes / No
History	How, Why	No	No
Case study	How, Why	No	Yes

Table 2.3 – Relevant situations for different research strategies (Source: Yin 2003, 1994)

Table 2.4 represents detailed questions of the research in this thesis and the types of selected strategies:

Chapter		**Research Method**	
		Detailed questions	***Strategy***
Chapter 3		- **What** is complexity and supply chain?	Literature study
Chapter 4	Section 4.1	- **What** is supply chain complexity?	Literature study, analysis
	Section 4.2	- **Why** studying supply chain complexity?	Literature study, analysis
	Section 4.3	- **What** are counterparts of complexity themes in context of supply chains?	Analysis, survey
Chapter 5	Section 5.1	- **How** identifying SC complexity?	Analysis, experiment
	Section 5.2	- **How** classifying SC complexity?	Analysis, literature study
	Section 5.3	- **How** measuring SC complexity?	Analysis, literature study
	Section 5.4	- **How** modeling SC complexity?	Analysis, literature study
	Section 5.5	- **How** simplifying SC complexity?	Analysis, literature study, survey
Chapter 6		- **How** simplifying complexity with agents? - **What** are intelligent supply chains?	Analysis, literature study, survey, experiment

Table 2.4 – Detailed questions of the research in this thesis and the types of selected strategies

2.7. Methods of data collection

Data collection means gathering data and information to address questions of the thesis. There are many methods available to gather data, and a wide variety of sources. The selection of a method must balance several concerns including: resources availability, credibility, analysis and reporting resources, and the skill of the evaluator (The Ohio State University).

According to Ekwall (2007), data resources are normally divided into primary and secondary sources. Patel & Davidson (1994 cited in Wänström 2006) state that it is the degree of closeness that determines whether or not a data source is primary. They classify eyewitness descriptions and first-hand accounts as primary sources (like observations, interviews, questionnaires and so on). Secondary data are based on a primary source and consist of an interpretation of events that have taken place. Books, journals, theses, database, internet and so on are examples of secondary sources. In this thesis, both primary and secondary data were used as follow:

Literature and documents

Literature and documents in this thesis are related to books, articles, journals, magazines, PowerPoint files as well as doctorate, licentiate and master theses. They are the main sources of data in all parts of this research. Furthermore, different documents were compiled by participating in different seminars, conferences, exhibitions, and lectures.

Interviews

According to Wänström (2006), in order to find relevant information it is important to prepare interviews thoroughly and to choose the right respondents, since this is crucial to the final result. It is also advisable to allow the interviewee to read through the transcribed interview text afterwards to avoid misunderstandings. Interviews can be divided to different types like: face-to-face interview, group interview, telephone interview and so on.

All interviews conducted in relationship with this thesis were 'face-to-face' ones and were done by the author. The main interviewee was supervisor of this thesis, Prof.Lumsden who is a full professor and expert of logistics and supply chain. Other interviewees were examiner of this thesis, some teachers at Swedish universities, and some experts of logistics, manufacturing, IT and supply chain management.

Observations

According to Andersson (2007) and Wänström (ibid), there are two types of observations: direct and participant. In the direct observation, researcher only observes while in participant observation, researcher is not only a passive observer. The participant observer can gain a direct insight into the process and can, by his/her knowledge and experience, understand the observations rather than relying on the respondent's description.

Both kinds of observations have been used in this thesis. Some observations were done during company visits in different courses of master degree.

2.8. Validity and reliability

The hallmark of science is the pursuit of truth and the limitation of error. *Validity* and *Reliability* are ways of demonstrating and communicating the rigor of research processes and the trustworthiness of research findings.
In short, Validity is about the closeness of 'what we believe we are measuring' to 'what we intended to measure'. On the other hand, Reliability describes how far a particular test, procedure or tool will produce similar results in different circumstances, assuming nothing else has changed (Roberts P *et al* 2006).
Figure 2.4 depicts a graphic presentation of possible combinations of validity and reliability.

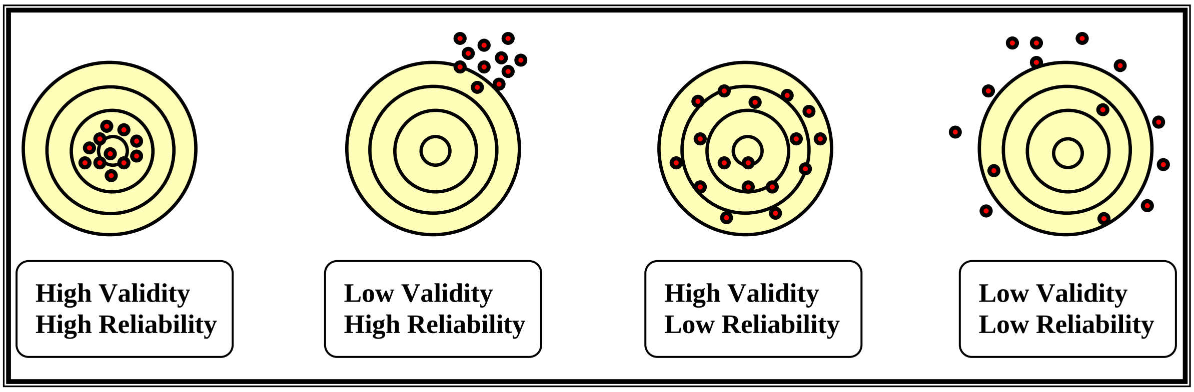


Figure 2.4 – Validity and reliability; graphic presentation of possible combinations (Source: Bengtsson 2007)

Validity and Reliability could be divided to several types and dimensions. Voss et al (2002) as well as Yin (1994, 2003) discuss validity and reliability of case research based on table 2.5.

Tests	Case study tactic	Phase of research in which tactic occurs
Construct validity	- Use multiple sources of evidence - Establish chain of evidence - Review draft case study report	- Data collection - Data collection - Composition
Internal validity	- Do pattern matching - Do explanation building - Do time-series analysis - Use logic models	- Data analysis - Data analysis - Data analysis - Data analysis
External validity	- Use theory in single-case studies - Use replication logic in multiple-case studies	- Research design - Research design
Reliability	- Use case study protocols - Develop case study database	- Data collection - Data collection

Table 2.5 – Reliability and validity in case research (Yin 1994, 2003)

Construct validity
"Construct validity is the extent to which we establish correct operational measures for the concepts being studied" (Voss et al 2002).
In this thesis, construct validity comes from using multiple sources of evidence and different methods of data collection (refer to section 2.7). Furthermore, observing

predicted characteristics of complex and chaotic systems in context of supply chains also shows construct validity of the thesis.
According to Wänström (2006), interviews are an important part to gather the information in all case studies and consequently have a strong influence on validity. Respondents may not have the ability to answer some questions or may fail to be objective in their answers regarding their work. In this thesis, these effects have been minimized by asking several interviewees the same questions and making and scrutinizing a fair copy of each interview.

Internal validity
"Internal validity is the extent to which we can establish a causal relationship; whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships" (Yin 1994, p.35).
Internal validity in this research was dealt with by pattern matching, explanation building and using logic models. The validity of introduced models in chapters 4, 5 and 6 was judged by involving people with deep insight into their elements.
In this regard, for finding counterparts of science of complexity in discipline of supply chains as well as determining logic models of complexity classification and simplification, at first explanatory frames were built and then different interviews were done to analyze the frames. After analyzing the interviews data, the models were justified. Later, frequent feedbacks were rendered to the supervisor to approve the internal validity of the work.

External validity
"External validity is to know whether a study's finding can be generalized beyond the immediate case study (Voss et al 2002). Yin (1994) distinguishes between two types of generalization, 'statistical generalization' and 'analytical generalization'. Statistical generalization is the classic approach employed in surveys and, as the name indicates, uses statistical methods. In analytical generalization, previously developed theory is used as a template with which to compare the empirical results of the case study.
The frameworks and models developed in this thesis were to a large extent derived from the well established literature in the area of supply chains, complexity science and agent-based systems. It has been attempted that the introduced frames be general and applicable to most contexts and be operationalized by using well known definitions and themes.
It is asserted that the introduced frameworks and models in sections 4.1, 4.2 and chapter 5 are highly externally validated as they can be generalized both statistically and analytically. It is claimed that different sources of supply chain complexity and complication can be classified and studied based on these frames. Frame of section 6.7.3 has also this validity to be generalized analytically.

Reliability
Reliability is the extent to which a study's operations can be repeated, with the same results (Yin 1994, p.36). Bell (1995 cited in Wänström 2006) points out that the research should provide the same result at different times, if the conditions are identical. A way of minimizing the occurrence of random errors is to indicate the number of observations or questions of a certain area (Hellevik 1984 cited in Wänström ibid).
Reliability in this theoretical thesis comes from well documented and reliable data collections. According to Ekwall (2007), a good way to achieve high reliability is to use obvious and clear questions. During an interview is it important to give the interviewee all the time he/she needs and that the interview is conducted in an environment where the interviewee feels safe. All interviews were compiled in documents labeled with dates and respondent's name and profession. Furthermore, it has been struggled that mentioned

literature and works of other researchers at first be verified as reliable by supervisor of this thesis.
It would be, however, interesting for the author of this thesis to test reliability of this research in further companies and practice.

2.9. Gant chart (timeline) of the thesis

In figure 2.5 several activities for accomplishment of this thesis during the time are presented.

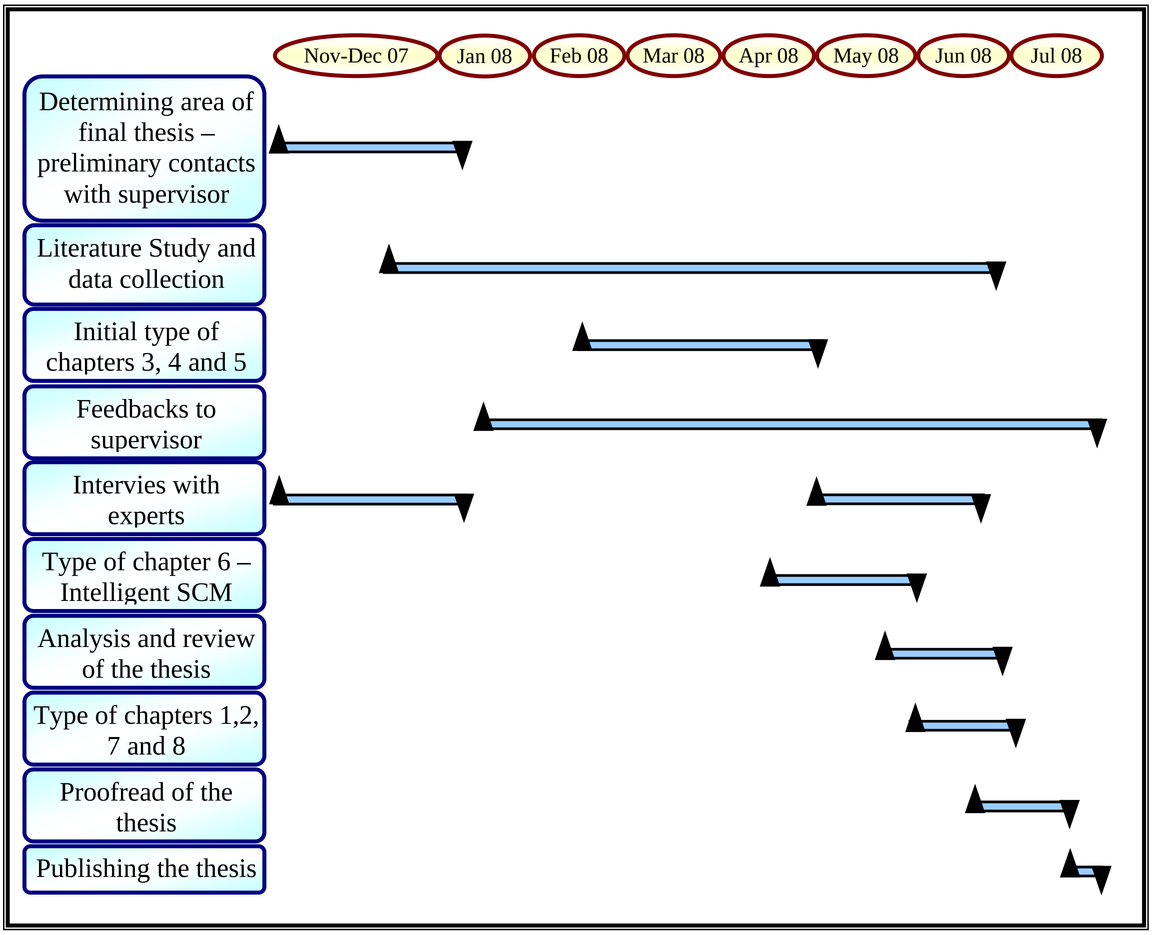


Figure 2.5– Gant chart of the thesis

3. Terminologies and Definitions

"Complexity science is the 'structural engineering' of organizations." (James W Herriot)

In this chapter, at first various definitions of Supply Chain Management (SCM) and Logistics as well as their building blocks are reviewed.
Later on, sundry definitions and perspective of complexity as well as chaos, a brief history of them and their main themes are presented. Finally, some reasons for ubiquitous application of complexity in different contexts are introduced.

3.1. Logistics and Supply Chain Management

There are many ways of defining logistics and supply chain management from different perspectives.
According to Scandinavian definition of logistics, it is*: "That perspective and those principles according to which we plan, develop, co-ordinate, organize, manage and control the material flow from the raw material supplier to the end customer".*

European Logistics Association (ELA) defines logistics as follow:
"Logistics is the organization, planning, control and execution of goods flow (hardware and software) from development and purchasing, through production and distribution, to the final customer in order to satisfy the requirements of the market at minimum cost and minimum capital use".

Council of Logistics Management (CLM) has presented two definitions of logistics. According to the former one;
"Logistics is the process of planning, implementing and controlling the efficient, effective flow and storage of raw materials, in-process inventory, finished goods, services, and related information from point of origin to point of consumption (including inbound, outbound, internal, and external movements) for the purpose of conforming to customer requirements".
And the later definition states:
"Logistics is that part of the supply chain process that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from the point of origin to the point of consumption in order to meet customers' requirements".

According to Simchi-Levi (2004), *"Supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements".*
Whilst the phrase 'supply chain management' is now widely used, it could be argued that it should really be termed "demand chain management" which reflects the fact that the chain should be driven by the market (from downstream to upstream) not by suppliers. Equally the word "chain" should be replaced by "network" since there will normally be multiple suppliers and, indeed, suppliers to suppliers as well as multiple customers and customers' customers to be included in the system (Christopher 2005; Lumsden 2001). Furthermore, it is argued that, from management perspective, the word management is better to be replaced by 'leadership'.
Based on later definition of logistics presented by CLM, it is discussed by some researchers that supply chain management is a wider concept than logistics. Christopher

(2005, p.17) states that logistics is essentially a planning orientation and framework that seeks to create a single plan for the flow of product and information through a business; Supply chain management builds upon this framework and seeks to achieve linkage and co-ordination between the processes of other entities in the pipeline, i.e. suppliers and customers, and organization itself. […] thus, the focus of supply chain management is upon the management of relationships in order to achieve a more profitable outcome for all parties in the chain.
In a supply chain three key business processes can be identified: Time to market (TTM), Time to cash (TTC) and Customer creation and retention (CCR). TTM is the process for development and improvement of products and services; TTC is the total materials, information and financial flows and CCT is the process for creation and retention of customers all the way from the very first contact, via after sales, follow up and continuous improvement (Ericsson 2001 cited in Andersson & Torstensson 2006). Supply chain management is an integrative philosophy to integrate, manage, planning, development, coordination, organization, integration, control and review of key business processes across the chain.

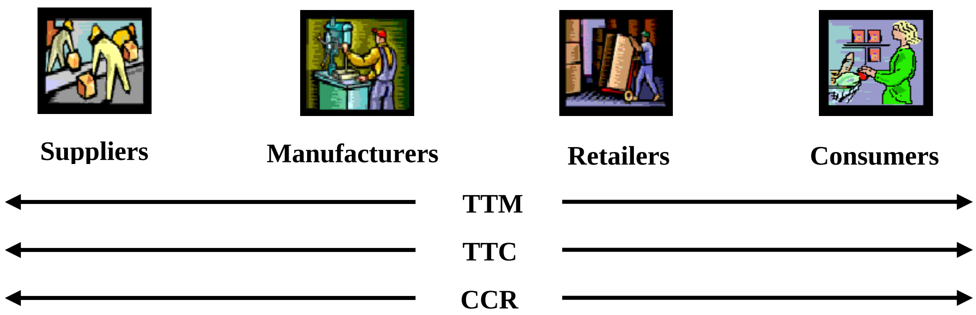


Figure 3.1- Key business processes in a supply chain (Source: Hilledoft 2006 cited in Andersson & Torstensson 2006)

Christopher (2005) states that supply chain is in fact a value chain (Figure 3.2). In a supply chain, value (and cost) is created not just by the focal firm in a network, but by all the entities that connect to each other. According to Michael Porter (cited in Christopher ibid), value chain activities can be categorized into two types: Primary activities (inbound logistics, operations, outbound logistics, marketing and sales, and service) and Support activities (infrastructure, human resource management, technology development and procurement).

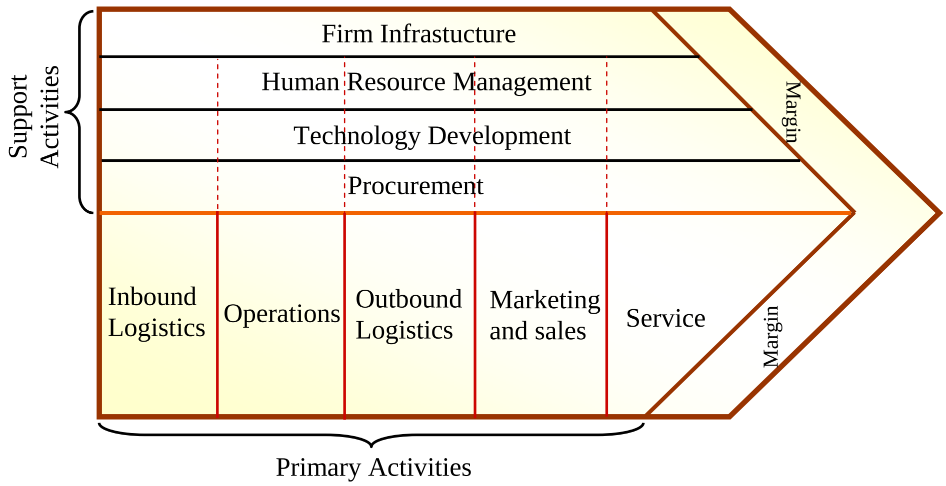


Figure 3.2- The value chain (Source: Christopher 2005)

3.2. Concept of Complexity

Giving a sharp definition of complex system is hard since the term is used in such a wide variety of contexts. Because of this, we will only give a notion, to have a better idea of what we are speaking about (Gershenson 2007). In fact, the use of the term complexity to describe a system derives from the nature of the system which is studied (McMillan 2006) and eyes of its beholder.

According to Gershenson (2007), Complexity is itself a complex concept, as we cannot make an unambiguous distinction between simple and complex systems.

The first meaning of the word comes from the Latin complexus, which means what is woven together ("entwined" or "embraced"); (Morin 2005).

Complexity arises from the nonlinear interactions of many parts of a system, with interactions being highly sensitive to the history of the components and to their current context (Hogue & Lord 2007).

According to Cilliers (2005), complex systems are open systems which operate under conditions not at equilibrium and the state of the system is determined by the values of its inputs and outputs.

Complex systems all consist of many elements, and the functions and properties of the system are a result of the elements' interactions. Nevertheless, tracking functions and properties of the systems to single elements or interactions is not an easy task (Gershenson & Heylighen 2004).

According to Pavard & Dugdale (2000), a complex system is one which it is difficult, if not impossible to reduce the number of parameters or characterizing variables without losing its essential global functional properties.

Casti (1997) discusses that complex systems are non-linear systems, composed of many (often heterogeneous) partially connected components that interact with each other through a diversity of feedback loops. Their complexity derives from the partially connected nature and the non-linear dynamics which make the behavior of these systems difficult to predict.

From Allen's perspective (2001), a complex system is a one which has within itself a capacity to respond to its environment in more than one way.

An important feature of complex systems is that we don't know how they work. We don't understand them except in a general way; we simply interact with them. Whenever we think we understand them, we learn we don't; sometimes spectacularly (Crichton 2005).

Examples of complex systems are everywhere. We can mention a cell, a society, an economy, an ecosystem, the Internet, the weather, a brain, a city (Gershenson 2007).

One complex system that most people have dealt with is a child. If so, you've probably experienced that when you give the child an instruction, you can never be certain what response you will get; especially if the child is a teenager. And similarly, you can't be certain that an identical interaction on another day won't lead to spectacularly different results (Crichton 2005).

3.2.1. Complex versus complicated

Based on dictionary definitions of complexity and complication which both simply mean "made of many interrelated parts", a distinction between a complicate system and a complex system could be inarticulate.

A system is complicated if it can be given a complete and accurate description in terms of its individual constituents, no matter how many, such as a computer. Complication is a quantitative escalation of that which is theoretically reducible. A system is said to be

complex when the whole cannot be fully understood by analyzing its components (Reitsma 2001).
According to Pavard & Dugdale (2000), it is important to highlight the difference between complicated and complex. A complicated system is a collection of a number, often very high; of elements whose collective behavior is the cumulative sum of the individual ones. In other words, a complicated system can be decomposed in sub-elements and understood by analyzing each of them. On the contrary, a complex system can be understood only by analyzing it as a whole, almost independently by the number of parts composing it.

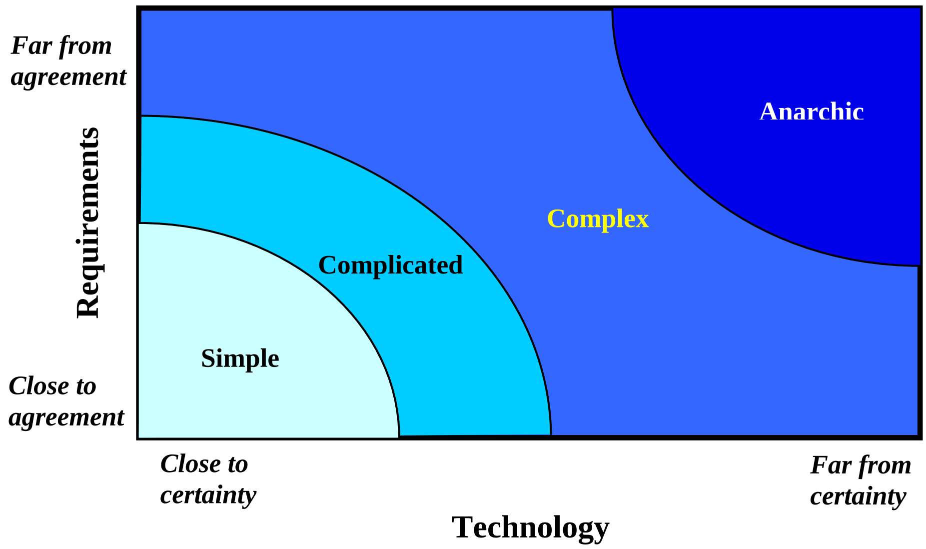


Figure 3.3- From simple to anarchic systems

3.2.2. A brief history of complexity

McMillan (2006) recounts that complexity emerged and developed as a major area of scientific study from the work of a number of scientists during the 1970s and early 1980s. One of the first scientists to research and develop theories that led to the foundation of complexity as a new science was a Russian-born, physical chemists, Ilya Prigogine. Prigogine, winner of Nobel Prize in 1978, developed the theory of "dissipative structures" which was the first description of what is also called, "self-organizing" systems. He showed in his work how systems existing in highly unstable conditions can induce changes in themselves which can lead to new patterns of order and stability emerging. Dissipative structures or self organizing systems, which will be discussed more in this chapter, are the basic structures of all living systems, including human being, and understanding of this concept is now being used in technology, economics, sociology, biology, medicine and many other aspects of life including politics and business.
The concept of self-organization was pursued by Hermann Hakan, a German physicist, and Eric Jantsch in 1970 and 1980s.
McMillan (ibid) demonstrates that biologists have also played an important role in the development of complexity science. Two key figures are the US biologists Stuart Kauffman and the UK-based biologist Brain Goodwin. Both have contributed through their research and writing to our understanding of self-organizing systems, notions of the edge of chaos, and evolution and complexity.
In the 1980s, the US computer scientist, John Holland's use of computer modeling led to the serious study of complex, adaptive systems.

Complex adaptive systems with their self-organizing attributes and emergent properties are the central concept which underpins complexity science.
Originating from the study of immune systems, nervous systems, multi-cellular organisms, ecologies, and insect societies the theory progressed to the study of artificial systems such as parallel and distributed computing systems, large-scale communication networks, artificial neural networks, evolutionary algorithms, large-scale software systems; economies (Brodbeck 2002) and even human cultural, political and social systems (McMillan 2006).

Time period	***Theory/Concept***	***Key researcher(s)***	***Discipline***
1960s-1970s	Dissipative structures (Self-organization)	Ilya Prigogine	Chemistry
	Self-organization/ Self-organizing systems	Herman Hakan	Physics
	Self-organization, evolution and compelxity	Stuart Kauffman	Biology
		Brain Goodwin	Biology
	Patterns and patterning	Ian Stewart	Mathematics
	Self-organization / Autopoiesis	Humberto Maturana	Biology
		Francisco Varela	Biology
1980s	Edge of chaos	Chris Langton	Anthropology and computing
1990s	Complex adaptive systems	John Holland	Mathematics
		Murray Gell-Mann	Physics
	Emergence	Chris Langton	Anthropology and computing

Table 3.1-Developments in complexity science (Source: McMillan 2006)

3.2.3 Some issues and themes of complexity

After a brief introduction of concept of complexity, some main themes of it are also presented for solicitous readers. These themes are: self-organization, adaptability, emergence, evolution, Co-adaptation and Co-evolution, fitness landscape and non-linearity.

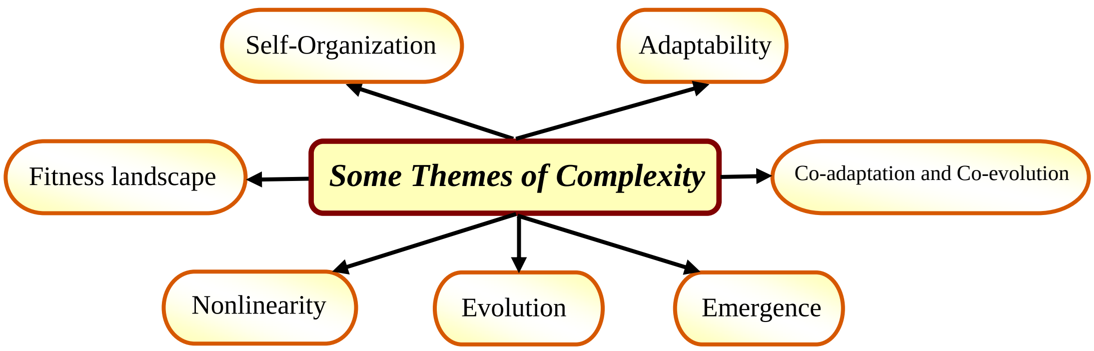


Figure 3.4- Some main themes of complexity discussed in this thesis

3.2.3.1. Self-organization

Self-organization is the ability of complex systems to spontaneously generate new internal structures and forms of behavior. This generative aspect takes the complex systems' concept of self-organization beyond the early cybernetics concept of self-organization, which focused on the self-regulatory and control aspects of organization. The generative process of self-organization in complex systems highlights that they are open systems, with continuous flow of energy and resources passing through them enabling them to maintain an existence far from equilibrium. In the self-organization process, the components spontaneously re-orientate and restructure their relationships with neighboring components giving rise to the emergence of structures that embody an increased level of internal complexity (Merali 2006). Heylighen (2002) and Kauffman (1995) state that the system spontaneously arranges its components and their interactions into a sustainable, global structure that tries to maximize overall fitness, without need for an external or internal designer or controller.

The word self-organization had emerged and had been used as of the end of the 50's by mathematicians, engineers, cyberneticians and neurologists (Morin 2005).

According to Hedlund et al (2004), Self-organization is the process of bringing to order or increasing regularity without outside guidance, making a self-organizing system, a system that increases its order or regularity. This means that when viewing a system that self-organizes, it is important to abandon the black-box view and focus on studying the smallest parts or elements that have any impact on the system. The black-box view assumes that the dynamics in a system derives from the inputs and the outputs, neglecting what goes on inside the studied object, such as interactions between heterogeneous elements inside the system. By abandoning the view and accepting heterogeneity, the possibility to understand connections within the system emerges (Figure 3.5).

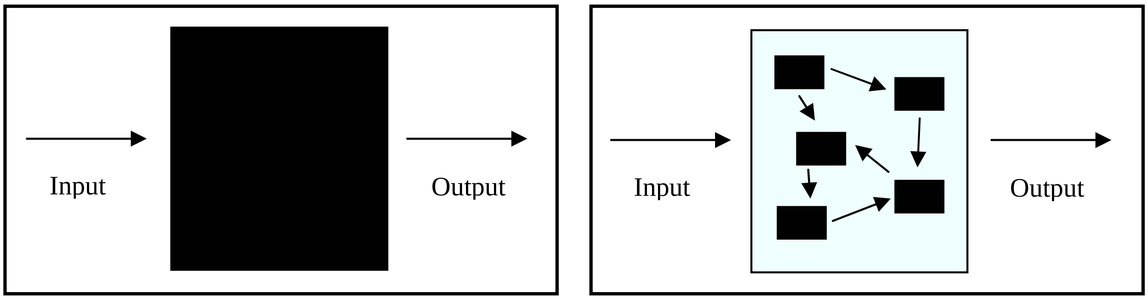


Figure 3.5- A visualization of the two ways of viewing a system (Source: Hedlund et al 2004)

According to Gershenson (2007), a system described as self-organizing is one in which its elements interact in order to achieve dynamically a global function or behavior.

For a system to self-organize, its elements need to communicate: they need to "understand" what other elements, or mediators, "want" to tell them. This is easy if the interactions are simple: sensors can give meaning to the behaviors of other elements. But as interactions become more complex, the cognition required by the elements should also be increased, since they need to process more information (Gershenson ibid).

According to McMillan (2006), spontaneity is an important feature of self-organizing systems as they interact and reshape themselves. The ability to spontaneously self-organize, for example, enables fish to shoal to protect themselves from predators, birds to flock for foraging or protection, and social ants and termites to organize themselves so that their nests or mounds are built and their young fed. People also unconsciously self-organize themselves and create small communities, towns, markets and economies to help meet their material needs. People, insects and animals, like birds in flight, respond and adapt to the actions of those nearby so that they unconsciously organize themselves. Self-organization is the principle which underlies the emergence of the wide variety of complex systems and complex forms that exist whether physical, biological, ecological, social or economic.

An example of a self-organizing system can be the Internet. There is no central control; each node of the network has its own task, and the Internet protocol was designed so that a package of information can reach from origin to destination through many different possible paths. So if some servers go down, the traffic can be still maintained by other servers. The Internet also adapts constantly to the growing traffic of information (Gershenson & Heylighen 2004).

3.2.3.2. Adaptability

According to McMillan (2006), Complex Adaptive Systems (CAS) are self-organizing, but they differ from some self-organizing systems in that they *learn* to adapt to changes in circumstances. Complex adaptive systems are adaptive, because they do not respond passively to events, but they actively seek benefits from any situations. For example, the human brain is always organizing and recognizing its billions of neural connections in order to learn from its experience, and economies constantly respond to changes in trading and lifestyles. Waldrop (1992) discusses that complex adaptive systems are constantly reconsidering and reorganizing themselves as they gain experience. According to Gell-Mann (1994), complex adaptive systems are pattern seekers which interact with their environment, learn from their experiences, and then adapt which non-living complex systems do not. Furthermore, CAS can anticipate the future (Holland 1992).

The concept of CAS serves very well to characterize the phenomenology of organization in the interconnected world. CAS are characterized as open, non-linear dynamical systems that adapt and evolve in the process of interacting with their environments – they have the potential (capacity) for adaptation and transformation. Adaptation at the macro-level (the 'whole' system) is characterized by emergence (see below) and self-organization based on the local adaptive behavior of the system's constituents. The emergent global systems behavior is very sensitive to initial local conditions (Merali 2006).

To be able to adapt and anticipate, a system should also be robust. If a system is fragile, it will "break" before it is able to counteract a perturbation. Thus, we can say that a system is robust if it continues to function in the face of perturbations (Gershenson 2007).

3.2.3.3. Emergence

Emergence refers to the phenomenon whereby the macroscopic properties of the system arise from the microscopic properties (interactions, relationships, structures and behaviors) and heterogeneity of its constituents. The emergent macroscopic 'whole' displays a set of properties that is distinct from those displayed by any subset of its individual constituents and their interactions. In other words, the whole is more than (and certainly different in kind to) the sum of its parts (Merali 2006; Letiche 2000). In the other words, describing the macro-behavior (or emergent behavior) of the system, not all the micro-features can be taken into account (Cilliers 2005).

Ashby (1956, p.110, 1984 edition) writes that "The concept of "emergence" has never been defined with precision, but the following examples will probably suffice as a basis for discussion: (1) Ammonia is a gas, and so is hydrogen chloride. When the two gases are mixed, the result is a solid – a property not possessed by either reactant. (2) Carbon, hydrogen, and oxygen are all practically tasteless, yet the particular compound "sugar" has a characteristic taste possessed by none of them. (3) The twenty (or so) amino acids in a bacterium have none of them the property of being "self-reproducing", yet the whole, with some other substances, has this property. "

Similarly, a musical piece has the properties of rhythm, melody and harmony, which are absent in the individual notes that constitute the piece. A car has the property of being able to drive. Its individual components, such as motor, steering wheel, tires or frame, lack this property. On the other hand, the car has a weight, which is merely the sum of the weights of its components. Thus, when checking the list of properties of the car you are considering to buy, you may note that "maximum speed" is an emergent property, while "weight" is not (Heylighen et al 2005).

According to Nilsson (2004), emergence could be addressed as the outcome of collective behavior i.e. self-organization of several units, elements or human beings i.e. agents, performing something individually, or together, that creates some kind of pattern or behavior that they themselves cannot produce.

McMillan (2006) discusses that social ants, like human beings, have discovered that by working together rather than operating individually they are better equipped to rear the next generation and to survive in the world. For both species obtaining food, defending territories, and building and repairing homes are all better achieved by working collectively.

The phenomenon of emergence is an important example of the failure of linear thinking. Because networks evolve through non-linear interactions among parts (e.g. people in a group, components on a printed circuit board, agents in a supply chain), adding more interactions can result in a sudden and radical change in the property of the aggregate (Kogut 2007).

One of the main reasons for studying emergence is to find ways of designing systems that have desirable emergence (Johnson 2006).

3.2.3.4. Evolution

Evolutionary systems are moving into an open and changing range of possible futures (Stacey *et al* 2000), while self-organizing systems are merely moving within a set of predetermined possible futures; this is a fundamental difference (Allen 2001).

3.2.3.5. Co-adaptation and co-evolution

In the management and strategy literature as well as economics literature, an environment is often viewed as a disjointed entity that exists independent of the individual members that reside within the environment. As such, some organizational theorists posit that the main goal of the organizational system is to react to the environment in a cybernetic fashion (Simon 1957 cited in Choi et al 2001). Other organizational theorists have a more radical view that environments are enacted or created by the system itself (Weick 1979 cited in Choi et al 2001). Complexity theory posits that a CAS both reacts to and creates its environment.

The relationship between the system and the environment is a reflexive one: changes in the system both shape and are shaped by changes in the environment. If a number of systems cohabit in a particular environment, the environment is itself an emergent manifestation of its multiple interactions with the systems it 'hosts'. While in classical representations of systems, the environment is viewed as the source of a discrete set of inputs and a sink for a

discrete set of outputs, the CAS paradigm imposes the need to consider the dynamics and mutually defining consequences of the relationship between the system and its environment, taking us from issues of simple adaptation to issues of co-adaptation and co-evolution in dynamic contexts (Merali 2006).
Johnson (2006) states that one difficulty in predicting the emergent behavior of complex systems is that we do not know where they begin and end; that is, where their boundary is within their environment (Figure 3.6-a).
The problem arises because many systems interact with their environment, affecting and being affected by it. Because of this, the system co-evolves with its environment. For example, consider a business selling a product in the market place. When the product is launched, there are certain latent demands for it. If the product is very successful, some of those demands are satisfied, and a new demand may be created (e.g. the Sony Walkman created a new perception of need for mobile personalized entertainment, which has become a multibillion dollar business). Thus, the business has changed its market environment.
The picture is even more complicated because the interaction between the whole and its environment depends on the internal interactions between subsystems, which themselves have ambiguous boundaries (3.6-b).
The problem is that almost everything seems to be related to almost everything else by intermediate chains of connection. In order to structure our universe, human beings tend to focus on strong connections, and define system or subsystem boundaries in these terms; with weak connections making the boundary imprecise.

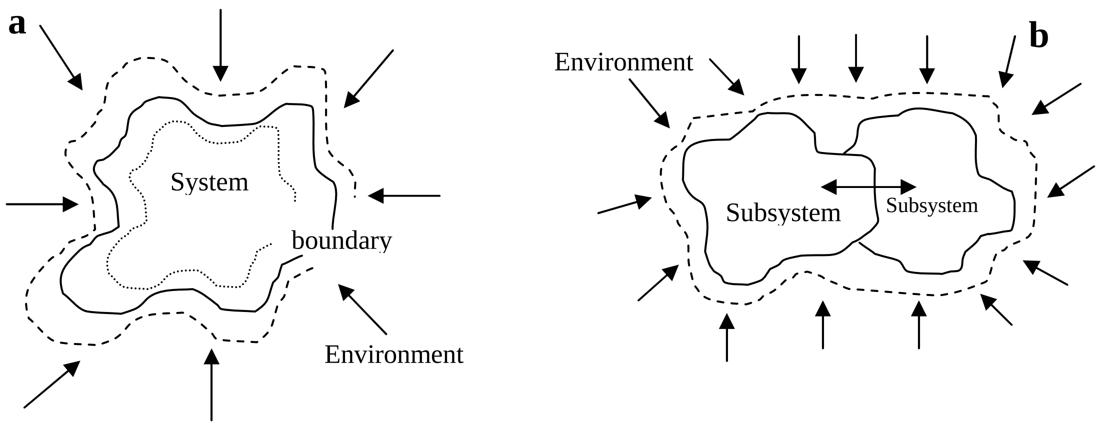


Figure3.6- The problem of defining boundaries of system and subsystem in their environments; (a) The system – environment boundary problem, (b) boundaries of co-evolving subsystems (Source: Johnson 2006).

3.2.3.6. Fitness (dynamic) landscape and genetic algorithms

As highlighted in the last part, the paradigm of Complex Adaptive Systems (CAS) imposes the need to consider the dynamics and mutually defining consequences of the relationship between the system and its environment.
For example, consider an ecosystem cohabited by a diversity of species. The environment, each individual and each species will affect and be affected by the actions of the other individuals and species. The fitness or chances of survival for each species will be related to its ability to adapt to the environmental changes; and over time, selective pressures (resulting from the interaction of the habitat and surviving cohabiting species) will lead to the evolution of new traits in the various populations, changes in the habitat and the emergence of new species. Co-adaptation and co-evolution in dynamic environments can

be viewed as important mechanisms for sustainability of the ecosystem. The capacity for adaptation is predicated on the capacity for self-organization described above.

Fitness landscapes are often used to explore these dynamics. The fitness landscape is a simulation constructed from representations (in terms of the fitness function, which is a mathematical expression of the relative value of a population with reference to a particular criterion) of the relative fitness of all actors. The peaks and valleys in the landscape represent, respectively, the most and least fit. Each actor only has knowledge of the local environment and acts accordingly. The landscape undergoes distortions due to the actions of the actors, and to changes in the environmental conditions. The concept of fitness landscapes has been used extensively to develop simulations of competitive landscapes, notably deploying Kauffman's NK model (Merali 2006).

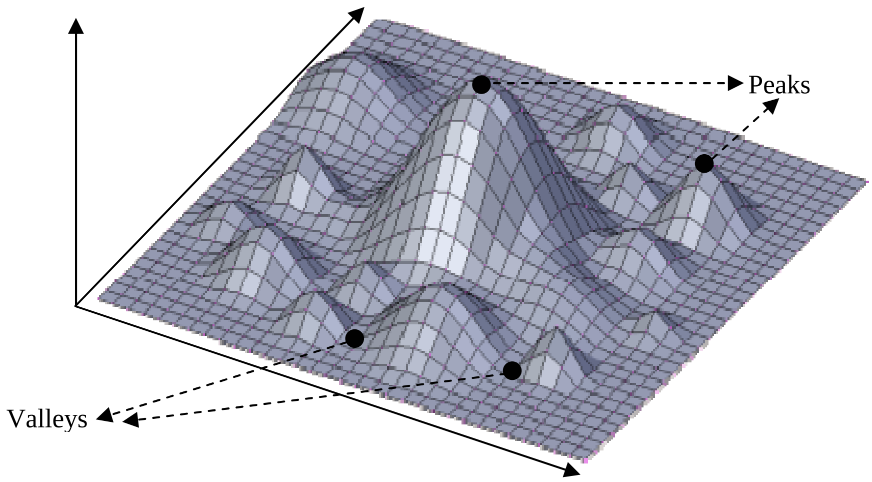


Figure 3.7-A rugged fitness landscape (Source:http://cairnarvon.rotahall.org)

The concept of Fitness landscapes is similar to term of "genetic algorithms" in computer science. According to Stewardson et al (2002) and Goldberg (1989), Genetic Algorithms are stochastic search techniques for approximating optimal solutions within complex search spaces. The technique is based upon an analogy with biological evolution, in which the fitness of the individual determines its ability to survive and reproduce. The Genetic Algorithms mechanism starts by encoding the problem to produce a list of genes. The genes are represented by either numeric (binary or real), or alphanumeric characters. The genes are then randomly combined to produce a population of chromosomes, each of which represents a possible solution. Genetic operations are performed on chromosomes that are randomly selected from the population. This produces offspring. The fitness of these chromosomes is then measured and the probability of their survival is determined by their fitness.

Genetic Algorithms have been widely applied to scheduling problems. Each gene represents an operation, whilst the chromosome represents the sequence of the entire schedule. Croce et al (1995) and Reeves (1995) compared Genetic Algorithms with other methods for solving production scheduling problems like Simulated Annealing, Shifting bottleneck procedure and Taboo search. They found that Genetic Algorithms obtained better solutions and results as well as quicker (Stewardson et al 2002).

Genetic Algorithms perform a multidirectional search by maintaining and using a population of potential solutions. Each iteration of the Genetic Algorithms process therefore exploits the best solutions within the population and also explores different parts of the solution space simultaneously (ibid).

3.2.3.7. Nonlinearity

A common characteristic of models of complex systems is that they are nonlinear. This means that the elements of a system interact in ways that are more complex than additions and subtractions. In a linear system, we just add the properties of the elements, and we can deduce and predict the behavior of the system. Nevertheless, when there are many interactions and these are nonlinear, small differences multiply over time, yielding often chaos and unpredictability.

In a nonlinear system, causes are not directly proportional to their effects. Big changes can have little or no effect, while small changes can have drastic consequences. This makes complex systems to be not completely predictable (Gershenson & Heylighen 2004).

Ashby's comments suggest a division between an "old science" of simple systems (Newtonian-Cartesian paradigm), and "new science" of complex systems. One characteristic of the old science is linearity which means analyze the parts and add them together, with the whole being the sum of its parts. Most complex systems exhibit both linearity and non-linearity in their subsystems (Johnson 2006).

Capra (1996 cited in McMillan 2006) has categorized a number of broad dimensions along which he compares the Newtonian-Cartesian world view with that of the complexity paradigm. He shows clearly the differences between the two and the implications they have for the thinking that underpins strategic theory and practice. Carlisle and McMillan (2002 cited in McMillan 2006) build upon this comparison and expand Capra's work to construct a more comprehensive categorization for use in organizational analysis (Table 3.2).

Newtonian-Cartesian paradigm perspective	***Complexity science paradigm perspective***
Essentially mechanistic	Essentially dynamic / self-organizing
Linear	Non-linear
Controllable	Uncontrollable
Centralized	Networked
Hierarchical	Non-hierarchical
Limited connectivity	Highly connected
Uniformity	Diversity
Cause and effect	Effect and effect
Predictable	Unpredictable
Reductionism	Holistic
Objective focus	Subjective and objective foci
Entity focused	Process focused
Correlation	Patterning
Highly preclusive	Highly inclusive
Evolutionary	Revolutionary and evolutionary

Table 3.2- Newtonian-Cartesian paradigm versus Complexity paradigm (Source: McMillan 2006)

3.3. Concept of chaos

Chaos Theory is in some respects a precursor of Complexity Theory. There are several definitions for chaos in different literatures.

Technically, a chaotic system is a deterministic system that is difficult to predict. As Bar-Yam (2000) points out, in practice, the concept of chaotic systems presents a paradox. Based on dictionary definition of chaos, it is a state of complete confusion and lack of order.

By definition, a deterministic system is one whose state at one time completely determines its state for all future times, but in practice a chaotic system is difficult to predict because of its sensitivity to initial conditions; what happens in its future is very sensitive to its current state (Merali 2006).

According to McMillan (2006), an interesting definition of chaos offered by Gleick (1993) is that "where chaos begins, classical science stops". McMillan (ibid) states that many early chaos researchers were intrigued and challenged by areas that the laws of classical science failed to provide answers for and they were often particularly attracted to some of the more difficult questions. Classical science suggested mechanistic views of the world and these encouraged scientists to search for fixed theories using linear methods and simple cause and effect approaches.

3.3.1. A brief history of chaos

According to McMillan (ibid), chaos science has its origins in the late 1960s and the 1970s when a number of scientists from a wide range of disciplines became uneasy and sometimes dissatisfied with existing scientific explanations. By the 1980s, chaos had become a fast growing movement that had created its own range of special techniques using computers and specialized graphics.

<table>
<tr><th>Time period</th><th>Theory/Concept</th><th>Key researcher(s)</th><th>Discipline</th></tr>
<tr><td>1854-1912</td><td>Topology (strange attractors)</td><td>Henri Poincare</td><td>Mathematics</td></tr>
<tr><td rowspan="4">1970s</td><td>Sensitive dependence on initial conditions</td><td>Edward Lorenz</td><td>Meteorology</td></tr>
<tr><td rowspan="3">Strange attractors</td><td>David Ruelle</td><td>Mathematics and Physics</td></tr>
<tr><td>Floris Takens</td><td>Mathematics</td></tr>
<tr><td>Edward Lorenz</td><td>Meteorology</td></tr>
<tr><td rowspan="6">1980s</td><td>Chaotic properties of dynamical systems</td><td>Stephen Smale</td><td>Mathematics</td></tr>
<tr><td>Notions of order and disorder</td><td>James Yorke</td><td>Mathematics</td></tr>
<tr><td>Order within chaos</td><td>Robert May</td><td>Biology and Physics</td></tr>
<tr><td>Fractals</td><td>Benoit Mandelbrot</td><td>Mathematics</td></tr>
<tr><td>Universality</td><td>Mitchell Feigenbaum</td><td>Physics</td></tr>
<tr><td>Flow</td><td>Albert Libchaber</td><td>Physics</td></tr>
</table>

Table 3.3- Developments in chaos science (Source: McMillan 2006)

3.3.2. Some issues and themes of Chaos

In this part, a review of some main themes of chaos theory and chaotic systems sounds essential. These themes are: Butterfly effect, Edge of chaos, and Pattern.

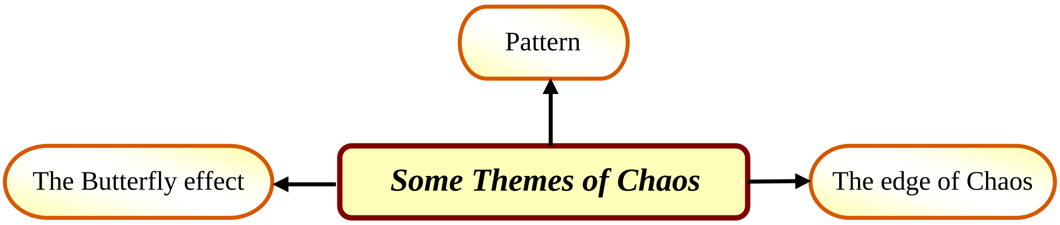


Figure 3.8- Some main themes of chaos discussed in this thesis

3.3.2.1. The butterfly effect

According to McMillan (2006), Edward Lorenz is credited with the discovery of the phenomenon of “sensitive dependence on initial conditions”. Working in the 1960s, Lorenz discovered that small variables in weather conditions could have a major impact on developing weather patterns. His discovery later became known as the “butterfly effect” as a result of his paper: “Predictability: does the flap of a butterfly’s wings in Brazil set off a tornado in Texas?”

In the other words, a tiny effect of a butterfly flapping its wings could potentially change the emergent pattern of the large-scale atmospheric dynamics (Priya Datta 2007).

The butterfly effect demonstrates that all systems are exceptionally sensitive to their initial or starting conditions and that small variable over a period of time can lead to major changes in a non-linear system. Nevertheless, it is important to realize that because a system is not predictable in the long term, it does not mean that it is impossible to understand or even to explain its behaviors. Also it should be possible to build theories that offer explanations for the generic properties of the system without necessarily knowing the small details (Kauffman 1995).

The name chaos may be misleading to some who associate chaos with total randomness. Chaos equations do not reveal randomness but instead yield complex patterns (Stapleton et al 2006).

According to McMillan (2006), a chaotic system may appear to be behaving erratically and unpredictably at first glance, but observation over a longer time period or on a wider panorama or visual scale will show patterns emerging that echo each other and weave around to form an unexpectedly stable tapestry of behaviors.

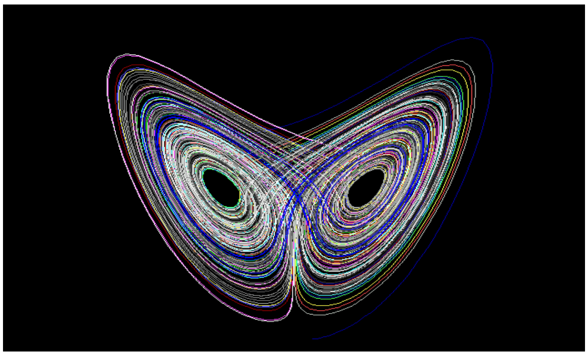


Figure 3.9-
The Lorenz attractor (Source: Ferreira 2001)

3.3.2.2. The edge of chaos

The region between the order and the random is called *the edge of chaos* (Lewin 1993, p.53). A lot has been written about the edge of chaos. Generally, it is considered to be a region in the state space of systems in which interesting and creative things can happen (Johnson 2006). According to McMillan (2006), the edge of chaos is a place, or rather a zone, where the parts of a system never quite lock into place, and yet never quite break up either.

Ordered systems, such as a crystal, are characterized by the fact that their components obey strict rules or constraints that specify how each component depends on the others. Disordered systems, such as a gas, consist of components that are independent, acting without any constraint. Order is simple to model, since we can predict everything once we know the initial conditions and the constraints. Disorder too is simple in a sense: while we can not predict the behavior of individual components, we can implement statistical independence. It means that we can accurately predict the average behavior of individual components, which for large numbers of components is practically equal to their overall behavior. In a truly complex system on the other hand, components are to some degree independent, and thus autonomous in their behavior, while undergoing various direct and indirect interactions. This makes the global behavior of the system very difficult to predict, although it is not random (Heylighen et al 2005).

Waldrop (1992) demonstrates that “the edge of chaos is a place where the components of a system never quite lock into place, and yet never quite dissolve into turbulence either. The edge of chaos is where life has enough stability to sustain itself and enough creativity to deserve the name of life. The edge of chaos is where new ideas and innovative genotypes are forever nibbling away at the edge of the status quo, and where even the most entrenched old guard will eventually be overthrown. The edge of chaos is constantly shifting battle zone between stagnation and anarchy, the one place where a complex system can be spontaneous, adaptive, and alive”.

However, the most interesting behavior occurs on the cusp of stability and instability, or what physicists call the phase transition (like boiling water to steam) or edge of chaos (Smith 2005).

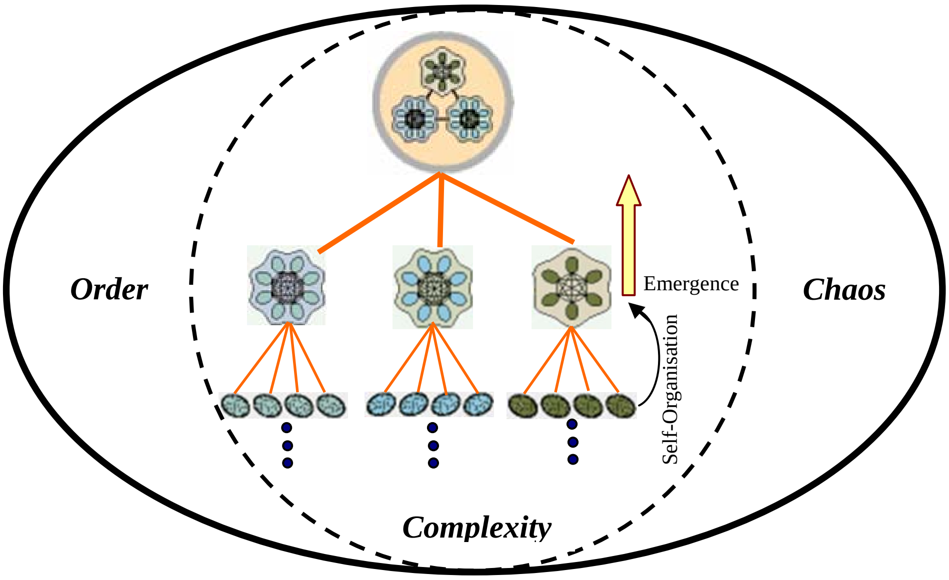


Figure 3.10 - Edge of chaos (Inspired from Ferreira 2001 and Lowson et al 1999)

3.3.2.3. Pattern

Pattern is an important feature of many aspects of chaos and complexity. According to Wheatley (1994 cited in McMillan 2002), a self-organizing system has a rich mix of positive and negative feedbacks which create their own patterns and one can not appreciate the phenomenon of self-organization without understanding pattern. Fractals are raised from repeating patterns on different scales. Complex adaptive systems seek for patterns as they interact and learn from their environment (Lewin 1993 cited in McMillan 2002). Pattern recognition is a key way of recognizing, learning and understanding things that is used by the human brain, itself a complex adaptive system.

3.3.2.4. Chaos Theory versus Complexity Theory

Chaos Theory deals with simple, deterministic, nonlinear, dynamic, closed systems. They are extremely sensitive to initial conditions resulting in an unpredictable chaotic response to any minute initial difference or perturbation. Complexity Theory focuses on complex, non-linear, open systems. Complex systems respond to perturbation by self-organizing into emergent forms that cannot be predicted from an understanding of its parts (Reitsma 2001).

Chaotic systems share properties with complex systems, including their sensitivity to initial conditions. However, models of chaotic systems generally describe the dynamics of a few variables, and the models reveal some characteristic behaviors of these dynamics. Conversely, complex systems generally have many degrees of freedom (Merali 2006).

3.4. Ubiquitous Complexity

Trace of complexity science could be followed in different contexts. The results of a sketchy search for the term “complexity” in a database or search engine verify this claim. Nevertheless complexity science in context of Supply Chain Management and Logistics is not hoary and necessitates more research and probes.

But why is complexity ubiquitous? And why has it rooted in different fields?

Brodbeck (2002) states that complexity theory does not conceptualize the world around us as linear and mechanistic or cause-and-effect, rather it takes a holistic, organic and nonlinear approach at looking at systems and systems-emergent behavior. By trying to influence through a procedure the forces/environment in which the agents of a system interact, a directed adaptive outcome, consistent with a desired result, may emerge.

Keene (2000) demonstrates: “In the old Newtonian paradigm of seeing the world and organizations in a mechanistic way, fluctuations and disturbances are seen as signs of trouble. We tend to associate control with order. However, what complexity tells us is that disorder plays a key role in the creation of new and higher forms of order. The space of complexity is that state which the system occupies and which lies between order and chaos. It is a state which embraces paradox; a state where both order and chaos exist simultaneously. It is also the state in which maximum creativity and possibility exist for the system to realize and explore”.

According to Kogut (2007), one major reason that complexity is becoming more important to social science and management studies is the confluence of ever-more powerful computers and the digitalization of content. The growing power of computers has long changed the methods and contents of research.

4. SUPPLY CHAIN COMPLEXITY (FRAME OF REFERENCE)

“If a man writes a better book, preaches a better sermon, or makes a better mousetrap than his neighbors, though he built his house in the woods, the world will make a beaten path to his door.”(Ralph Waldo Emerson)

According to Whetten (1989), a complete theory contains four elements: (1) what, (2) why, (3) how, and (4) who, where, when. In this chapter, the two initial ones are addressed. At first, several definitions of supply chain complexity are reviewed and a novel approach to this field is presented.
Later, it is delineated that why supply chains have been tremendously complex and what consequences would be rendered from such complexity.
Finally, some main themes of complexity and chaos, which were introduced in chapter 3, are embodied in the context of supply chain management.

4.1. Context of Supply Chain Complexity

The aim of this section is to deal with *what* of supply chain complexity. For dealing with context of supply chain complexity, some definitions and perceptions of it are brushed up based on reviewing several literatures. In most written words, such definitions and descriptions are based on perception of authors about what make supply chains (or some part of it) complicated and complex.
After that, a novel approach to supply chain complexity management is raised based on constituent words of “Supply Chain Complexity Management” phrase.

4.1.1. Background and literature review

Finding a precise definition for supply chain complexity is Herculean. It arises from difficulty in delineation of complexity as well as demarcation of supply chains. That is probably why several researchers, for describing supply chain complexity, have focused their eyes on just one or some part(s) of it.
According to Nilsson (2005), the complexity often addressed in common logistics (and supply chain) literature is interpreted as complicated, not complex. The major reason for this interpretation is that complexity is, in most literature, addressed as being derived from an interpretation of logistics systems which are difficult to understand since they consist of a great number of parts, connections, and flows.
According to Wu et al (2007), in manufacturing and supply chain management, complexity implies number of elements or subsystems, degree of connectivity and interaction among the elements, unpredictability, uncertainty, and variety in products and system states.
Choi & Krause (2002) have set their eyes on “supply base complexity”. They rehearse that all businesses engaged in value-adding activities purchase goods and services from a group of suppliers. This group of suppliers is called the ‘‘supply base,’’ and the buying company that purchases from its supply base is referred to as the ‘‘focal company.’’
The focal company manages the suppliers in the supply base through contracts and purchasing of parts, materials, and services. To facilitate better management of a supply base, the authors observe complexity as a key area of managerial consideration and apply the literature on complexity to the supply base. Supply base complexity is conceptualized in three dimensions: (1) the number of suppliers in the supply base, (2) the degree of differentiation among these suppliers, and (3) the level of inter-relationships among the

suppliers. Furthermore, they propose that the degree of supply base complexity affects transaction costs, supply risk, supplier responsiveness, and supplier innovation.
Deshmukh et al (1998) and ElMaraghy et al (2005) have focused on manufacturing systems complexity. Scott et al (2000) demonstrate that viewing manufacturing operations as complex systems can provide useful, novel insight and challenge our intuitive views of company's behavior and performance.
In Yates' (1978, p. r201) opinion, complexity in a system (as well as in supply chains) usually arises whenever one or more of the following five attributes are found:
1) Significant interactions;
2) High number of parts, degrees of freedom, or interactions;
3) Nonlinearity;
4) Broken symmetry [. . .]; and
5) Non- homonymous constraints.

In logistic context, Lumsden et al (1998) discuss that one way of dealing with complexity is working with it as a conceptual term without assigning a precise, measurable meaning to it. According to the authors, some aspects of the conceptual term of logistics complexity can be identified: a large number of system states, heterogeneous system, distributed decision making and uncertainty.
Waidringer (2001) clarifies that three different properties of transportation and logistics systems give a satisfactory account for the total complexity of the system. These three properties are as follow:
1) The network property: Overall, the network complexity is primarily concerned with design and redesign of a transportation or logistics system.
2) The process property: The process perspective is primarily concerned with the operations of an actual set-up of a transportation or logistics system.
3) The stakeholder property: The stakeholder perspective is primarily concerned with management and control of the process and network.

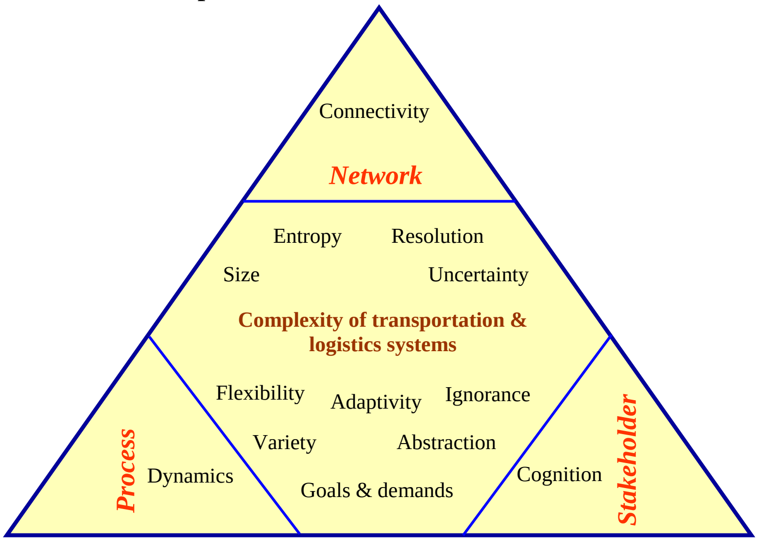


Figure 4.1- The perspectives of transportation and logistics systems' complexity (Source: Waidringer 2001)

According to Nilsson (2004), logistics complexity is often derived from an interpretation of logistics systems as being difficult to understand since these systems consist of a great number of parts, relationships and flows, i.e. they should be heavily reduced and simplified in order to be dealt with.

Rao and Young (1994) authenticate how the complexity of international logistics operations can vary significantly among firms as a result of the products they make, the processes they employ, the areas in which they trade and the financial/business strategies they pursue.
Faber et al (2002) have studied warehouse complexity and its relation with warehouse planning and control structure. They demonstrate that warehouse complexity refers to the number and variety of items to be handled, the degree of their interaction, and the number, nature i.e. technologies used, and variety of processes determined among others by the warehouse's position in the logistic chain and the nature of its market.

Definitions of complexity in organizational context can be traced in several articles like Smith (2005); Keene (2000); Caldart & Ricart (2004); Browaeys & Baets (2003); Allen (2002); Lewis (1994); Smith (2003); Potter (2000); McKenna (1999); Siemieniuch & Sinclair (2002); Ashmos et al (2000); Letiche (2000); Meijer (2002); Fuller & Moran (2001); Price (2002); Backlund (2002); Cunha & Cunha (2006).
Burnes (2004 cited in Smith & Graetz 2006) states that rapid environmental change has increasingly led academics and practitioners to consider organizations through the lens of complexity theory; a perspective he notes that has a significant impact on how organizations should be structured.
Following the above characterizations of complexity, a complex organization could be said to be an organization whose behavior is complex (i.e. it can behave in many different ways and the behavior is non-random and cannot be described by any linear equations, i.e. great external complexity), or whose inner structure is complex, or whose processes are complex *(*Backlund 2002).
According to Brodbeck (2002), complexity theory does have a place in procedural design as a means of leveraging self-organizing and self-motivating behavior for improved organizational performance.

Expositions of complexity in context of Information Systems and Flows can also be found in several articles like Merali (2006), Gault & Jaccaci (1996).
Merali and McKelvey (2006) have provided a review of some articles to show how concepts from complexity theory can be used to explore and yield insights into issues central to the IS (Information Systems) domain.
As Miller (1999) points out, every living system has a certain degree of complexity. Organizations are considered to be living systems in the sense used by Miller. Every organization is also an information system, "As any organization is tied together by information" (Langefors 1995, p.53). Any such information system will thus have a certain degree of complexity.
Jacucci et al (2006) have explored complexity and how it could be addressed in information systems (IS) research. There are at least three aspects which make complexity an important topic for IS research and practice: (1) Technical; (2) organizational; and (3) societal.

4.1.2. A systematic approach to context of Supply Chain Complexity Management

A helpful procedure to perceive the phrase of "supply chain complexity management" and its elements is looking to its four constituent words: Supply, Chain, Complexity and Management. It means defining it based on "Supply complexity", "Chain complexity", "Complexity of complexity (Intangible complexity)" and "Management complexity". (Figure 4.2)

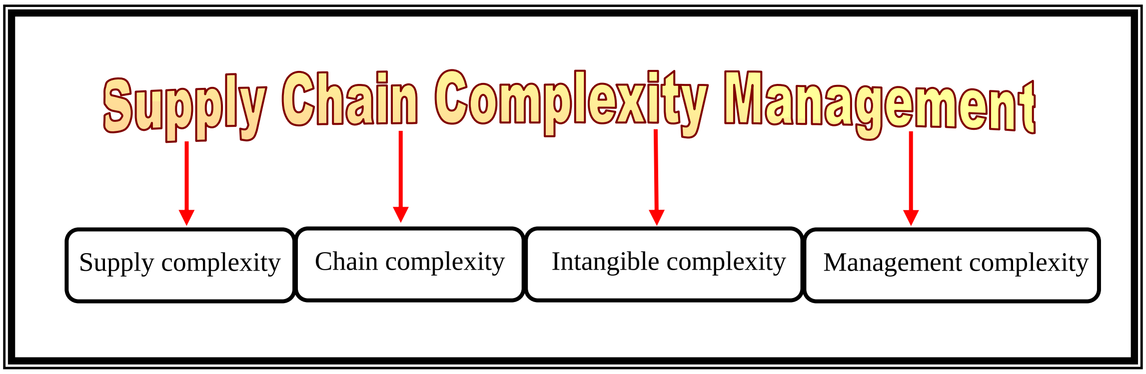


Figure 4.2- Definition of Supply Chain Complexity Management based on its constituent words

In figure 4.2, **Supply complexity** delineates complexity of supply and demand. In fact it means any sort of complexity which is rendered from decisions about supply as well as demand of materials and resources.

Supply (and demand) complexity, which is excogitated in section 4.2, could be driven by: number of suppliers, several methods of supply, risk of supply, lead-time of supply, different methods of cost and pricing calculation, number of customers, volatility in demand, mass customization and variety, number of function delivery, push-pull boundary and so on.

Chain complexity denotes complexity of network constellation and configuration, several processes in the network, and different flows in a network (material flow, information flow, resource flow and monetary flow).

Network constellation and configuration refer to location and layouts of agents (both in macro and micro levels) of the network.

Different processes in the network point out operational processes, production and manufacturing methods, quality processes, maintenance processes, inventory control processes, transportation processes, business and commerce processes, marketing processes and etc.

Different and diverse flows mention all kinds of constraints and obstacles which hinder smooth movement of materials (row materials, in-process and finished ones), information (data, information and knowledge), resources (humans, vehicles and cargo carriers) and money (credits and deposits).

Intangible complexity represents the complexity of cognition, describing and demarcating the supply (value) chain. In fact depicting a specific border for such complex system is impossible. Another complexity is that agents and entities of the system always self-organize and adapt with environment. In fact, at all times, new patterns of agents of the system are emerged.

Management complexity illustrates complexity of controlling and managing supply (value) chains due to several rules and laws, cultural differences, lack of holistic view, different perspectives, and ignorance and so on.

4.2. Effects of complexity on supply chain management

The aim of this section is to deal with *why* of supply chain complexity. In recent decades, millions of articles, books and journals have been written and thousands seminars and conferences have been held to present increasing importance of supply chains both in practice and theory. It is non-negotiable that, nowadays, success is not just tied-up in processes of a focal company but in processes of all its value chain and network. In this regard, for surviving in highly competitive markets, it sounds essential that all processes and entities of the supply and demand network be analyzed and value-adding ones be separated from those which are not.

One of the origins of non-value adding processes is non-value adding complexity. So, a systematic study and analysis of supply chain complexity and rendering remedies for simplicity are essential.

In this section, increasing complexity of supply chains and some consequences of it are signaled. In this regard, at first some literature and articles are reviewed and then a systematic approach based on section 4.1.2 is presented.

4.2.1. Background and literature review

According to Blecker et al (2005), 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. He states that high complexity is due to several causes such as customer tailored and elaborative products, global procurement and distribution, or technological innovations.

Gottinger (1983) stresses that to manage a system, complexity of that system must be understood first; otherwise, interventions would lead to sub-optimization.

Sheffi (2005 cited in Marley 2006) states that as systems become more complex, they become increasingly more vulnerable to experiencing supply chain disruptions. Therefore, developing strategies to mitigate disruptions has become a necessity for today's managers and a critical area of research.

Lewis and Sheinfeld (2006) demonstrate that successfully managing supply chain complexity enables companies to capture a powerful operational competitive advantage through improved top-line and bottom-line financial performance. Lower supply chain complexity drives shorter lead times, improved forecast accuracy, higher on-time delivery to request rates and higher perfect-order fulfillment rates.

Sun (2005) has applied a number of tools in his paper to analyze product complexity related to product variety and identify product complexity reduction opportunities associated with product attributes.

He demonstrates that product complexity is mainly resulted from product design and marketing influence, and can have a significant impact on the manufacturing system and supply chain. Providing product complexity within a product can lead to higher costs of manufacturing and the supply chain.

Anderson et al (2006) have assessed the interactions among customization and complexity. According to the authors, complexity becomes unnecessary and value draining when companies fail to address the trade-off between customization and complexity – between the costs associated with customization, the value derived from it, and the price that should be charged for it. Clearly, a lot of valuable learning occurs in the management of the tradeoff between customization and complexity. So, complexity per se is not the problem. The problem is the inability to manage and control it.

Meepetchdee & Shah (2007) have investigated logistical network design with robustness and complexity considerations. They have tendered that highly complex logistical networks potentially imply that more resources and effort are required to synchronize and coordinate activities within the network. Highly connected logistical networks are highly complex and will require greater levels of coordination and more information and business processes for decision making, implying higher costs under higher complexity.
Rao and Young (1994) demonstrate how the complexity of international logistics operations can vary significantly among firms as a result of the products they make, the processes they employ, the areas in which they trade and the financial/business strategies they pursue.

Funk (1995) presents a model in his article that hypothesizes relationships between logistical complexity and both the importance of JIT manufacturing and the most appropriate organization structure for implementing JIT manufacturing. The model hypothesizes that the greater the logistical complexity of a factory, the greater the importance of JIT manufacturing and the greater the number of internal teams that need to work together and with supplier-based teams.
The greater a product's logistical complexity, the more information is needed to produce that product. Therefore, as logistical complexity increases, more informal and formal communication links are needed between teams.
The greater the logistical complexity of a product, the more cross-training is needed.
As logistical complexity increases, performance measurement systems may become more complex.

One of the striking characters of complexity is that it attempts to fill a gap in conventional approaches to dealing with change and environmental turbulence (Smith 2005). In fact, complexity is the best science for explaining "supply chain change management" as well as investigating interactions among supply chain system and its environment.

Johnson (2006) discourses that the science of complexity can help us understand risk (and supply chain risk) better as:
-complexity science offers new methods for modeling complex systems and risk;
-complexity science enables us to understand better why some systems are complex;
-complexity science enables us to understand the nature of rare events;
-complexity science leads to new measures of risk.

According to Koudal (2005), companies which are master in managing complexity of their value chains are far more likely to exceed their goals for growth, capital/asset returns, and shareholder value. These companies excel at coordinating activities throughout the life of a product — product development, supply chain operations, and marketing, sales, and after-sales service.
Behind the ability to create a profit cycle by effectively synchronizing the value chain, four key ingredients make complexity masters stand out: visibility, flexibility, collaboration, and technology.

Visibility: Complexity masters have better visibility both upstream and downstream in the value chain because of better information on future scenarios, product profitability, and manufacturing and distribution costs.

Flexibility: To effectively manage products across their lifecycles, complexity masters build flexibility into product development, manufacturing, and other operations so they can quickly shift manufacturing loads, change production volumes and product mixes, and modify products to meet market demand.

Collaboration: Complexity masters collaborate more extensively with customers to define product requirements, and with suppliers to design components and new materials and to develop more efficient and flexible processes

Technology and systems: Complexity masters are ahead of the pack in using advanced technologies for PDM (Product data management), PLM (Product lifecycle management), CRM (Customer relationship management), and APS (Advanced planning and scheduling).

Complexity makes a supply chain inflexible and inefficient. It also hampers on-time delivery and creates problems for product quality. The more complex the supply chain, the greater the possibility it will fail in one or more of its functions; and failures jeopardize a company's relationships with customers (Hoole 2006).

4.2.2. Soaring complexity of supply chains and its consequences

In this section, a systematic approach is presented to reflect soaring complexity of current supply chains as well as some effects of complexity on supply chains.
The presented systematic approach is based on section 4.1.2 and elements of “supply chain complexity management”.
To figure out some remedies for non-value adding complexity please refer to section 5.5.

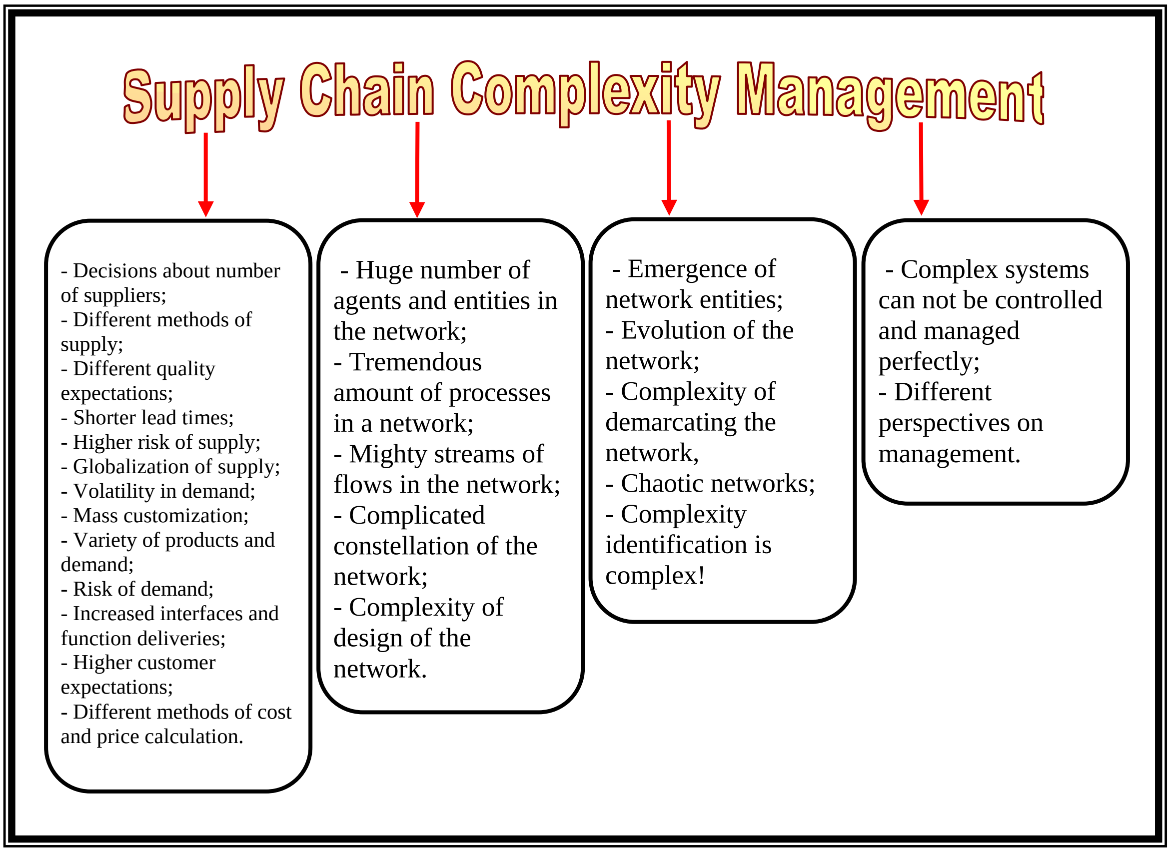


Figure 4.3- A systematic approach for addressing soaring complexity of supply chains

- By focusing on **Supply** part, several issues have made the system complex. Decisions about design of supply like number of suppliers, different policies and methods of supply, different expectations from quality of suppliers, higher pressure on shrinking time of supply (shorter lead times), high risks of supply, globalization of supply, different ways of cost and price calculation, and so on show tremendous complexity of the system.

Furthermore, in this part we must also add complexity of demand: Volatility in demand (bullwhip effect), mass customized products, varieties of demand, risk of demand, increased number of interfaces and function deliveries, higher customers’ expectations (like better after-sale services, longer warranties) and so on.

Variety and mass customization of products are some significant sources of supply and demand complexity.
Christopher (2008) has investigated effects of variety of products (based on ABC or Pareto Analysis) on total cost and revenue of the system (Figure 4.4).

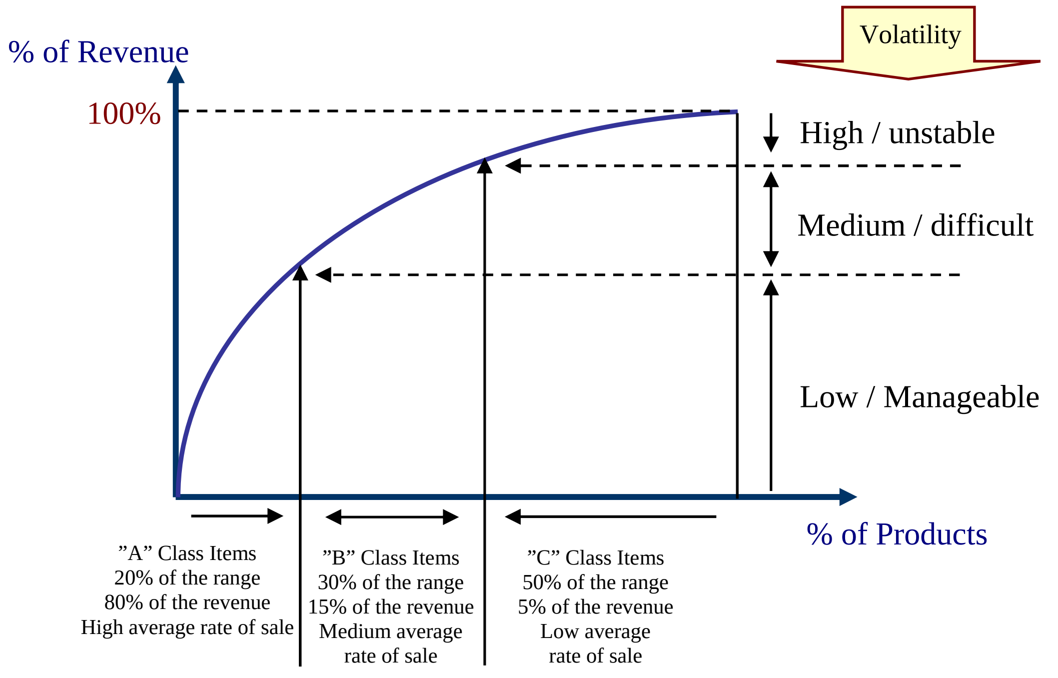


Figure 4.4 - What is the cost of variety? (Source: Christopher 2008)

➢ By focusing on **Chain and network**, several events have made it complicated and complex:

- ***Network constellation and configuration***

As it rises from the word "network", different chains are engaged in different networks. This makes supply chains fairly complex specially the ones which act globally.
More engaged entities and agents (actors, companies, products and so on) in the network mean more transportation, location, layouts and as a result more complexity.
Location, here, means sites of different engaged entities (macro perspective) and layout means internal arrangements of each entity (micro perspective, like layout of departments, work stations and so on).

- **Different Processes**

A process can be defined as a logical series of activities that converts input(s) to output(s) (Figure 4.5).
By adding feedbacks to a process (from outputs to inputs), it is called a system.

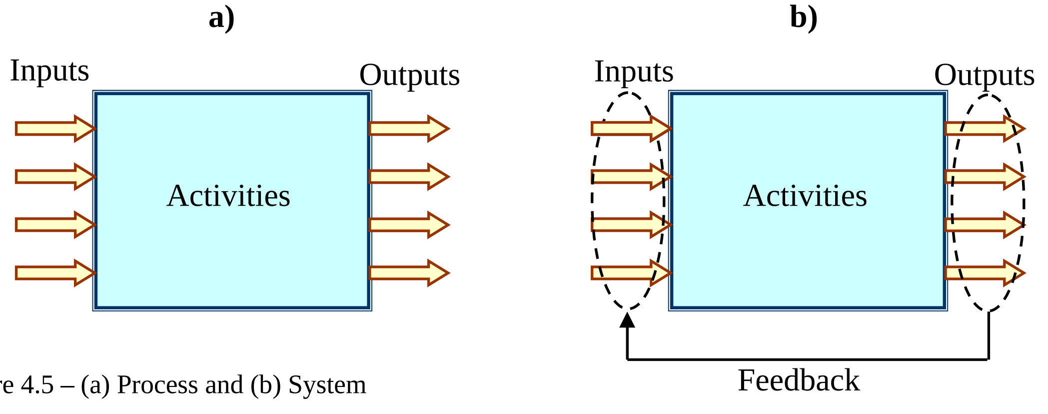


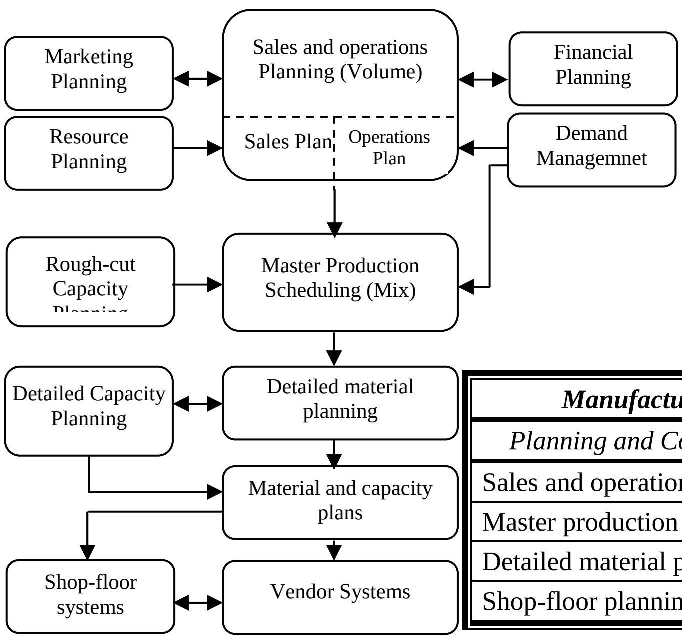
Figure 4.5 – (a) Process and (b) System

Zillion different processes in the network represent obviously the complex and complicated nature of supply chains.
Such processes could be: operational processes, quality processes, maintenance processes, inventory control processes, forecasting processes, management processes, support processes, transportation processes, business and commerce processes, marketing processes and etc. Different production and manufacturing methods are also complicated processes (Table 4.1).

Characteristics	**Job Production**	**Batch Production**	**Mass Production**	**Flow Production**
Description	Refers to manufacturing of products to meet specific customer requirements. Each order may require different processes and also different technological order of sequences.	Refers to the system of manufacturing, a number of identical units in batches at a time. When one batch of product is over, then the production of the next product is taken up.	Refers to the manufacturing of large number of units or products, on which the equipments are fully engaged. Usually the same production process is continued for a long period of time.	It is similar to mass production, except that, in this case the plant, equipment and layout are primarily designed to manufacture a specific product only.
Purpose	To meet the specific requirements of customer's orders.	To produce the stock for internal consumption in the assembly section or to meet the demand of external order.	To produce a large number of identical products.	To produce a large number of specific products all the time.

Table 4.1 – Different types and methods of production and manufacturing (Source: Arora 2004)

Different production and manufacturing scheduling and planning procedures for several products and their sub-groups (BOM) are also complicated processes (Figure 4.6).



Manufacturing Planning and Control Systems		
Planning and Control Level	*Approaches*	
Sales and operations planning	Level	Chase
Master production scheduling	MTS ATO	MTO
Detailed material planning	Rate-based	Time-based
Shop-floor planning	JIT-type	MRP type

Figure 4.6 – Different Manufacturing Planning and Control Systems (Source: Vollmann et al 2005)

Volatility in manufacturing planning systems is one of the main sources of uncertainty and complexity. As each product is dependent to its sub-products (Bill of Materials (BOM)), changes in production planning of product will alter production planning of its sub-products and vice versa.

Volatilities in market processes are also important causes of complexity which may have undesirable effects. According to Emerson & Piramuthu (2004), mismatches in demand and supply arise primarily due to market volatility. And, there are opportunity costs that are associated with these mismatches.
Examples include decrease in quarterly earnings in 1996 by $900 million for General Motors due to a 18-day labor strike at a brake supplier factory that idled workers at 26 assembly plants; Boeing's $2.6 billion loss in 1997 due to failure of two key suppliers to deliver critical parts on time; during 2000, Sony's console shipment in US was 50% less than planned due to shortage of PlayStation2 graphic chips; Ericsson's loss of three market-share points against Nokia in 2000 that forced exit from handset market due to fire in Philips Electronics plant in New Mexico leading to disruptions in supplies of chips for key new handset.

- **Different and diverse flows**

  According to Lumsden (2001) different flows in a logistics and supply chain network can be classified to material flow, resource flow, Information flow and monetary flow (Figure 4.7).

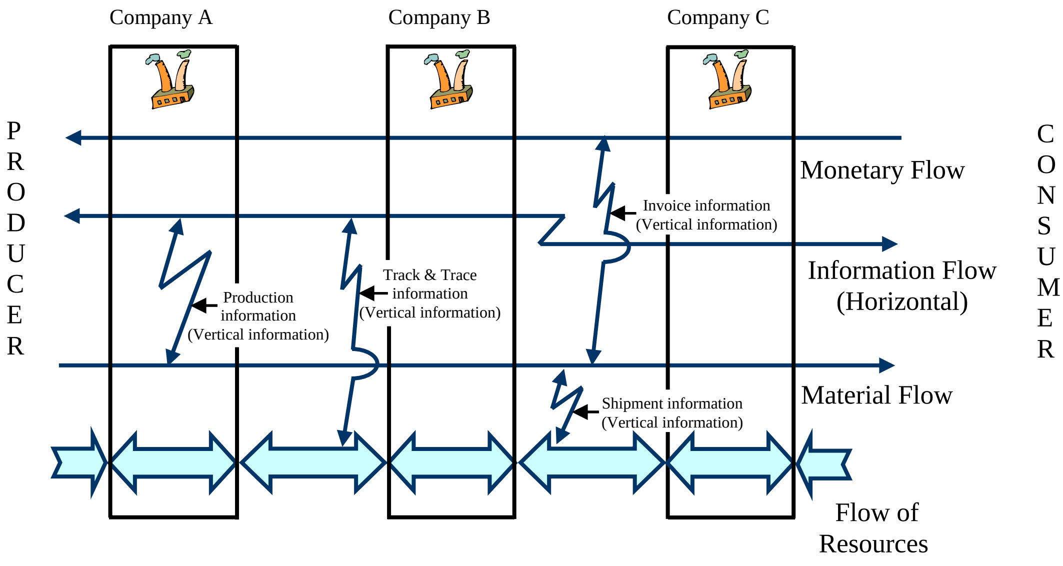


Figure 4.7 – Different flows in a logistics and supply chain network (Source: Lumsden (2001) and Stefansson (2007)).

- By setting the eyes on material flow; huge amount of materials (row materials, in-process and finished goods), different structure - shape - components – maintenance - and package of materials and products, different methods of inventory control and so on show other parts of extremely complex supply chains.

- Resources are defined here as man (humans) and machines (vehicles, robots, cargo carriers, machineries and so on). To figure-out resource complexity better, just think to the number of engaged humans and machines in a global or even national and local supply chain!

-By considering information flow, another feature of supply chain complexity is detected. Huge amount of data, information and knowledge as well as high speed and frequency of information transfer and exchange delineate the soaring complexity of supply chains.
In this category, asymmetry of information should also be added. This asymmetry can be due to political considerations, different perception and so on.

-Finally, tremendous monetary flow certainly in global supply chains obviously illustrates the increasing complexity. This complexity can be due to different currency exchange rates, different economic rules and laws, different methods of payment and so on.

- By focusing on **Complexity** part, an initial problem is demarcation of the supply chain and network. As the chain is tied to different other chains of different networks, depicting a border of the system sounds impossible. The scenario even becomes worse when a chain enters a new market and becomes engaged with several new actors, agents and so on.
Another complexity is that the supply chain is a nonlinear system. Here, agents and entities of the system always self-organize themselves and adapt with environment. In fact, based on different circumstances, strategies and markets, they do co-adaptation and co-evolution. Furthermore, all times, new patterns of agents of the system are emerged.
Another important issue is chaos. As supply chains are chaotic systems, just a tiny change or problem in the system can lead to catastrophic consequences and different emerged patterns.

- By focusing on **Management** part, it is non-negotiable that control and manage of complex and complicated systems such as supply chains are impossible.
Furthermore, simplicity in one part may lead to complexity in another part of the system.

As Allen (2006) states: “There is no guarantee that the combined behaviors within an organization work really well, or deal well with any disturbance or shock. We only know that they work sufficiently well to be there, but do not know how well they could work, nor how they may respond to a shock that has not occurred before. Because of the interacting behaviors of its multiple agents, a supply chain network is highly non-linear and shows complex multi-scale behavior through a complex interplay of its structure, environment and function. This complication and lack of predictability makes it difficult to manage and control them”.

According to Priya Datta (2007), Supply chains are becoming increasingly difficult to manage due to:
• Large network of interlinked entities including suppliers, manufacturers and distributors across multiple organizations across the globe;
• Each of these members may have conflicting objectives;
• Dynamic and uncertain nature of the supply chain.

Different Conflicting Objectives
Companies do not make isolated decisions anymore. Since each company impacts on and is impacted by its partners in a supply network, any decision by a company to maximize its

profits may disturb other companies, which may result in globally sub-optimal decisions, because organizations may have different conflicting objectives.

Supply networks are dynamic

Different entities in a supply chain operate subject to different sets of constraints and objectives and their performance are dependent on the performance of others. The significant operational challenges presented by supply networks are driven by the dynamical behavior of the supply chain as its members interact with one another and these interactions evolve over time making the supply networks a dynamic system. The changing demands of the marketplace, constant changes in product specifications, together with other continuous improvement initiatives within the organizations and the wider industry as a whole imply that the supply chains never actually reach a stable steady state. Even supply chain structures should not be expected to be stable. In fact, supply chain structures cycle between integral/vertical and horizontal/modular forms influenced by the pace of the industry.

Supply networks are more vulnerable to disturbances

Supply chains are constantly subject to disturbances. Disturbances are unpredictable events that can influence the supply chain's ability to achieve its performance objectives adversely. Disturbances can arise from various sources either internal or external to the supply chains.

4.3. Complexity themes in context of supply chain

By accepting supply chain and logistics as complex systems (not just complicated ones), finding counterparts of themes and concepts of complexity science, as well as chaos, in context of supply chain could be interesting. In this section, it is briefly discussed how supply chains self-organize, adapt, emerge, evolve and so on and so forth.

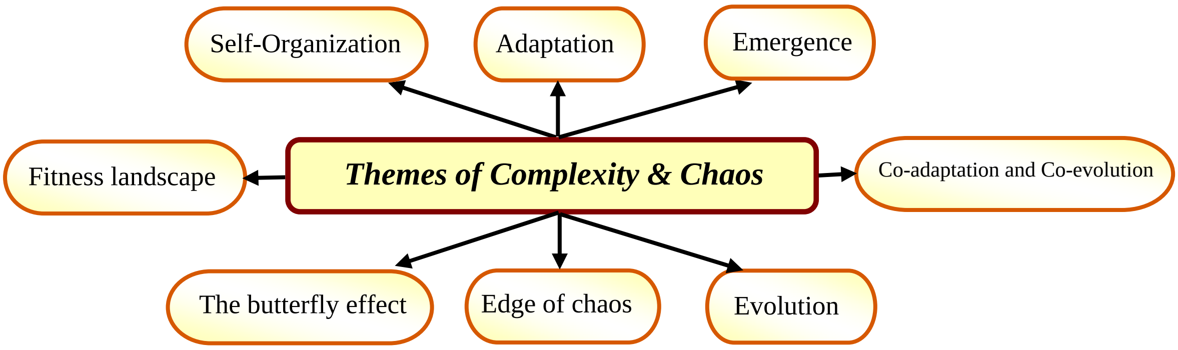


Figure 4.8- Some main themes of complexity and chaos in context of supply chain discussed in this thesis

4.3.1. Self-organization in discipline of supply chain

To better understand self-organization among entities of a chain, let's consider the following example. A newly-established family composed of a man and a woman constitutes a self-organized system (the family) which has two self-organized subsystems (the spouses). In this case, the couple communicates with each other to orient themselves with new situations.

Similarly in a supply network, each agent (company, organization, human and so on) communicates with several other agents through numerous chains. In this case, the supply chain entities self-organize themselves to new orientations and strategies. A supply chain system may follow different strategies in different markets; this requires organizing the chain in a way which leads to maximum effectiveness (doing the right things).

For example, according to Fisher (1997), market of functional products calls for efficient (doing things right) supply chain and innovative products calls for responsive supply chain. Different supply chain strategies necessitate different organization of processes, networks, and information.

Self-organization is not the result of a priori design; it surfaces from the interaction of system and environment, and local interactions between the systems components (Merali 2006).

According to Hedlund et al (2004, p.36), when a system allows self-organization, it enables the agents to, by themselves, explore the environment and solve problems in different formations. It is through this kind of interaction that emergence occurs and the interactions can only exist in an open system. Self-organization is a powerful drive to make the system robust and adaptive.

Gershenson (2007) demonstrates that when a system or environment is very dynamic and/or unpredictable (like supply chains), it is useful to describe it as self-organizing.

According to Harkema (n.d.), self-organization in organizational context results if people are let free to network with each other and interact whereby they are not restricted by organizational or functional boundaries.

Scott et al (2000) state that lean production systems are excellent examples of self-organizing systems, as such are actively using the principles of dissipative structures and bounded chaos.

4.3.2. Adaptation in discipline of supply chain

In a supply chain, each entity (agent) interacts with others. Based on rendered experience and patterns of interaction, the entities learn how to revise and adapt. Waldrop (1992) demonstrates that one of the fundamental mechanisms of adaptation in any given system is revision and recombination of the building blocks.
Adaptation necessitates resilience and robustness of supply chains. In fact, supply chain must resist to its probable changes and revision.
In our family example, in this step, the couple interacts with each other to get experience and find patterns of contact. In fact, they *learn* how to adapt in different occasions.
Adaptation is a natural condition in all aspects of life. From living organisms to businesses, survival often depends on the ability to adapt. In today’s rapidly changing marketplace, adaptation is no longer optional; it is mandatory. The Internet and the ubiquity of information technology are requiring businesses to possess the flexibility to continually change and adapt to their environment. That's where adaptive supply chain networks come into play (SAP, 2002).
According to Wycisk et al (2008), logistics systems such as supply networks adapt to their environment by adapting their structures by adding or deleting relations between agents (e.g. connecting with new suppliers, serving new customers, etc.), changing their physical abilities (e.g. implementing new technologies) and adapting their behavioral processes, i.e. shifts in strategies. In doing so, a supply network reacts to environmental demands and at the same time creates a new environment for its competitors. Processes of adaptation take place in different levels of the supply network at different times and different dimensions.
In a SAP white paper (2002), characteristics of traditional supply chains have been compared with characteristics of adaptive ones (table 4.2).

Characteristic	***Traditional supply chain***	***Adaptive supply chain network***
Information propagation	Sequential and slow	Parallel and dynamic
Planning horizon	Days / Weeks	Hours / Days
Planning characteristics	Batch	Dynamic
Response reaction	Days / Hours	Hours / Minutes
Analytics	Historical	Real-time
Supplier characteristics	Cost / Delivery	Network capability
Control	Centralized	Distributed
Exception management	Centralized / Manual	Distributed / Automated
Integration	Stand-alone point solution	Intra- and Inter- enterprise
Standards	Proprietary	Open

Table 4.2- Traditional Supply Chains versus Adaptive Supply Chain Networks (Source: SAP white paper 2002)

According to SAP white paper (ibid), Companies have to focus on and put in place key sequential enablers to manage the competitive pressures and make the adaptive supply

chain network's vision come to life. Management of visibility, management of velocity, and management of variability across the supply network are the three key process enablers that need to be mapped to the three key information enablers – quality of information, timeliness of information, and depth of information – to maximize network responsiveness and thereby enhance the efficiency of value creation (Figure 4.9-a).
To create an adaptive supply chain network, companies must advance through specific stages. The time it takes to evolve through the different stages will vary depending on the degree of technology, the process maturity, and the characteristics of the industry. However, once the network operations begin to streamline, benefits will become visible almost immediately. The three key stages to the evolution are integrated, collaborative, and adaptive (Figure 4.9-b). An adaptive supply chain network leverages the integrated and collaborative network to manage variability better than other networks, and it fully capitalizes on the mass-customization environment and peer-to-peer relationships. Its visibility and velocity enable it to manage variability with a minimal loss of operational and financial efficiency.

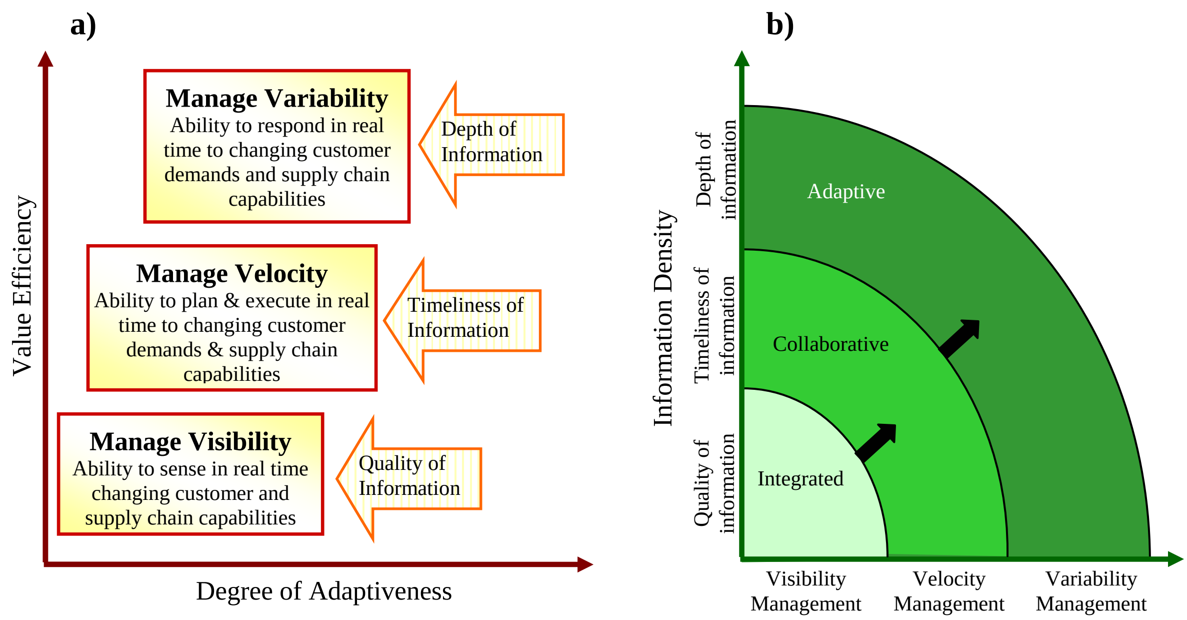


Figure 4.9- a) Enablers of Adaptive Supply Chain Networks; b) Stages to Adaptivity (Source: SAP white paper 2002)

4.3.3. Emergence in discipline of supply chain

In a supply chain, behavior of the system is emerged from behaviors of all its entities (agents), although each entity (agent) may represent a different behavior solely or in another system.
According to Nilsson (2004), Emergence is commonly referred to as the global behaviors that emerge from the interactions individuals make with each other in a local context. Local context refers to connections in either spatial and/or conceptual space. This means that emergent properties are to be found in the collective of constituent agents, since these do not have these properties themselves.
So, in studying agents of a supply chain, it sounds essential that its performance be assessed by its interactions with other agents not just its performance lonely. In fact a supply chain is more than just the sum of its agents.

Von Bertalanffy (1969, p.55 cited in Johnson 2006) writes, the meaning of the somewhat mystical expression "The whole is more than the sum of its parts" is simply that constitutive characteristics are not explainable from the characteristics of isolated parts. The characteristics of the complex, therefore, compared to those of the elements, appear as "new" or "emergent". If, however, we know the total of parts contained in a system and the relations between them, the behavior of the system may be derived from the behavior of the parts.

Some writers claim that emergence is unpredictable. This misrepresents the concept of emergence, and fortunately it is not true in general. For example, an electrical engineer designing a circuit board knows the properties of all the components and can calculate some of their interactions from this information. On this basis, the engineer specifies how the components are to be connected and lays them out on a board with electrical tracks to make those connections, with the intention that the whole has a pre-specified emergent behavior. This is an example of engineering emergence (Johnson 2006).

Surana et al (2005) state that with the individual entities obeying a deterministic selection process, the organization of the overall supply chain emerges through a natural process of order and spontaneity.

This emergence of highly structured collective behavior over time from the interaction of the simple entities leads to fulfillment of customer orders.

Demand amplification and inventory swing are two of the undesirable emergent phenomena that can also arise. For instance, the decisions and delays downstream in a supply chain often leads to amplifying a non-desirable effect upstream, a phenomenon commonly known as the 'bullwhip effect'.

Choi et al (2001) write: Although it is true that individual firms may obey the deterministic selection process, the organization of the overall supply network emerges through the natural process of order and spontaneity. In other words, all firms operate according to self-interest and to promote their own fitness criteria and are, thus, governed by the invisible hand, which brings order and spontaneity over a course of time.

What that means for individuals is that they need to constantly observe what emerges from a supply network and make adjustments to organizational goals and supporting infrastructure. Further, they should realize that it is quite normal for them to behave in a deterministic fashion based on few salient rules and performance measures.

Key is to stay fit and agile and be willing to make appropriate adjustments in the face of changing environment and not be apologetic about making structural changes over a course of time.

One of the main reasons for studying emergence is to find ways of designing systems that have desirable emergence. For example, when assembling teams of people, the behavior of the team emerges from the interactions of the individuals. Management would be impossible if the emergent behaviors were always completely unpredictable and surprising. Thus, it is misleading to say that emergence is characterized by unpredictability (Johnson, 2006).

Perceiving the emerged behavior of a supply chain system is one of the most decisive elements of supply chain risk management.

According to Scott et al (2000), emergence is also critical to the management of quality in repetitive and innovative processes.

4.3.4. Evolution in discipline of supply chain

Macintosh & Maclean (1999) state: "if one accepts the notion that systems not only complex and adaptive, but that their complexity and adaptiveness can itself change; then one can see different implications for the evolution of organizations."

Studying embodiment of evolution in context of supply chains sounds a little tough. The reason for this clam is that usually evolution is studied in long-term perspective and supply chains in short-terms.
According to Surana et al (2005) supply chain management plays a critical role in making the network evolve in a coherent manner.

4.3.5. Co-adaptation and Co-evolution in discipline of supply chain

An important consideration is that changes in the supply chain both shape and are shaped by changes in the environment. In fact supply chain is co-adapted and co-evolved by its interacting environment and market.
According to Johnson (2006) some systems can be perceived as having interacting subsystems. For example, the land-use – transportation planning system is concerned with two interacting subsystems. Decisions to locate new land-uses such as houses, super-markets, and warehouses in the land-use subsystem depend on the available infrastructure in the transportation subsystem. But new land-uses generate new travel demands and the construction of new transportation infrastructure. This then constrains further land-use decisions and the two subsystems co-evolve with each other.
A complex adaptive system and its environment interact and create dynamic, emergent realities. Because "there is feedback among the systems in terms of competition or co-operation and utilization of the same limited resources", the environment forces changes in the entities that reside within it, which in turn induce changes in the environment. For instance, in a team situation, as team members grow more cohesive (internal effect), they collectively become more distant from the outside environment (external effect), and vice versa.
Such bilateral dependencies ensure that a great deal of dynamism will exist in the environment (Choi et al 2001 cited in Hedlund et al 2004).
Surana et al (2005) state that a supply chain reacts to the environment and thereby creates its environment. Operationally, the environment depends on the chosen scale of analysis, e.g. it can be taken as the customer market.
Typically, significant dynamism exists in the environment, which necessitates a constant adaptation of the supply network. However, the environment is highly rugged, making the co-evolution difficult. The individual entities constantly observe what emerges from a supply network and adjust their organizational goals and supporting infrastructure. Another common adaptation is through altering boundaries of the network. The boundaries can change as a result of including or excluding particular entity and by adding or eliminating connections among entities, thereby changing the underlying pattern of interaction. As mentioned before, supply chain management plays a critical role in making the network evolve in a coherent manner.
According to Hedlund et al (2004) an example of co-evolution is the supply-tier system. When a firm decides to choose one supplier as a system supplier (supplier of main systems and not just individual parts), this creates a completely new stage for second-and third-tier suppliers that now supply the new system supplier

4.3.6. Fitness landscape in discipline of supply chain

According to Brodbeck (2002), organizational (here supply chain) "fitness" is described as an organization's ability to self-organize and adapt both internally and externally in the face of change
The idea is to design the formal organization such that structures, systems and processes "fit" the goals, rewards and structures of the informal organization.

A fitness landscape consists of a multidimensional space in which each attribute of the organization is represented by a dimension of the space and a final dimension indicates the fitness level of the organization.
In organizational studies, fitness can be represented by profit or by a mix of variables related to the organization's goals (Levinthal & Warglien 1999).
Choi et al (2001) write: a complex product, supported by a complex supply network can be thought of as a system of attributes. These attributes combine in some manner to form a "fitness" or goodness value to the product. For example, an automobile may be judged by its cost, its speed, its handling, and its reliability. In most cases, making the product or offering a service better means attending to these underlying features.

4.3.7. Chaos in discipline of Supply Chain

Edge of chaos is considered to be a region in the state space of systems in which interesting and creative things can happen. For this reason, business consultants urge their clients to run their companies "at the edge of chaos", but, since neither the companies nor the consultants have any mathematical model or data on the state space, the meaning of such advice is not very clear.
Indeed, metaphorical interpretations of the mathematical theories of complexity could place organizations at considerable risk. The qualitative interpretation of moving a system towards the edge of chaos suggests decreasing the order in the system. For organizations "stuck in a rut", this may be a good thing. The danger is that with no model and no data, managers of companies are not to know where the edge of chaos is, and, if they shake up the system too much, it becomes, literally, chaotic and uncontrollable (Johnson 2006).

4.3.8. Butterfly effect in discipline of Supply Chain

A counterpart of the butterfly effect in supply chain could be the "bullwhip effect". Like butterfly effects, the bullwhip effect describes how tiny initial shifts (in customer demand or order quantity) can result in chaotic and extreme events along the supply network via dynamical (non-linear) processes (Wycisk et al 2008).
According to Lee et al (1997 cited in Wycisk et al 2008), there are four major causes of the bullwhip effect: demand forecast updating, bulk purchases (e.g. encouraged through quantity discounts), price fluctuations, and shortage gaming (e.g. regarding veridical customers demands), which could be understood as Holland's "butterfly levers."
Butterfly effect is an important cause of supply chain risk. Risk is described as a combination of the probability of an undesired event and the magnitude of its consequence, or, more specifically, the expected value of a set of consequences (Christopher & Peck 2004 cited in Andersson & Torstensson 2006).
The butterfly effect delineates that just a tiny problem and failure in the system could lead to a catastrophic consequence and as a result risk of the supply chain.
Application of chaos theory to various supply chain issues and key functional areas is a necessity. The results may produce an increase in the level of understanding of supply chain ambiguity and how chaos theory may provide valuable insight into the effective management of supply chain networks.
The future of the world might well depend upon the butterfly effect of a seemingly insignificant variable, but it could also pivot upon some macro conditions like the price of oil, which while perhaps not always predictable, remains accessible to the scenario analyst. It does not matter what the original cause of a world-changing event is, scenario planning is capable of capturing many macro outcomes of it (Smith 2005).

5. STRUCTURE OF (A RECIPE FOR) STUDYING SUPPLY CHAIN COMPLEXITY

"It is neither the strongest of the species that survive, nor the most intelligent; but those most responsive to change". (Charles Darwin)

This chapter deals with *How* of supply chain complexity. In this regard, a systematic recipe for studying logistics and supply chain complexity is suggested (Figure 5.1).
The first step in this instruction is identification of causes and roots of supply chain complexity.
In the next step, classification of complexity causes is essential. Classification is a beneficial tool for predicting emergence of supply chain agents. This step empowers a system analyzer to detect and prioritize constraints and complexity of the system (Theory of constraints in supply chain complexity!).
Complexity measurement and calculation, in next stage, provide a quantitative gauge of the supply chain.
In general, complexity classes need to be evaluated to calculate the classes' impact on overall complexity. Measurement can be viewed as a decision support tool for predicting complexity impacts.
Next step is modeling of supply chain complexity. Repeated runs of the model reveal collective states or patterns of behavior as they emerge from the interactions of entities over time.
The last step is simplification. It is essential that non-value adding complexity be omitted and value-adding one be managed effectively and efficiently. Simplification of non-value adding complexity is a forever task as there is no any end for improvement of the system.

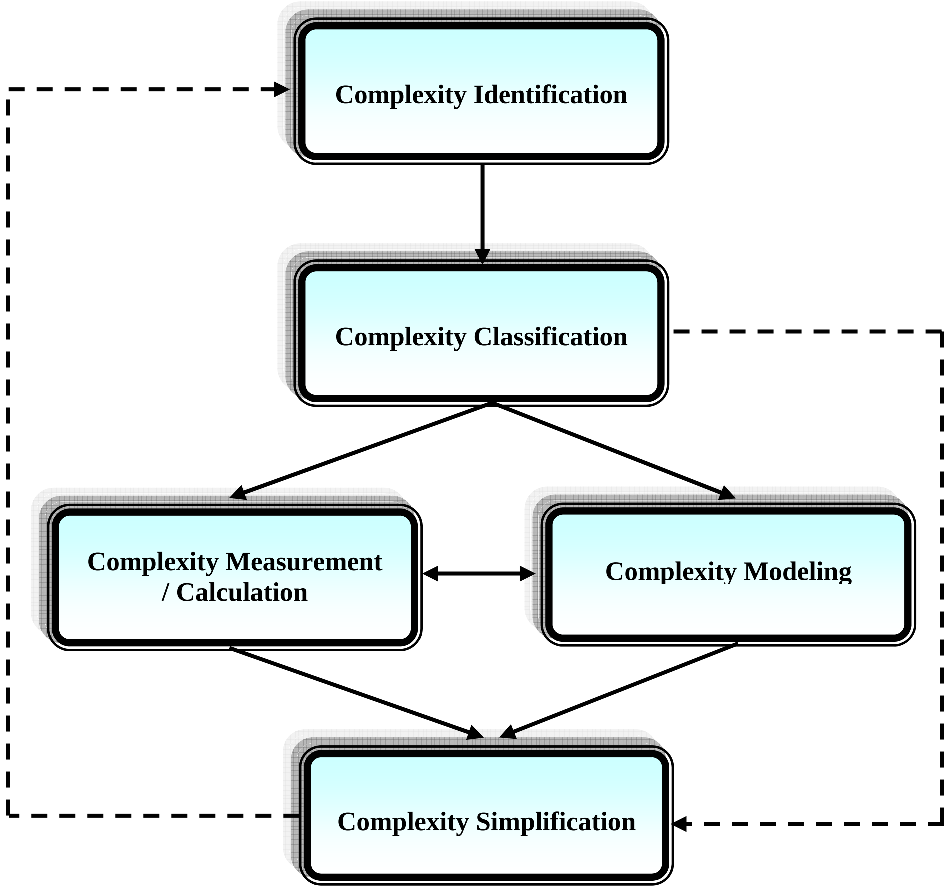


Figure 5.1- Structure of (a recipe for) studying supply chain complexity

5.1. Complexity Identification

This step entails detection of complexity in practice. Identification can be done by profound analysis of processes, entities, agents and modules of supply chain.
In this part, two helpful hints in detection of complexity are suggested: Translation of the supply chain language and detection of hidden complexity in Sherlock Holmes' procedure.

5.1.1. Translating the supply chain language

A **language** is a system of visual, auditory, or tactile symbols of communication and the rules (grammar) used to manipulate them (the symbols). Because language also includes grammar, it can manipulate its symbols to express clear and regular relationships between them (wikipedia.org).
On the other hand, **Translation** is the interpretation of the meaning of a text in one language (the "source text") and the production, in another language (the "target language"), of an equivalent text (the "target text," or "translation") that communicates the same message. Translation must take into account constraints that include context, the rules of grammar of the two languages, their writing conventions, and their idioms (wikipedia.org).
The counterparts of these definitions happen in business and supply chain. A business can be considered as a language which is constituted of symbols and grammar. Symbols are what the business or company implements to present itself in the market and grammar is the way that it manipulates and relates the symbols. Translation in this scenario is the way that the business or company interprets its business language to other languages such as consumers' languages and so on.
For each company in the chain (network) two issues should be considered: First, the company has to define its symbols and grammar as simple as possible. The symbols can be the mission, vision, policy or objectives of the company and Grammar is the rules and activities which it implements to relate its symbols. Second, it is essential that the company's business language be translated. It means defining how a company translates its symbols and grammar to its customers' languages, suppliers' languages, or language of each entity in its value chain which it communicates with. The ubiquitous simple translation of the company's language would lead to better business design and solid business structure.

5.1.2. Detecting defects and complexity in Sherlock Holmes' Procedure

By referring to definitions of business, one meaning and philosophy of it is finding solutions for existing and hidden problems. According to this definition, we can make a striking analogy between business (in fact the company or organization which does the business) and detective stories. They are both built around problem-solving in a social context. Here, "something" is amiss which is neither clear nor obvious. This "something" must be explained (the problem, here complexity must be diagnosed) and the way of solving, here simplifying, the problem ought to be prescribed.
Another striking similarity between business and detective stories is the one who diagnoses the problems and defects. In detective stories it is done by a detective and in business by a consultant.
Another analogy concerns the narrative structure, shared by classical detective novels and business (organization) studies. The plot of a detective novel consists of two stories: one is the story of criminal action, which is hidden, and which is revealed through the second story, that of investigation, or acquiring knowledge, which is mystifying to the reader, who

does not understand the actions of the detective until the first story is uncovered, and sometimes not even afterwards.
In both, an exceptional event (murder, complexity, loss of profits, decline, and fraud or …) is an interruption that –for a short moment- reveals the well-ingrained structure of the everyday world, which is forgotten and institutionally sealed from inspection in everyday proceedings. This is in fact the first story of the detective novels and business (or organization) study.
The most important is probably the second story which is “abduction” and it is the “logic of discovery”. In detective stories, Sherlock Holmes is an absolute master in abduction. Holmes uses abduction not to revolutionize general laws but to arrive at narrow range hypotheses and theories, theories of a particular case, fitting in well with the received view of the universe. Holmes does “normal science”. It has been suggested that Holmes in fact never verifies his hypotheses, thus failing to follow strict logic and opening himself to a number of parodies that emphasizes just a particular defect. Finally he presents the solution to the naïve and stupefied criminal, Dr Watson, and, sometimes, a police inspector or other witnesses.
A business and organization study might resemble the Sherlock Holmes detective story. A company should at first define its internal and external hidden complexity, problems, failures and defects. Internal complexity and problems are the ones related to internal language (both symbols and grammar) of the company. On the other hand, External complexity and problems are the ones which caused by competitors, consumers or when the company translates its language to other languages. After define process, detection (discovery) process should be done based on deduction, induction and abduction. In this step, the abduction process, the Sherlock Holmes’ procedure must be considered. A company has to find the root causes of complexity, problems and defects based on hypotheses which are not found easily by parody (what naïve people like Dr.Watson or police officers may do).

5.2. Complexity Classification

The purpose of classifying complexity is to get a viewpoint on several kinds of complexity or categorize groups of factors which contribute in supply chain complexity. A more precise classification of complex systems means better identification of their behavior in practice as well as better prediction of their emergence. Furthermore, by classifying complexity, the analyzer or manager can prioritize them and cope initially with the classes that contribute the maximum complexity (Theory of constraints in supply chain complexity!).

In this part a framework for classification of logistics and supply chain complexity is presented. Later, based on the mentioned framework, some classified frameworks mentioned in several literatures are reviewed. These classes can be categorized in two groups: 1) Assortment of complexity causes or 2) classification of complex systems.

5.2.1. A framework for classification of logistics and Supply Chain Complexity

In this part, a frame for classification of complexity in context of logistics and supply chain is introduced.

For this sake, complexity is classified in two groups: Structural (static) and Operational (dynamic).

Structural complexity is defined by Frizelle & Woodcock (1995) as that associated with the static variety characteristics of a system and that linked to the static design dimensions of the system.

Static complexity can be viewed as a function of the structure of the system, connective patterns, variety of components, and the strengths of interactions (Deshmukh et al 1998).

Operational complexity, can be defined as the uncertainty associated with the dynamic system (Frizelle & Woodcock 1995; Frizelle 1998; Sivadasan et al. 2002a) like uncertainty associated with managing the system, given the level of control and the detail of monitoring, or uncertainty of information and material flows within and across organizations.

Dynamic complexity is concerned with unpredictability in the behavior of the system over a time period (Deshmukh et al 1998).

Later, dynamic or static behavior of the system is categorized based on three levels of an organization (the managerial pyramid of logistics or supply chain): strategic, tactical and operational (Figure 5.2).

Surana et al (2005) and Simchi-levi et al (2004) define these levels as follow:

1) Strategic: deals with decisions that have a long-lasting effect on a company. This includes decisions regarding the number, location and capacities of warehouses and manufacturing plants, demand planning, distribution channel planning, strategic alliances, new product development, outsourcing, IT selection, pricing, network structuring and the flow of material through the logistics network.

2) Tactical: includes decisions that are updated anywhere between once every week, month or once every quarter. This includes purchasing and production decisions, inventory policies, transportation strategies including the frequency with which customers are visited, material handling and layout design.

3) Operational: refers to day-to-day decisions such as scheduling routings and loading trucks, workforce scheduling and packaging.

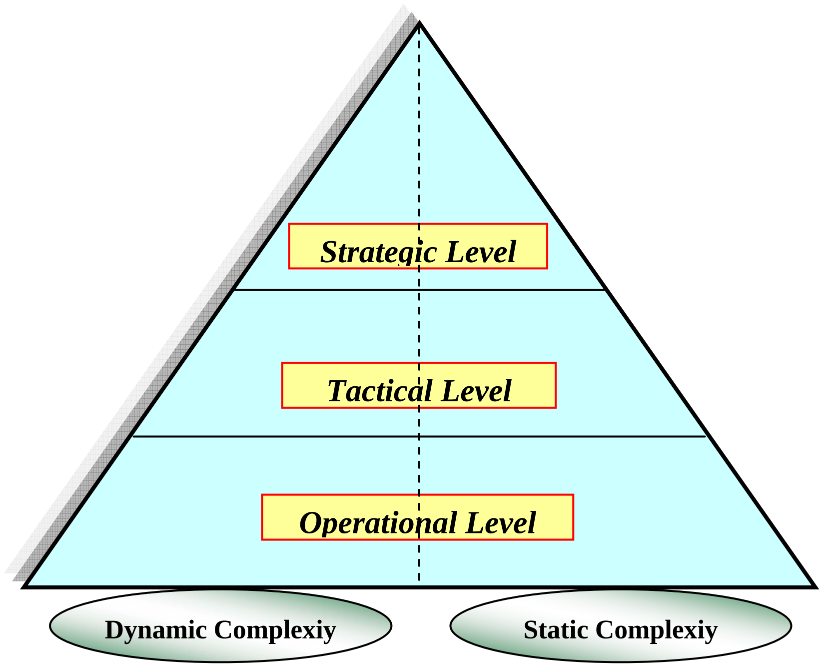


Figure 5.2- A framework for classification of logistics and Supply Chain Complexity

5.2.2. Different classification systems mentioned in several literatures

In this part, some former classified frameworks of logistics and supply chain complexity mentioned in several literatures are reviewed. Furthermore, positions of mentioned classified frameworks in figure 5.2 are explained.

5.2.2.1. Lumsden et al 1998

In this article, complexity has been discoursed in logistic networks as well as logistic systems. Complexity in logistic networks has been classified to *Algorithmic*, *Topologic* and *Metric*.

Later on, complexity in logistic systems has been discussed based on the following framework:

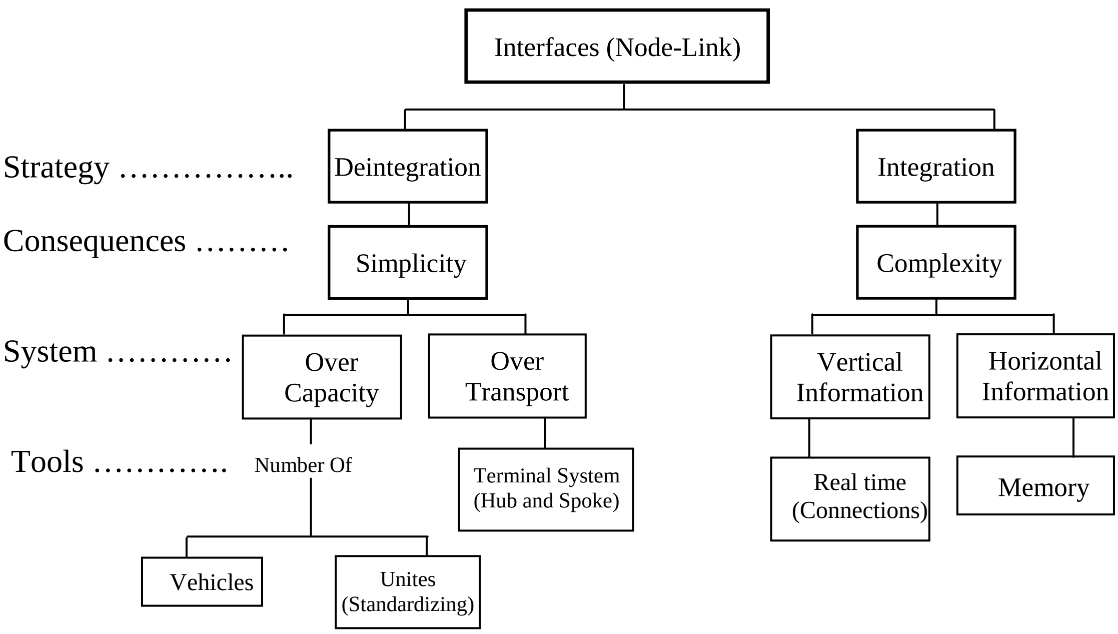


Figure 5.3 - Complex Logistics Systems

- ➢ Algorithmic, Topologic and Metric complexity could be related to static complexity in all levels of the system.

5.2.2.2. Lumsden & Eftekhar 2007

In this article, the authors have classified the causes of complexity, by focusing on logistic context, according to the follow:

- **Scale** (refers to the number of components which are involved in the system): In logistic context, it can be referred to EOS (Economy of Scale), number of partners, different suppliers / customers locations, distances, infrastructure limitations;
- **Diversity** (is the extent of different elements which make the system): In logistic context, it can be pertained to different perspective to management in the chain, variety of transportation transactions, amount of product diversity;
- **Connectivity** (means the relationships between components, kind of quality of connection): In logistic context, it can be related to parallel interactions in the chain, lack of information, lead-time and so on.

- ➢ Scale could be related to static complexity and Diversity & Connectivity to both static and dynamic complexity in all levels of the system.

5.2.2.3. Lumsden 2006

In this interview, Professor Lumsden classified complexity according to the follow:

- **Complexity in the logistics chain:** is the result of the alternative routes and modes through which freight can be moved from the producer to the consumer. The number of alternative solutions will easily exceed the amount that could be evaluated.
- **Complexity on the horizontal level:** This type of complexity arises from the fact that the size of the consignment is reduced as a result of the industrial demand for production from a customer order. To increase the effectiveness of the transport system, a number of consignments need to be consolidated in the vehicles. As a result, the freight in one link, e.g. in a vehicle, can consist of more a thousand consignments, with different addresses and destinations.
- **Time Complexity:** This type of complexity is generated by given time restrictions.

- ➢ Complexity in the logistics chain as well as complexity on the horizontal level could be related to dynamic complexity in both tactical and operational levels. Time complexity could be referred to dynamic complexity in operational level.

5.2.2.4. Nilsson & Waidringer 2005

In this article, three properties have been identified within the logistics areas that have significant impact on the management of logistics activities. These are *the structure property, the dynamics property,* and *the property of adaptation.*

The *structure property* is related to infrastructure in the context of logistics, and covers physical as well as information and communicational structures. The *dynamics property* is related to the processes performed on the network i.e. the flow of goods, money and information within the structure and hence the dynamics in these processes. The *property of adaptation* is related to the organization and the decision-making i.e. the management and control of the structure and the dynamics, in order to realize the processes on the network.
Furthermore, these properties have been put into three different levels of resolution in the context of logistics and then emergent behaviors or patterns in the transition between the levels have been discussed. The chosen levels are: *the individual/parts, the firm* and, *the network.*

➢ Structure property and dynamic property are obviously related to static and dynamic complexity, respectively. They could happen at all levels of the organization. Property of adaptation could be referred to both static and dynamic complexity in strategic level.

5.2.2.5. Milgate 2001

This article, has elaborated the synthesis and abstraction of supply chain complexity along three primary dimensions: uncertainty, technological intricacy, and organizational systems.

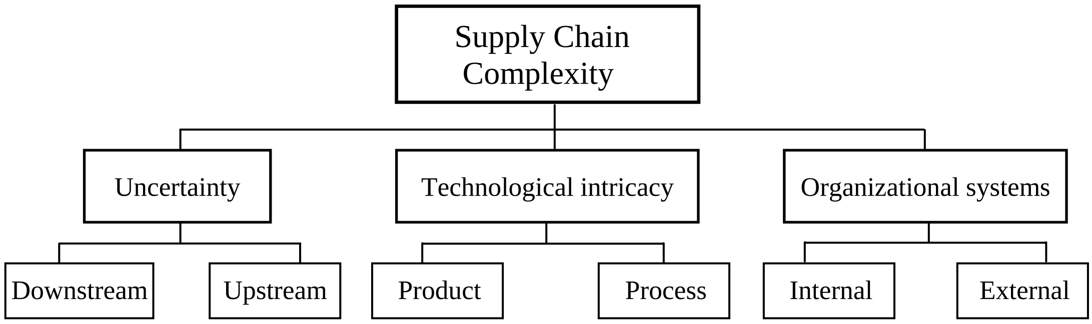


Figure 5.4 - Supply Chain Complexity

It is discoursed that uncertainty exists at every echelon in the supply chain. For example, upstream uncertainty can be manifested through late deliveries by suppliers or poor quality of the incoming materials and parts. Looking downstream, uncertainty takes the form of unforeseen demand variability, which in turn creates problems in planning, scheduling, and control that jeopardize delivery performance.
Technologies have been broadly classified based on their linkages to either the product design or process structure, both of which have been considered in assessing and managing manufacturing complexity. One major aspect of technological intricacy related specifically to the product is the number of parts needed to produce a manufactured good or a service (e.g. lines of code encrypted in software). The second major aspect of technological intricacy is related to the process. The pioneering work of Woodward (1965) identified a general process classification (i.e. small batch, mass production, and continuous flow) and linked this to a number of technical attributes. Since then, other researchers like Kotha & Orne (1989) have expanded this work and proposed three related dimensions: the level of mechanization (interface between labor and equipment), the level of systematization (degree of standardization and formal control), and the interconnection level (integration level of various process operations).
The strategy literature historically has differentiated between systems that are internal to a firm and those that provide an interface to the external business. Applying this basic delineation to supply chain management, the internal organizational systems consider both the level and form of integration between different departments within an organization. In contrast, external organizational systems focus on informational, product and service transactions and relationships with other organizations. With respect to complexity of external organizational systems, the number of suppliers is often identified as a factor contributing to the complexity of the supply chain, with potentially negative implications for plant performance.

➢ Uncertainty is related to dynamic complexity in all three levels (strategic, tactical and operational). Technological intercity could be related to both static and dynamic complexity in tactical and operational levels. Organizational systems could be referred to both static and dynamic complexity in strategic level.

5.2.2.6. Blecker & Abdelkafi 2006

For identifying and examining the origins of complexity in a mass customization system, the authors of this article have resorted to Suh's complexity theory. According to this theory, there are two kinds of complexity: Time-independent and Time-dependent.

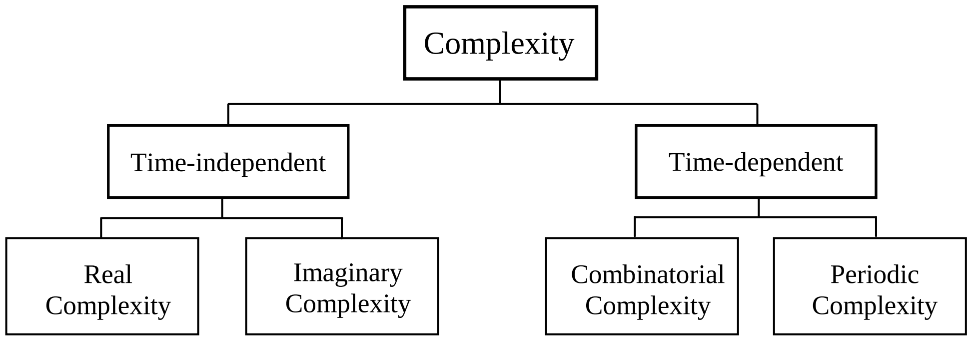


Figure 5.5 - Suh's complexity definition

Authors discuss that "Time-independent real complexity" arises when the system range is not embodied in the design range. In other words, there is an uncertainty in achieving the functional requirements with the current system design. On the other hand, "Imaginary complexity" is triggered by the lack of knowledge and understanding of the specific design.

"Combinatorial complexity" is an event-driven complexity. It arises when the system range moves away from the design range in the course of time because of the unpredictability of several future events. Suh provides the scheduling function of a job shop manufacturing system as an example for combinatorial complexity. In effect, the future scheduling is affected by decisions made earlier in the past and the system may exhibit a combinatorial complexity over time, which leads to a chaotic state or system failure. Finally, "Periodic complexity" is defined as the complexity that only exists in a finite time period; resulting in a finite and limited number of probable combinations. Thus it is desirable to prevent the system range from continuously moving away from the design range by transforming combinatorial complexity to periodic complexity.

- Time-independent complexity could be related to static complexity in strategic level and time-dependent complexity to dynamic complexity in operational level.

5.2.2.7. Gröbler et al 2006

According to this article, the kind of complexity which is addressed in business administration can be found outside and inside organizations; so the authors speak of external and internal complexity. They assume that a bi-directional influence exists between the two: external drivers of complexity force the organization to internally build-up complexity to cope with demands from the outside.

For the task of a more detailed analysis, both external and internal complexity can be split up into more concrete complexity determinants. For example, the authors have detailed internal complexity into complexity related to process configuration. On the external side, they have distinguished between complexity of products and complexity of customers.

Of course, the nature and variety of products is also a matter of internal complexity because it is a management decision, for instance, what range of products is manufactured. However, these internal complexity aspects of products are only indirectly incorporated into the model presented here. Aspects of product complexity that are addressed in the article's analysis are derived from market requirements. Thus, they are external to the organization. Nevertheless, the product range as well as the speed at which new products have to be introduced to the market affects the organization. After such requirements have been established in the marketplace, by either customer needs or by competitors, they influence internal aspects of manufacturing firms such as process configuration and improvement goals.

- Internal complexity could be referred to static complexity in all three levels (strategic, tactical and operational). External complexity could be related to both static and dynamic complexity in all three levels.

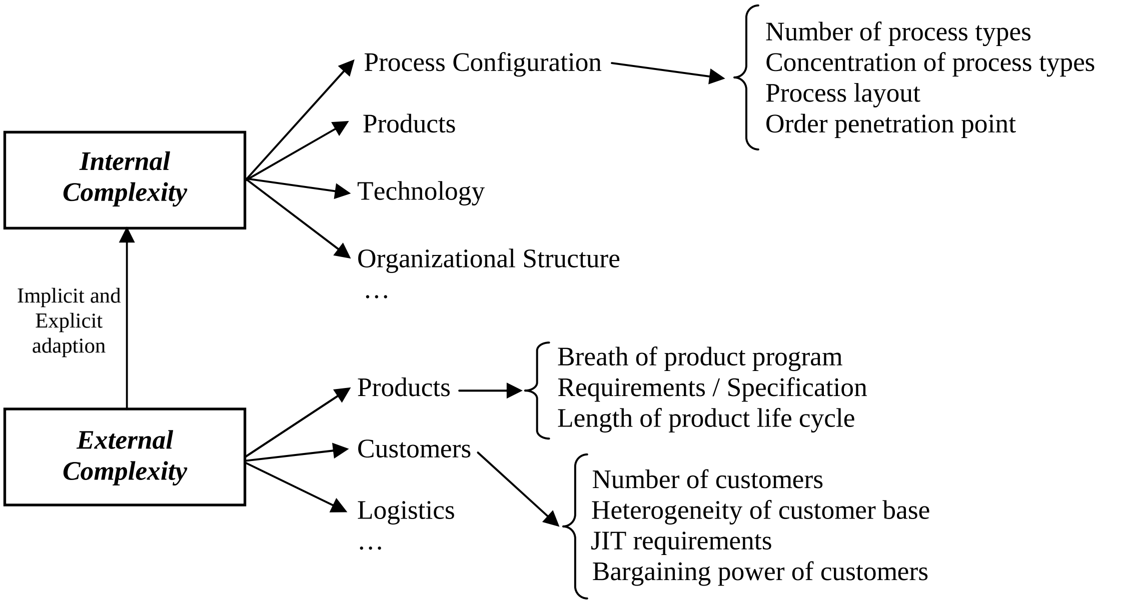
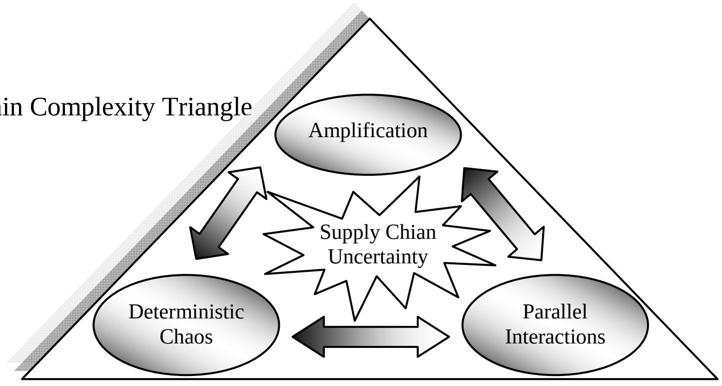


Figure 5.6 - A conceptual framework of complexity in and around manufacturing firms

5.2.2.8. Wilding 1998

According to this article, three interacting yet independent effects would seem to cause the dynamic behavior (and complexity) experienced within supply chains. These are deterministic chaos, parallel interactions and demand amplifications. The combination of these effects can significantly increase the degree of uncertainty within a supply chain system.

Figure 5.7 - Supply Chain Complexity Triangle



In this article, Chaos is defined as a periodic (the same state is never repeated twice), bounded (on successive iterations the state stays in a finite range and does not approach plus or minus infinity) dynamics in a deterministic system (there is a definite rule with no random terms governing the dynamics) with sensitivity dependence on initial conditions (two points that are initially close will drift apart as time proceeds) , and has structure in

phase space (Non-linear systems are described by multidimensional vectors. The space in which these vectors lie is called phase space (or state space)). Furthermore, it is discussed that chaos in supply chains results from decision-making processes or control systems.
The term "parallel interactions" is defined to describe interactions that occur between different channels of the same tier in a supply network. An example of parallel interactions occurs when a first tier supplier can not supply a customer. This results in re-scheduling within the customer organization resulting in the customer changing its requirements from other first tier suppliers. This results in uncertainty and complexity being generated within the supply network.
Finally, demand amplification (Bullwhip effect) role in supply chain complexity is discussed by referring to four causes of it: demand forecast updating, order batching, price fluctuations, and rationing and shortage gaming.

- Deterministic chaos, parallel interaction and demand amplification are all related to dynamic complexity in all three levels of organization.

5.2.2.9. Blecker et al 2005

The aim of this article is to provide an overview of different types of complexity drivers and their point of origin. Regarding this matter, a two dimensional approach has been used according to the following table (Table 5.1).

KEY DRIVER CATEGORIES		ORIGIN: Internal Organization	ORIGIN: Supplier-Customer Interface	ORIGIN: Dynamic Environment
	Product/ Technological Intricacy	• Heterogeneous demands • Raising product complexity • New technologies	• Non-synchronized supply chain planning and control systems • Incompatible IT systems	• Technological innovations • Changing resource requirements • Technological customer demands
	Organizational Aspects	• Process-related deficits • Structural deficits	• Different strategies • Non-harmonized decisions and actions • Supply chain bottlenecks • Information gaps • Non-harmonized processes • Supplier and customer reliability	• Development of business environments • Provisions of law • Globalization • Shortened product lifecycle
	Uncertainty	• Subjective estimations • Changing skill requirements	• Demand amplification (bullwhip) • Parallel interactions • Non-synchronized decisions and acting	• General uncertainty of future development • Economic trends • Decreasing accuracy of forecast

Table 5.1- Supply Chain Complexity Causes

- ➢ Uncertainty is related to dynamic complexity in all three levels (strategic, tactical and operational). Organizational Aspects could be referred to both static and dynamic complexity in strategic and tactical levels. Product / Technological intricacy could be related to both static and dynamic complexity in all three levels.

5.2.2.10. Lamming et al 2000

In this article, complexity is viewed from perspective of products and networks. Based on this perspective, a frame is depicted and supplemented by a survey results. The frame, as shown in the following, is a two dimensional one which connects complexity to supply network of innovative as well as functional products.

Characteristics	*Supply networks of innovative and unique products*	*Supply networks of functional products*
Higher complexity	**Complexity priority:** speed and flexibility, innovation, quality supremacy **Sharing of resources and information:** large amounts of non-strategic information enabled by IT - problematic when involving sensitive information and knowledge Example from survey: -	**Competitive priority:** cost reduction, quality sustainability, service **Sharing of resources and information:** large amounts of non-strategic information enabled by IT – generally unproblematic: may include cost breakdowns and strategic knowledge Example from survey: off-road car
Lower complexity	**Competitive priority:** speed and flexibility, innovation, quality supremacy **Sharing of resources and information:** problematic exchange of sensitive information and knowledge - IT less critical Example from survey: drugs, LED semi-conductor, communications technology	**Competitive priority:** cost (by high volume production), service **Sharing of resources and information:** generally unproblematic - may include cost and strategic knowledge - IT less Critical Example from survey: canned soft drinks, beer cans, wheel cylinders, window wipers

Table 5.2 - Revised classification of supply networks

- ➢ This framework could be affiliated to dynamic complexity in all three levels of the organization.

5.2.2.11. Vickers & Kodarin 2006

In this article, complexity drivers have been grouped into three categories:

- Configuration and Structure: the physical network of the supply chain and the organizational structure used to manage it;
- Products and Services: the portfolio of offerings managed by the supply chain; and
- Processes and Systems: the processes and systems used to manage the supply chain.

Within each of these areas, certain factors play major roles in creating complexity which have been summarized in table 5.3.

➢ Configuration and structure are related to static complexity in all three levels. Product and services as well as processes and systems could be referred to both static and dynamic complexity in all three levels of the organization.

The Drivers of Supply Chain Complexity		
Configuration and Structure	• Number of Suppliers • Number of manufacturing locations • Number of distribution channels	• Number of distribution centers • Number of ship-to locations • Number of customers
Products and Services	• Number of Products / services • Number of direct materials	• Number of shipments • Number of orders
Processes and Systems	• Supply chain processes and practices • Supply chain organization	• Manufacturing strategy • Number of legacy information systems

Table 5.3 - The Drivers of Supply Chain Complexity

5.2.2.12. Vachon & Klassen 2002

In this article, a two-by-two conceptual framework for supply chain complexity has been proposed by using the technology and information processing dimensions. Later on, the role of this framework on supply chain's delivery performance has been assessed.

		Technology	
		Process / Product (Structure)	**Management Systems (Infrastructure)**
Information Processing	**Complicatedness**	• Skills and know-how required to operate processes or to manufacture the product • Number of tasks and sub-processes • Number of parts / components • Level of interactions between parts / components • Level of decomposability of processes	• Product variety and customization • Extent of supply network • Extent of customer base • Geographical span of suppliers and customers • Number of echelons in the supply chain
	Uncertainty	• Process capability of the focal firm (quality failures) • Process capability of suppliers • Throughput time variation and stochastic set-up time	• Product scheduling changes • Late product delivery by supplier • Demand volatility

Table 5.4 - Supply Chain Complexity

➢ In this table, Complicatedness row (both structure and infrastructure) could be referred to static complexity in all three levels. Uncertainty row could be related to dynamic complexity in tactical and operational levels.

5.2.2.13. Lewis & Sheinfeld 2006

In this essay, complexity has been divided to Internal and External categories. Although, the authors have not mentioned the internal drivers of complexity in details, they have considered the external drivers as the follow:

- Increasing numbers of mergers, acquisitions and joint ventures to achieve geographic coverage and market penetration;
- Broadening supplier footprint spanning different geographic areas;
- Rising rate of new product launches to combat commoditization and meet increasingly segmented customer needs;
- Customers demanding higher delivery service levels in terms of speed, reliability and flexibility.

➢ The first two factors could be related to static complexity in strategic level and the next two ones related to dynamic complexity in all three levels of the organization.

5.2.2.14. Wildemann 2001 cited in Hellingrath 2007

Environmental drivers of complexity		
Society	***Market***	***Technology***
• Dynamics and diversity of rules and shift in values • Regulations	• Dynamics of markets • Customization of demand • Globalization	• Dynamics of technological development • Decrease in technology and product life cycles

System – related drivers of complexity			
Personnel	***Input***	***Output***	***Equipment***
• Information asymmetry • Lack of qualification • Over- specialization • Dominating individual goals	• Number of suppliers • Structure of suppliers • Number of different supply items	• Number of customers • Distribution structure • Product and variant diversity • Number of orders in relation to order volume	• Low compatibility of tools and machines • Non-compatible information systems
Organization			
• Number of hierarchic levels • Functional organization • Number of control entities		• Number of interfaces • Excessive documentation requirements	

Figure 5.8 – Sources of Supply Chain Complexity

➢ Environmental drivers reflect dynamic complexity in strategic and tactical levels and system-related drivers represent both static and dynamic complexity in all three levels.

5.2.2.15. Ratliff 2004

In this PowerPoint file, several root causes of supply chain complexity have been categorized as the follow:

1. Uncertainty: Not knowing about future events, not knowing about present status, not knowing process;

2. Variability: Requirement and/or resource changes over time;

3. Synchronization: Matching requirements and/or resources with time;

4. Unity: Dealing with indivisible products and/or resources;

5. Size: Number of actions to perform or consider for performance;

6. Speed: How quickly actions must be performed;

7. Diversity: Differences among products and/or resources.

➢ Uncertainty, variability, synchronization, unity and speed are related to dynamic complexity in all three levels. On the other hand, Size and diversity are related to static complexity in all three levels of organization.

5.2.2.16. Perona & Miragliotta 2004

In this article, classification of complexity dimensions, sources and managerial levers have been proposed. It has been discussed that the amount of physical complexity (i.e. variables and relationships among them) existing within a manufacturing or logistic system could be classified in five dimensions, each of which pertains to a specific business process (Figure 5.9).

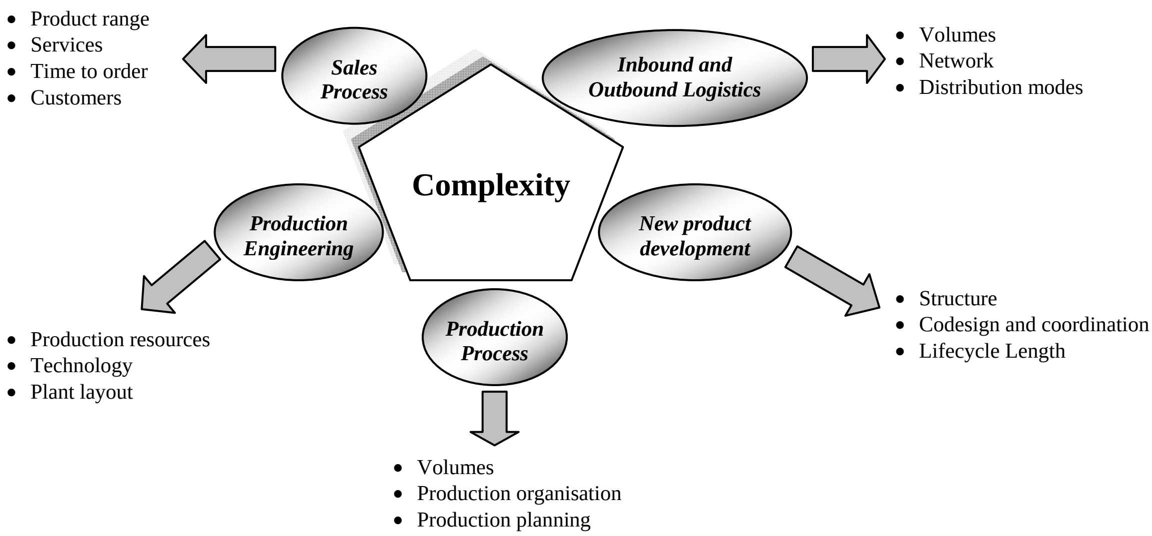


Figure 5.9 - Complexity dimensions for manufacturing or logistic systems

➢ Sales process is related to both static and dynamic complexity in all three levels. Production engineering reflects static complexity in strategic and tactical levels. Production process is referred to both static and dynamic complexity in tactical and operational levels. New product development and Inbound and outbound logistics reflect static complexity in strategic and tactical levels.

Later on, the authors have depicted a complexity model based on empirical observations. According to this model, each manufacturing or logistic system is characterized by some strategic objectives (e.g., to be a service leader, to be a fast follower, etc.), by some context variables (e.g., to belong to a small group, etc.), by its available resources (human, financial, technological, etc.) and by its attention to the various issues of complexity (generally speaking, the care put in controlling and managing variety within and without the system). What comes out of the combination of all these context factors is a certain level of *basic complexity*. This represents the standard amount of complexity which is needed, in a given environment, to reach the stated objectives given the available resources. Thus, we can expect companies that compete within the same geographical market and industry, to be affected by almost the same level of basic complexity.

Given its basic complexity level, a company can adopt some complexity reduction levers which will, in time, produce its effects by reducing the basic complexity to a lower level (*actual complexity)*. Thus, two companies that share almost the same level of basic complexity can have a much different level of actual complexity if only to implement a much different pattern of complexity reduction levers.

In turn, each company can adopt also complexity management levers, which will not reduce the actual complexity (indeed, they can as well increase it), but will reduce instead the negative impact a certain level of actual complexity can have on system's performances. Given that the impact on performances is similar to that achieved through a reduction in system's complexity; in this case the authors have defined the concept of *perceived complexity*, which is the (unattended) level of complexity leading to the observed performances.

Finally, perceived complexity, together with the context variables, determines business performances.

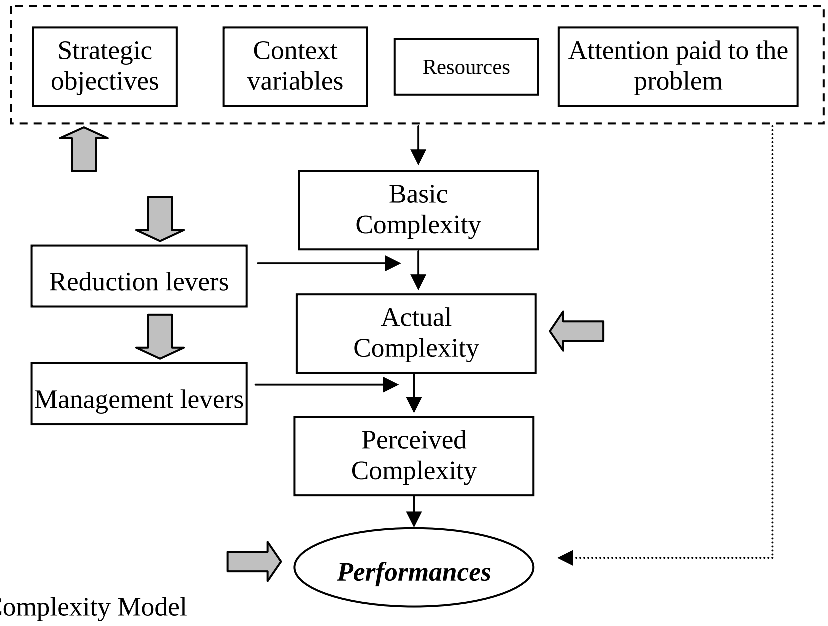


Figure 5.10 - Complexity Model

5.2.2.17. Horgan 1995

In this article, Horgan quotes 31 definitions of complexity given by Seth Lloyd, and selects some of them to illustrate the diversity:
Effective complexity: The degree of "regularity" (rather than randomness) displayed by a system.
Hierarchical complexity: The diversity displayed by different levels of a hierarchically structured system.
Grammatical complexity: The degree of universality of the language required to describe a system.
Time computational complexity: The time required for a computer to describe a system (or solve a problem).

Spatial computational complexity: The amount of computer memory required to describe a system.

- ➢ Effective, hierarchical, grammatical, and spatial complexity reflect the static complexity. Time computational complexity is referred to dynamic complexity. All these kinds of complexity may happen in all three levels of the organization.

5.2.2.18. Sivadasan et al 2002a

For sake of measuring the transferring operational complexity, as opposite of static complexity, of supplier-customer systems, two classes of operational complexity transfer have been identified: importing operational complexity and exporting operational complexity. According to this classification, shown in the follow, it may be broadly generalized that the greater the uncertainty between:

- Sales forecasts and sales orders, the greater the likelihood of importing operational complexity from customers;
- Sales orders and actual dispatch, the greater the likelihood of exporting operational complexity to customers;
- Purchasing forecasts and purchasing orders, the greater the likelihood of exporting operational complexity to suppliers;
- Purchasing orders and actual deliveries, the greater the likelihood of importing operational complexity from suppliers.

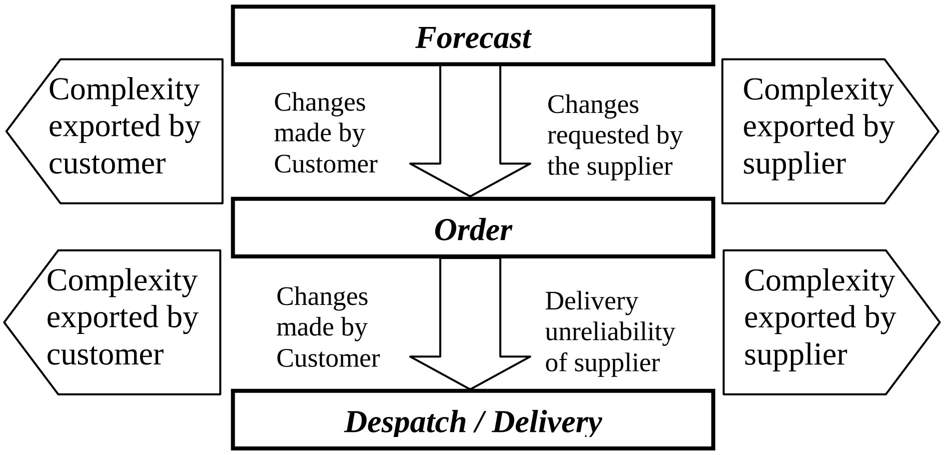


Figure 5.11 - External transfer of operational complexity

Furthermore, the authors have demonstrated that the transfer of operational complexity across the supplier-customer interfaces is affected by, and has implications on, internal organizational performance. Two classes of operational complexity transfer are identified within the internal system:

1) generating operational complexity; and
2) absorbing operational complexity.

Organizations can generate internal operational complexity through unreliable processes or procedures. Similarly, organizations can absorb uncertainty through internal flexibility, high inventories or excess capacity. These issues have been depicted in the following diagram (Figure 5.12).

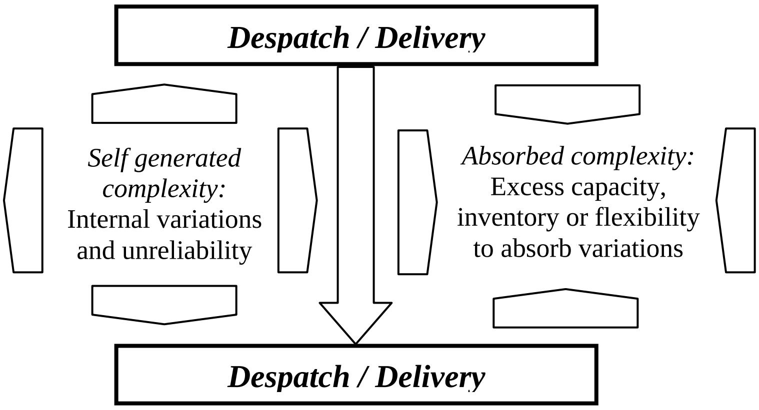


Figure 5.12 - Internal transfer of operational complexity

5.2.2.19. Anderson et al 2006

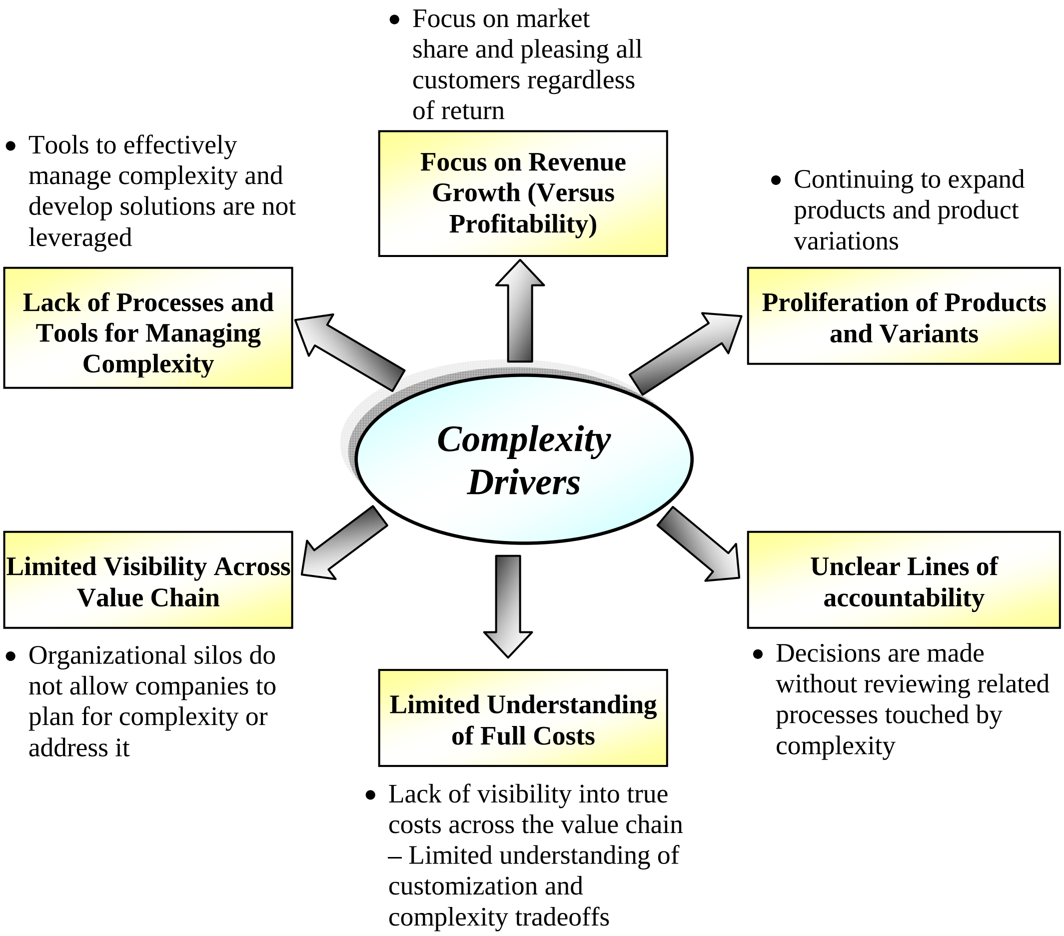


Figure 5.13 - What drives complexity?

➢ The mentioned complexity drivers could be referred to both static and dynamic complexity in strategic level.

5.2.2.20. Merali 2006

In this article, it is mentioned that the conceptualization of Information System as Complex Adaptive System (CAS) provides a framework for accommodating complexity at multiple levels of aggregation of heterogeneous agents as nested CAS addressing:

- **Societal Complexity:** Incorporating social, cultural, political and economic dimensions;
- **Collective (Group) Complexity:** Incorporating issues of coherence, communication, co-ordination and legitimization of representational and interpretive frames and relational constructs, for positioning in the dynamic landscape;
- **Individual Complexity:** Incorporating issues of selecting representational and interpretive frames and relational constructs, for positioning in the dynamic landscape;
- **Informational Complexity:** Incorporating issues of recognizing, interpreting, organizing and linking informational content from multiple diverse sources;
- **Technological Complexity:** Incorporating the issues of providing technological architectures and infrastructures to accommodate diversity, and deliver the requisite responsiveness, robustness and flexibility for the interconnected world.

➢ Social, collective, individual, and informational complexities reflect dynamic complexity in strategic and tactical levels. Technological complexity could be referred to both static and dynamic complexity in all three levels.

5.2.2.21. Becker & Dill 2007

This paper has analyzed the complexity drivers for air cargo revenue management (ACRM) and suggested approaches to handle this complexity.
It is discussed that the increased complexity is driven by several differences compared to the passenger airline business. Those complexity drivers can be clustered into supply (capacity offer) and demand (shipment, customer and market structure) based both affecting ARCM as the interfacing processes between markets demand and capacity supply.
According to the authors, this clustering helps to derive the measurements to handle the complexity, as the demand-based must be handled differently compared to the supply-based complexity drivers.

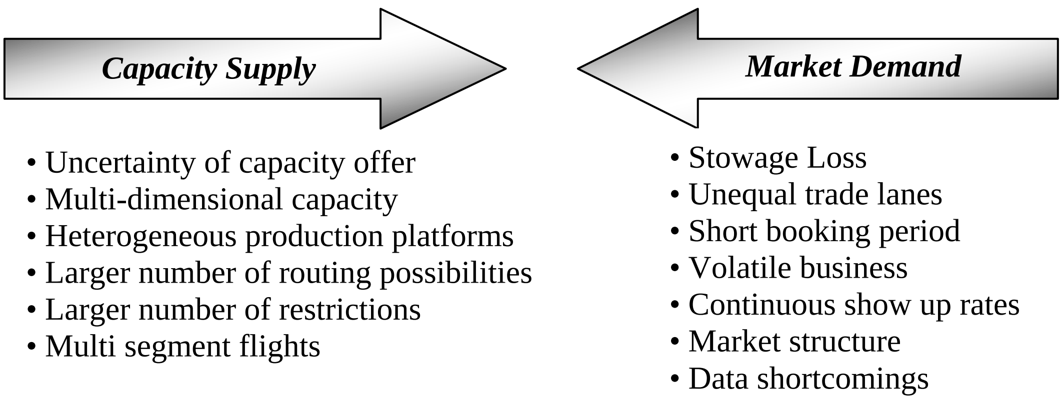


Figure 5.14 - Demand- and supply-driven complexity drivers of ACRM

➢ Both capacity supply and market demand reflect static and dynamic complexity of the organization in all three levels.

5.2.2.22. Ashmos et al 2000

According to this article, Complex adaptive systems theory offers managers and researchers a new way to look at organizational phenomena. Organizations are likely to choose one of two responses to environmental variety and complexity: complexity absorption or reduction. Based on this background, the authors have examined four dimensions of complexity absorption: complex goal systems, complex sets of strategic activities, complex patterns of interactions and relationships, and complex structures.

- **Goal Complexity:** Goal complexity is achieved when organizations pursue many different kinds of goals.
- **Strategic Complexity:** Strategic complexity is achieved when the organization simultaneously pursues a variety of strategic activities.
- **Interaction Complexity:** Interaction complexity is achieved when there are high levels of participation by multiple stakeholder groups in strategic decision making.
- **Structural Complexity:** Structural complexity is achieved when there is greater internal variety in the organization. This means that structural complexity is greater in organizations that are relatively decentralized and less formalized.

➢ Goal, strategic and interaction complexity reflect static and dynamic complexity in strategic level of the organization. Structural complexity refers to static complexity in tactical and operational levels.

5.2.2.23. Jacucci et al 2006

In this article, the authors have explored complexity and how it can, or needs to, be addressed in information systems (IS) research. Why should IS scholars take complexity seriously? There are at least three aspects which make complexity an important topic for IS research and practice:

- **Technical;**
- **Organizational; and**
- **Societal.**

First, from the technical point of view, increases in computing power, the growing number of systems and their inter-connectivity, together with increases in the speed and range of telecommunications, challenge current software development methods and practices.
Second, organizations are experiencing dramatic structural and operational transformations due to changing market demands, process reengineering, and increased workforce diversity. These require organizations to improve their responsiveness by learning quickly and reconfiguring flexibly to adapt to new competitive environments.
Third, globalization has created a flat world of interdependent organizational activities and social relations across geographical and organizational boundaries where local actions propagate to a global level with unintended side-effects.

➢ All the three mentioned aspects could be related to both static and dynamic complexity in strategic and tactical levels.

5.2.2.24. Stefanou 2006

This paper indicates complexity of accounting information systems (AIS) based on following factors:

- **Technological factors:** An example of the complex nature of modern AIS is provided by considering the emergence of new computing techniques. The adoption of distributed computing environment leads to efficient data processing but increases the complexity of Information System (IS) both on technical and human-related grounds.

- **Environmental factors:** Globalization, as a consequence of market deregulation, results in considerable competitive pressures on organizations and increases uncertainty. Under uncertain market conditions, financial managers require broad-scope accounting information for decision-making purposes, which most of the time is not available by current AIS. The web emerges as the real driving force to facilitate transactions, communication and decision making, involving trading partners across the value chain and contributing thus to AIS complexity.
- **Organizational factors:** Organizations are responding to highly competitive and changing business conditions by radically transforming the production process and organizational structure.
- **Social and ethical factors:** The importance of social and ethical issues has been acknowledged, researched and being researched in the IS discipline. However, it could be argued that issues such as the social responsibility of chief financial officers, management and financial accountants' and managers' fraud, information ownership, external and internal auditing as well as data security and integration, become more evident and important when considered in the confined context of AIS rather than in any other organizational IS, due to importance, sensitivity and discretion of financial information. Newly developed AIS, allowing remote access and transactions, require new control systems for the security of transaction databases and the integrity of financial information, a responsibility not only of the IS department's professionals, but also of financial and management accountants and managers.

➢ Technological factors could be related to dynamic complexity in strategic level. Environmental factors reflect dynamic complexity in strategic and tactical levels. Organizational factors are related to both dynamic and static complexity in all three levels. Social and ethical levels could be referred to dynamic complexity in strategic level.

5.2.2.25. Backlund 2002

By resorting to Yates' opinion (1978), this article demonstrates that complexity usually arises whenever one or more of the following five attributes are found:

- significant interactions;
- high-: number of parts, degrees of freedom, or interactions;
- nonlinearity;
- broken symmetry [. . .]; and
- non-homonymic constraints.

➢ The three initial ones reflect the static complexity and the two last ones refer to dynamic complexity in all three levels of the organization.

5.2.2.26. Sivadasan et al 2004

According to the author, complexity of a system can be described in terms of several interconnected aspects of the system; such as:

- Number of elements or sub-systems;
- Degree of order within the structure of elements or sub-systems;
- Degree of interaction or connectivity between the elements, sub-systems and the environment;

- Level of variety, in terms of the different types of elements, sub-systems and interactions;
- Degree of predictability and uncertainty within the system.

➢ All the mentioned aspects, instead of the last one reflect static complexity in all three levels of the organization. The last one represents dynamic complexity in strategic and tactical levels.

5.2.2.27. Rao & Young 1994

In this article, drivers of logistics complexity have been addressed based on three categories: Network complexity, Process complexity, and Product complexity.

- **Network complexity:** Refers to both the geographic dispersion of a firm's trading partners as well as the intensiveness of transactions with selected trading partners which can give rise to volume leveraging effects. Specific variables contributing to network complexity include:
  - Number of supplying and distribution trading partners;
  - Number of countries involved in the supply chain;
  - Number of continents (or regions) involved in the supply chain;
  - Stock-keeping unit (SKU) and origin/destination (OD) pair permutations.

- **Process Complexity:** This driver refers to time and task compression (or lack thereof) in the supply chain. When the logistics process is complicated by the number of tasks which have to be performed and co-coordinated within a short span of time, such as in JIT environments, numerous cost/service tradeoffs and functional interdependency arise in operations. Key variables useful in measuring this driver include:
  - Time sensitivity of transactions within the supply chain;
  - Manufacturing cycle times for components and products;
  - Order cycle times for customer orders.

- **Product Complexity:** This driver refers to the special circumstances required by products and materials due to the complexity of the environment (temperature, humidity, etc.) governing their transportation, storage and handling. Hazardous materials, goods with short shelf lives or those are susceptible to damage, and other physical properties make logistics more difficult in international trade.

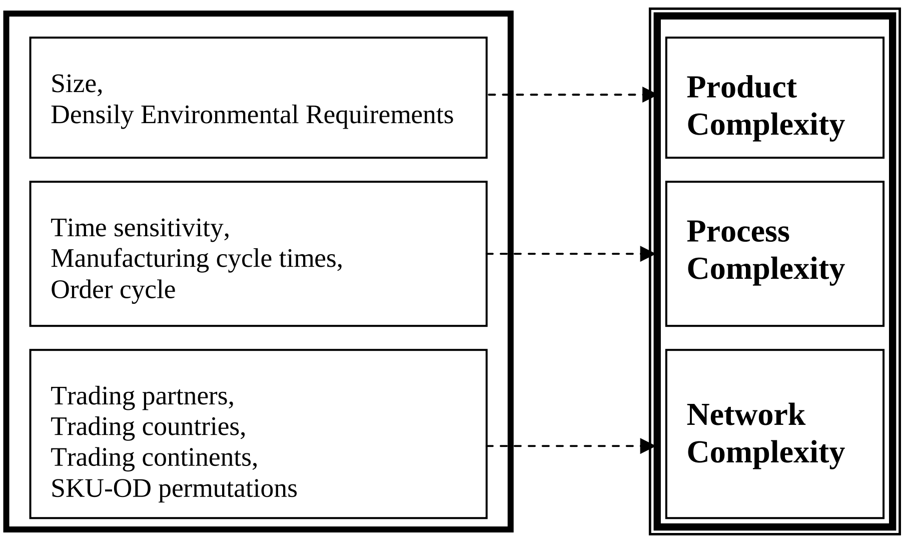


Figure 5.15 - Drivers in the Key Factors Interaction Model

➢ Product complexity reflects static complexity in strategic and tactical levels. Process complexity could be referred to dynamic complexity in all three levels. Final, Network complexity is related to both static and dynamic complexity in tactical and operational levels.

5.2.2.28. Raphel 2005

Based on this case study, there were three main types of complexity in Hewlett-Packard Company's North America Consumer Computing (NACC) division:

- **Component complexity** (number of components, number of suppliers, etc.);
- **SKU complexity** (configurations, factory allocations, etc.);
- **Retailer complexity** (number of retailers, forecasting, terms of sale, etc.

➢ Component complexity and SKU complexity are related to static complexity in strategic and tactical levels. Retailer complexity could be referred to both static and dynamic complexity in all three levels.

***5.2.2.29.* Tomiyama et al 2007**

The authors have identified two different types of complexity in multidisciplinary problems, ‘complexity by design’ and the ‘intrinsic complexity of multi-disciplinarity’. These two types of complexity come from interactions among design parameters and physical phenomena, which sometimes unexpectedly, cause undesired phenomena that result in design failures

➢ These two types of complexity could be referred to static complexity in strategic and tactical levels.

5.2.2.30. Christopher 2008

In this PowerPoint file, Martin Christopher has categorized supply chain complexity according to the following:

- Network complexity: many nodes and links
- Process complexity: many steps
- Offer complexity: wide a range
- Product complexity: many unique components
- Customer complexity: many service options
- Supplier complexity: many suppliers

➢ These classes reflect the static complexity in all three levels of the organization.

5.2.2.31. Rescher 1997

Modes of Complexity

Epistemic Modes

Formulaic Complexity

1. Descriptive Complexity: Length of the account that must be given to provide an adequate description of the system at issue.
2. Generative Complexity: Length of the set of instruction that must be given to provide a recipe for producing the system at issue.
3. Computational Complexity: Amount of time and effort involved in resolving a problem.

Ontological Modes

Compositional Complexity

1. Constitutional Complexity: Number of constituent elements or components. (Compare, for example, tricycles, automobiles and jet aircraft.)
2. Taxonomical Complexity (Heterogeneity): Variety of constituent elements: number of different kinds of components in their physical configurations. (Consider again of the preceding example. Or compare the domain of physical elements which come in some 100-plus types with that of insects of which there are many thousands of species.)

Structural Complexity

3. Organizational Complexity: Variety of different possible ways of arranging components in different modes of interrelationship. (Compare jigsaw puzzles with their two-dimensional arrangements with LEGO blocks with their three-dimensional modes of assembly.)
4. Hierarchical Complexity: Elaborateness of subordination relationships in the modes of inclusion and subsumption. Organizational desegregation into sub-systems. (For example: particles, atoms, molecules, macro-level physical objects, stars and planets, galaxies, galactic clusters, etc.; or again: molecules, cell organs, organisms, colonies, etc.)Here the higher-order units are, for this very reason, always more complex than the lower-order ones.

Functional Complexity

5. Operational Complexity: Variety of modes of operation or type of functioning. (Primates have a more complex lifestyle than mollusks. The processual structure of chess is vastly more elaborate than that of checkers.)
6. Nomic Complexity: Elaborateness and intricacy of the laws governing the phenomena at issue. (Steam engines are more complex in this manner than pulleys.)

- Descriptive and Generative complexity are related to static complexity in all three levels. Computational complexity is referred to dynamic complexity.
- Constitutional and Taxonomical complexity are related to static complexity in strategic and tactical levels.
- Organizational and Hierarchical complexity are static complexity in all three levels.
- Operational complexity is related to both static and dynamic complexity in tactical and operational levels. Nomic complexity reflects dynamic complexity in strategic level.

5.2.2.32. Zhou 2002

In this article, the author has classified the supply chain complexity based on four aspects: Technological Complexity, Organizational Complexity, Environmental Complexity and Output Complexity.

Type of Complexity			*Influence factors and/or Examples*
Technological Complexity			Product and process complexity
	Product design complexity		Number of product families, number of products in each product family, number of components in each product, component commonality, standardization, modularity, product decomposability and so on.
	Process design complexity		Number, type, technological intricacy degree of processes and their mutual linkups
		Production process design complexity	Number of production stages, number of parallel processes, continuity of processes, etc.
		Logistic process design complexity	Inventory locations and sizes, transport modes and costs, geographical distances between supply chain members, distance from customers, plant internal layout, etc.
Organizational complexity			Number of layers, number of departments, control structure, interactive patterns between departments, etc.
	Physical network complexity		Numbers and locations of supply chain members, suppliers and customers, conditions of traffic and transport and so on.
	Virtual network complexity		Application of information and communication techniques (ICT), frequency and speed of information exchange, degree of information sharing and so on.
	Planning and control complexity		Centralization and decentralization of decision-making, planning and control protocols and procedures, application of decision support software, etc.
Environmental Complexity			Uncertainty of process inputs, noise, failure, etc.
	Marketplace complexity		Number of market segments; competition patterns; cultural, institutional and geographical dispersion of market; demand forecast unpredictability and so on.
	Unexpected events		Unplanned emergency order changes, failures and quality defects in material supply, machine breakdown, absenteeism, natural disasters and so on.
Output Complexity			Unpredictable variations of practical performance from plan or expectation. For example: deviation of practical production quantity and completion time from schedule, defectiveness in product quality, failure to hit the targeted service level and so on.

Table 5.5 - A Classification of supply chain complexity

- Technological complexity reflects static complexity in all three levels of the organization.
- Physical network complexity represents static complexity in strategic and tactical levels. Virtual network complexity and planning and control complexity are referred to dynamic complexity in all three levels.
- Marketplace complexity reflects static and dynamic complexity in strategic and tactical levels. Unexpected events are related to dynamic complexity in tactical and operational levels.
- Output complexity reflects dynamic complexity in operational level.

5.3. Complexity Measurement / Calculation

5.3.1. Background

Next step to study complexity of the value chain (supply chain) is measurement. Measurement is the estimation of the magnitude of some attribute of an object relative to a unit of measurement.
Metrology is the scientific study of measurement. In measurement theory, a measurement is an observation that reduces an uncertainty expressed as a quantity. As a verb, measurement is making such observations (Wikipedia).
To understand the importance of measurement we need to take a tip from Lord Kelvin:
"When you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, our knowledge is of a meager and unsatisfactory kind".
In general, complexity classes identified in the previous step need to be evaluated to calculate the classes' impact on overall complexity. This step can be viewed as a decision support tool for predicting complexity impact.

Generally, the idea of a measure for complexity is some procedure that maps any system to a number, where systems with the highest complexity have the highest (or lowest) numbers.
Some systems, those that we call complex systems, are inherently unpredictable in the long term, and will always be. This is a quality of complex systems in general, and it probably explains why it is difficult to define measures of complexity, and why the use of complexity measures will always have limitations (Johnson 2006).
Johnson (ibid) adds that intuitively, one feels that the more complex a system is, the more risky it will be in terms of failure and the cost of failure. A good measure of complexity would surely be very helpful in managing risk.
Complexity hinders a company's ability to react to change by reconfiguring its products, processes, or organizational structure. So, a method for measuring complexity could also measure the agility of the system (Arteta & Giachetti 2004).

5.3.2. Literature review

Tools and methods of complexity measurement are not in the scope of this thesis. Nevertheless, a review of complexity measuring methods would be beneficial.
Edmonds (1999), in his Ph.D. thesis, gives an appendix in which he has explained and compiled a list of approaches for measuring complexity (Table 5.6).
The main lesson to be gained from Edmond's list is that there is no single measure of complexity (Johnson 2006).

In supply chain and manufacturing contexts, several measuring methods could be classified based on merging holistic measuring frames of Blecker et al (2005) and ElMaraghy et al (2005).
Four major categories can be defined to classify different complexity measurement approaches: performance maps, entropic approach, heuristic approaches and indices, and miscellaneous complexity measures.

(1) ***Performance maps***

The first category contains all approaches which are trying to map a supply chain's complexity by analyzing the system's performance or its flexibility (e.g. Beamon 1999; Sethi & Sethi 1990; Das 1996; Gupta & Goyal 1989). The basic idea is to somehow map the direct connection between a system's complexity and its flexibility and performance.

Measures of Complexity	
Abstract computational complexity	Algorithmic information complexity
Arithmetic complexity	Bennett's logical depth
Cognitive complexity	Connectivity
Cyclomatic number	Descriptive/Interpretative Complexity
Dimension of Attractor	Ease of Decomposition
Economic Complexity	Entropy
Goodman's Complexity	Horn Complexity
Information, Information Gain in Hierarchically Approximation and Scaling	Irreducibility
Kemeny's Complexity	Length of Proof
Logical Complexity/Arithmetic Hierarchy	Loop Complexity
Low Probability	Minimum Number of Sub Groups
Minimum Size	Mutual Information
Network Complexity	Number of Axioms
Number of Dimensions	Number of Inequivalent Descriptions
Number of Internal Relations	Number of Spanning Trees
Number of States in a Finite Automata	Number of Symbols
Number of Variables	Organised/Disorganised Complexity
Shannon Information	Simplicity
Size, Size of Grammar, Size of matrix	Sober's Minimum Extra Information
Sophistication	Stochastic Complexity
Syntactic Depth	Tabular Complexity
Thermodynamic Depth	Time and Space Computational Complexity
Variety	

Table 5.6 – Measures of complexity (Source: Edmond 1999)

(2) Entropic Approach

In this category all approaches are grouped, which are somehow using entropy based measures to identify and analyze a supply chains complexity (Frizelle & Woodcock 1995; Sivadasan et al 2002a; Efstathiou et al 2002; Bar-Yam 2004).
In thermodynamic systems, entropy measures the disorganization of the state of the matter. For example, in a gas the state or position of the molecules is uncertain whereas in a solid the position of the molecules is less uncertain. The gas is said to have higher entropy than the solid.
It was Shannon and Weaver (1949), who developed a measure of information, which has the same mathematical form as the entropy measure used in thermodynamics. Entropy has many interpretations. The prevalent interpretation is that entropy measures the amount of information necessary to specify the state of the system. A more complex system, for example having more sub-systems, more relationships, and nonlinear relationships, would

require more information to exactly specify the state at any specific instance of time (Arteta & Giachetti 2004).
A chaos-theoretic complexity measurement method proposed by Deshmukh (1993) concerns the dynamic part of complexity, which is equivalent to operational complexity. This method measures complexity in terms of the rate at which a system loses information per period.
Sivadasan et al (2006) have worked on measuring the operational complexity of a supplier–customer system. They demonstrate that this complexity and hence the amount of information required to describe the state of the system, can vary with the volatility of customer demands, reliability of material supply, predictability of internal performance, and the effectiveness of the management and control policies in place.
Efstathiou et al (2002) have used a web-based expert system and entropic measure to assess and monitor complexity of manufacturing systems.
Yu & Efstathiou (2000) present an entropic complexity measure to indicate the effect of modification on the manufacturing network.
In logistics systems, Lumsedn et al (1998) and Waidringer (2001, p.62) explain entropic approach by using algorithmic complexity.

(3) Heuristic Approaches and Indices

A third approach to quantify supply chain complexity uses heuristics and indices.
Heuristics is used for a method that often rapidly leads to a solution that is usually reasonably close to the best possible answer. Heuristics are "rules of thumb", educated guesses, intuitive judgments or simply *common sense* (Wikipedia).
As an example of heuristic approach in manufacturing context, Kim (1999) found that in lean manufacturing, the system complexity, as affected by increased product variety, is much less than in an equivalent mass production system. He proposed a series of system complexity metrics based on a complexity model developed using systems theory. These measures are: 1) Relationships between system components (number of flow paths, number of crossings in the flow paths, total travel distance by a part, and number of combinations of product and machine match), and 2) Elementary system components (number of elementary system components and inventory level).
According to Wu et al (2007), Complexity index measures were developed originally to measure complexity of a manufacturing system, which can be viewed as comprising two parts: a structural and an operational part.
The structural complexity index measures complexity of the system configuration, while the operational complexity index measures operational (dynamical) aspects when the system is running. Based upon the theory, methodologies for analyzing the operational complexity (Calinescu et al 2000; Sivadasan et al 2002b; Frizelle & Woodcock 1995) as well as structural complexity (Degtiarev 2000) have been developed.

ElMaraghy & Urbanic (2003) have exploited operational complexity index to measure manufacturing operational complexity. This index highlights the differences in complexity (hence skill level) as a result of the diversity of information and product volume. The operational complexity index is the measurable that needs to be used in a human performance model.
ElMaraghy and Urbanic (ibid), have also designed a new coding system for classifying and measuring the time-independent complexity of the major components of manufacturing systems.

(4) Miscellaneous Complexity Measures

Beneath of three major classes, further measuring approaches have been also developed like Kolmogorov complexity (Kolmogorov 1965), effective complexity (Gell-Mann & Lloyd 2003), specified process analyses (Raufeisen 2003), and structural exploration methods (Hartmann 1997; Ernst & Kamrad 2000; Scherf 2003).
Mc Carthy & Tan (2000) and Meepetchdee & Shah (2007) have developed some complexity measures based on fitness landscape.

In logistics context, Lumsden et al (1998); Meepetchdee & Shah (ibid) and Waidringer (2001) have introduced a complexity measure by using degree of connectivity within the logistical network (Topologic complexity). The authors argue that this measurement is more appropriate for quantifying logistical network complexity because this view of complexity can explicitly reveal the cost of complexity.
Other complexity measures in logistics context are: Metric complexity (Lumden et al ibid), Cognitive complexity (Waidringer ibid), an algorithm to measure the outbound transportation complexity (Lumsden & Eftekhar 2007), etc.

5.4. Complexity Modeling

5.4.1. Background

Reacting to a complex environment, however, necessitates having mental models of that environment, and often even engaging in internal simulations to test and update them.
Repeated runs of the model reveal collective states or patterns of behavior as they emerge from the interactions of entities over time (Gershenson 2007).
It is difficult to understand complex systems and make changes to globally improve their performance without a model of the system.
In science, models should ideally be as simple as possible, and predict as much as possible. These models will provide a better understanding of a phenomenon than complicated models. Therefore, a good model requires a good Representation. The "elegance" of the model will depend very much on the metaphors used to speak about the system. If the model turns out to be cumbersome, the Representation should be revised (Shalizi 2001; Lyons et al 2003).
It should be borne in mind that modeling in practice has limitations. As Edmonds (1996) demonstrates, although it may be hard to prove practical limits to modeling any specific problem, there are many general practical limitations:

1) Finiteness
It seems that we (us and our tools) are part of a finite universe, and are thus also finite. Any model we make, use or understand will also be finite. Quite apart from this, our formal communications (written articles) are definitely finite. Thus any *practically* useful model that we want to share will also be finite.
2) Limited computational resources
As well as limited memory, we also have a limited time to do the computations in. It has been calculated that quantum mechanics imposes a limit of bits/gram/sec on the amount of information that can be computed by each gram of matter per second. Thus problems which take undue computational time come up against a fairly fundamental computational limit, even if they are theoretically computable.
3) Complexity
Computational Complexity is concerned with the computational resources required, once the program is provided. It does not take into account the difficulty of writing the program in the first place.
More fundamental is "analytic complexity". This is the difficulty of analyzing (producing a top-down model) of something, given a synthetic (bottom-up) model. Given that our analytic capabilities will always be limited, such complexity will always be a practical barrier to us.
4) Context
Not all truth can be expressed in a form irrespective of context. The very identity of some things (e.g. society) is inextricably linked to context. Thus we will have to be satisfied that, for at least some truths, it will not be practical to try and express them in a very general context and hence acquire the 'hardness' of more "analytic" truths (like "all bachelors are men"). It is true that we can laboriously express larger and larger meta-contexts encompassing sub-contexts, but this will involve the construction of more and more expressive languages and require disproportionately more computational power - this will make this sort of endeavor impractical, beyond a certain level.
Choosing an appropriately restricted context is one of the most powerful means at our disposal for coping with otherwise intractable situations.

According to Lyons et al (2003), although many models adopt a relatively static view of the world (consistent with a deterministic, positivist view of the world), complex systems models highlight the dynamics of change (like system dynamics, agent-based models, evolutionary game theory and so on).
Equilibrium models which imply predetermined and forecastable futures or predict a ‘correct strategy’ are misleading.
McMillan (2002) presents a comparison between classical science models and complexity science models in organizational context.

Classical Science Model	Complexity Science Model
Linear	Non linear
Hierarchical	Non hierarchical
Reductionist	Holistic
Controlling	Self Organizing
Inflexible	Flexible
Uniform	Diverse
Centralized	Networked

Table5.7 – Classical Science Model vs. Complexity Science Model (Source: McMillan 2002)

Merali (2006) states that the manner in which modeling is deployed in the classical Information System paradigm is fundamentally different from the way in which it is used in the science of complexity. In the former, models are developed from definitions of the system. In the latter, models are arguably the specification of the system that emerges from the interactions of its specified components.
The most popular simulation methods are based on agent-based models deploying the logic of Boolean networks, cellular automata and genetic algorithms.

5.4.2. Supply chain modeling

Li et al. (2002 cited in Priya Datta 2007) state that the main motivations for supply chain modeling are:
1) Capturing supply chain complexity by better understanding and uniform representation of the supply chain;
2) Design supply chain processes to manage supply chain interdependencies;
3) Establish the vision to be shared by supply chain partners, and provide the basis for Internet-enabled supply chain coordination and integration;
4) Reduce supply chain dynamics at supply chain design phases.

The significance of supply chain modeling lies in capturing supply chain complexity by better understanding and uniform representation of the supply chain.
Modeling of supply networks is essential for robust strategy designs and understanding the dynamic behavior of supply network structures (Forrester 1961; Sterman, 2000).

According to Min & Zhou (2002 cited in Surana et al 2005) the individual models in supply chains can be categorized into four classes:
1) Deterministic: single objective and multiple objective models;
2) Stochastic: optimal control theoretic and dynamic programming models;

3) Hybrid: with elements of both deterministic and stochastic models and include inventory theoretic and simulations models;
4) IT-driven: models that aim to integrate and coordinate various phases of supply-chain planning on a real-time bases using application software, like ERP.

Generally, “Mathematical programming techniques” and “Simulation” have been two approaches for the analysis and study of the supply-chain models. Mathematical programming mainly takes into consideration static aspects of the supply chain.
Simulation, on the other hand, studies dynamics in supply chains and generally proceeds based on ‘system dynamics’ and ‘agent-based’ methodologies.
In this section, these two approaches are briefly explained:

5.4.2.1. Mathematical programming technique

Riddalls et al (2000) have done a review of the various mathematical methods used to model and analyze supply chains and have categorized them as continuous time differential equation models, discrete time differential equation models, and operational research techniques. They observed that differential methods are suited to different problems. According to them, OR tools have their place at a tactical level in the design of supply chains. They concluded that, while OR techniques are useful in providing solutions to local tactical problems, the impact of these solutions on the global behavior of the whole supply chain can only be assessed using dynamic simulation.
Porter & Taylor (1972 cited in Pathak & Biswas 2003), and several other researchers like Bradshaw & Daintith (1976 cited in Pathak & Biswas ibid); Bums & Sivazlian (1978 cited in Pathak & Biswas ibid) used discrete time differential equations based modeling approaches for modeling a supply chain.

5.4.2.2. Simulation

According to Lyons et al (2003), the dynamic nature of complex systems such as supply chains requires techniques which model it properly.
Qualitative phenomena like demand amplification can only be investigated and hence combated by methods based on the dynamics of the system. Further, implications of strategic design on supply chain performance can only be discovered by using broad-brush simulations based on the dynamics of the system.
Gilbert & Troitzsch (2005 cited in Johnson 2006) write that simulation is used to obtain a better understanding of some features of systems, to predict the behaviors of systems, to develop new tools to substitute for human capabilities, for entertainment, and to assist discovery and formulation of system properties.
Simulation requires a model of the system, comprised of ways of representing the states of the system, ways of representing transition rules between states, and a computer implementation of these. The model requires data in terms of the initial conditions and parameters relating to the rules.
According to Chatfield et al (2007), simulation modeling provides an important tool for understanding supply chain behavior and can give the information necessary to make informed decisions regarding supply chain design and management.
Pathak & Biswas (2003) have introduced a multi-paradigm simulator for simulating complex adaptive supply chain networks. Ho & Cao (1991 cited in Pathak & Biswas 2003) have represented and analyzed supply chains using discrete event simulation (DES) models.

Agent-based simulation has recently received great attention. The representation of systems as sets of autonomous units that perform actions and interact according to a set of defined rules or behavior is an attractive approach for modeling (Chatfield et al 2007).
In the following, a brief history of development of simulation approaches is depicted.

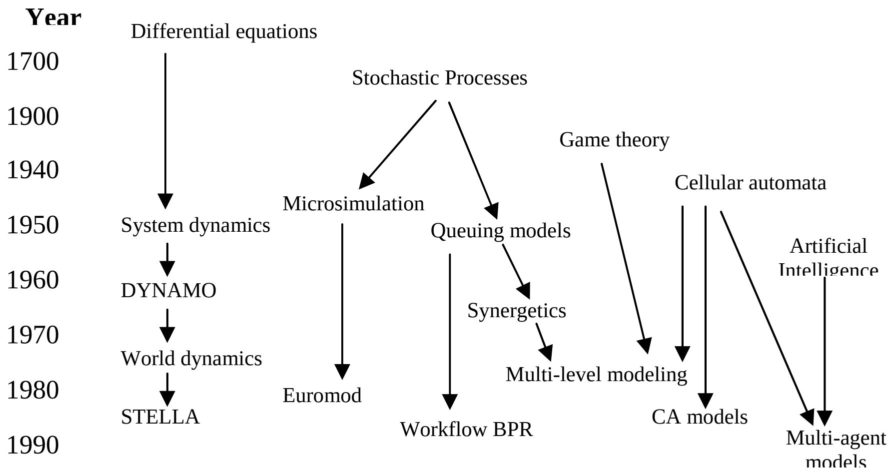


Figure 5.16 – The development of contemporary approaches to simulation (Source: Troitzsch 1997)

5.4.3. Complexity modeling approaches

There are several approaches for modeling a system's complexity. In table 5.8 some approaches are mentioned. In this thesis, just agent-based modeling is explained (in chapter 6). Other modeling methods are out of the scope of this thesis.

Author	Year	Type of Model
Mason-Jones & Towill (cited in Blecker et al 2005)	1998	Supply chain Uncertainty Cycle
Puhl	1999	Closed loop complexity model
Choi et al	2001	Complex adaptive systems
Li et al	2002	Co-ordination approach
Bolin & Hulten	2002	Supply Chain Information Exchange Complexity Model
Wu et al	2002	Simulation of supply chain complexity in manufacturing industry
Scherf	2003	Mathematic Complexity Model
Pathak & Biswas	2003	A multi-paradigm simulator for simulating complex adaptive supply chain networks
Jania (cited in Blecker et al 2005)	2004	Integrated model of Product and Structure
Perona & Miraglotta	2004	3 level & 5 dimension complexity model
Blackhurst et al	2005	-Network based approaches -Product Chain Decision Model
Turner & Williams	2005	Discrete-event simulation
Gábor	2006	Algorithms models
Priya Datta	2007	Evolutionary and self-organizing models
Kitto	2007	- Relational modeling - Quantum theories as models of complexity
Agent- based models are explained in chapter 6		

Table 5.8 – Some Complexity Modeling Approaches

5.5. Complexity Simplification

After identification, classification, measurement and modeling of complexity, it is essential that some decisions about complexity reduction be taken. It is discussed that complexity is not essentially an unpleasant phenomenon. As we are in the edge of chaos, as well as edge of order, some complexity in the system is requisite. The value-adding complexity would lead to innovation in the system. It is also a tool for competing with competitors. That is why we must validate the amount of complexity in the system (supply chain).

Simplification is reduction of non-value adding complexity in a continuous and ever task. According to Karlsson (2006), "*If we agree that 99% is sufficient, then:*

Nine words are incorrectly spelled at each side of a newspaper; almost four times a year we will not get our daily newspaper; we should be without electricity, water or heating about fifteen minutes each year; at least 8500 prescriptions should be incorrect each year, about 23700 transfers should each day be made to wrong accounts, drinking water in the water pipe system should be unstable about one hour each month".

In most decision making processes, ability of coping with complexity is a fundamental issue and influences the quality of the decisions in problem solving (Ghasem-Aghaee & Ören 2007).

Accordin to Nilsson (2004) complexity is often derived from an interpretation of logistics systems as being difficult to understand since these systems consist of a great number of parts, relationships and flows, i.e. they should be heavily reduced and simplified in order to be dealt with.

5.5.1. Background

Accordin to Heylighen et al (2005), until the early 20th century, classical mechanics, as first formulated by Newton and further developed by Laplace and others, was seen as the foundation for science as a whole. It was expected that the observations made by other sciences would sooner or later be reduced to the laws of mechanics. Although that never happened, other disciplines, such as biology, psychology or economics, did adopt a general *mechanistic* or *Newtonian* methodology and world view. This influence was so great, that most people with a basic notion of science still implicitly equate "scientific thinking" with "Newtonian thinking". The reason for this pervasive influence is that the mechanistic paradigm is compelling by its simplicity, coherence and apparent completeness.

The logic behind Newtonian science is easy to formulate, although its implications are subtle. Its best known principle, which was formulated by the philosopher-scientist Descartes well before Newton, is that of *analysis* or *reductionism*: "to understand any complex phenomenon, you need to take it apart, i.e. reduce it to its individual components. If these are still complex, you need to take your analysis one step further, and look at their components".

In essence, the philosophy of Newtonian science is one of *simplicity*: "the complexity of the world is only apparent; to deal with it you need to analyze phenomena into their simplest components. Once you have done that, their evolution will turn out to be perfectly regular, reversible and predictable, while the knowledge you gained will merely be a reflection of that pre-existing order".

Accoding to Johnson (2006), in engineering design it is usually considered desirable to reduce the number of parts in a system, thereby making it less complex and usually more reliable. Examples include integrating functionality into computer chips so that the overall component count for products reduces, with "less parts to go wrong".

Can this approach be applied to complex systems? Although simplifying systems can be advantageous, to work properly, systems have to satisfy Ashby's *Law of Requisite Variety.* This can be summarized as "for appropriate regulation, the variety in the regulator must be equal to or greater than the variety in the system being regulated. In the other words, if the variety within a system be greater; then its ability to reduce variety in its environment through regulation would be greater".
Only variety (in the regulator) can destroy variety (in the system being regulated). In other words, there is a limit to which systems can be simplified, and if control models be over-simplified, they cannot work.
The KISS (Keep It Simple Stupid) approach is, of course, to be used whenever possible, but one should bear in mind that complex systems are complex, and oversimplifying may destroy them; or produce models that severely misrepresent the original system. Oversimplification can increase risk rather than decrease it (Johnson 2006).

As Einstein is supposed to have said when asked how complex a theory should be: "Everything should be made as simple as possible, but not simpler".

According to Allen (2001), there are four assumptions used to reduce complexity to simplicity:
1) That we can define a boundary between the part of the world that we want to "understand" and the rest. In other words, we assume first that there is a "System" and an "Environment".
2) That we have rules for the classification of objects that lead to a relevant taxonomy for the system components, which will enable us to understand what is going on. This is often decided entirely intuitively.
3) The third assumption concerns the individual entities that underlie our system components. These entities may be called "agents" and may be particles, molecules, genes, organs, organisms, species, people, firms, etc. The assumption is that agents of a given type are either all identical to each other and to the average, or have a diversity that is at all times distributed "normally" around the average.
4) That the individual behavior of sub-components can be described by average interaction parameters.

As Johnson (2006) demonstrates, managing complex systems involves managing their system trajectories in a changing environment, when the long-term future is unknown. By using the new tools of complexity science, it may be possible to understand better the nature of the trajectories, and take policy decisions that keep systems in relatively safe regions. However, he suggests that the natural place for most human systems is at the edge of chaos. Thus, trajectory management will involve a trade-off between safety and necessary innovation and change.

Crichton (2005) states: "complex systems can not be controlled (some elements in a complex system can be controlled, but not the system as a whole). A complex system demonstrates sensitivity to initial conditions. You can get one result on one day, but the identical interaction the next day may yield a different result. We cannot know with certainty how the system will respond. When we interact with a complex system, we may provoke downstream consequences that emerge weeks or even years later. We must always be watchful for delayed and untoward consequences".
According to Crichton (ibid) there are people who have investigated complex systems management, and know how to do it; but it demands humility. He adds: "along with humility, managing complex systems also demands the ability to admit we are wrong, and to change course. If you manage a complex system you will frequently, if not always, be

wrong. You have to backtrack. You have to acknowledge error. And one other thing: If we want to manage complexity, we must eliminate fear. Fear may draw a television audience. It may generate cash for an advocacy group. It may support the legal profession. But fear paralyzes us. It freezes us. And we need to be flexible in our responses, as we move into a new era of managing complexity".

5.5.2. A systematic approach to supply chain complexity reduction

In this section, a systematic approach to supply chain simplification is introduced. In this regard, at first a framework for detection of all complexity roots is depicted (figure 5.17) and then some remedies for complexity roots are suggested.

According to figure 5.17 and table 5.9, supply chain complexity is addressed in four perspectives: Intra, inter, outer and intangible. Furthermore, intra, inter and outer perspectives contain qualitative causes or quantitative ones.

The terms "intra, inter and outer" depend on eyes of its beholder. In micro level they could be related to agents, entities and processes of a work station or production line and in macro level to a company or whole of a supply chain.

Intra, inter and outer complexity reflect complicatedness interpretation of complexity. "Intangible complexity" here is referred to complexity of a complex system. It is invisible hand of complexity which is vindicated by themes of science of complexity. In the other words, it is interpreted as arisen complexity by emergence and evolution of the system.

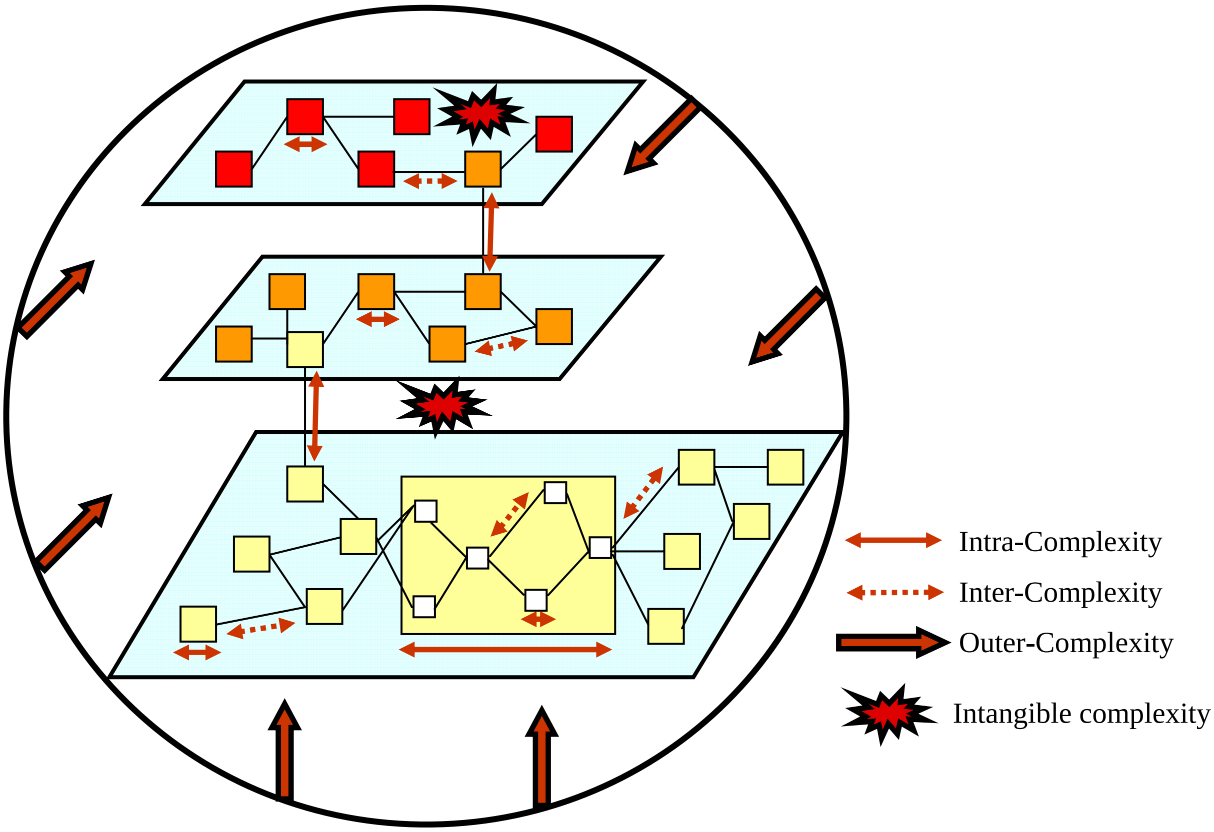


Figure 5.17 – Frame of supply chain complexity

In the follow, based on the mentioned frame, root causes of complexity are detected. Later, some hints for simplification are suggested.

<table>
<tr><th rowspan="2"></th><th rowspan="2"></th><th colspan="2">Root causes of complexity</th></tr>
<tr><th>Qualitative</th><th>Quantitative</th></tr>
<tr><td rowspan="4">Perspective</td><td>Intra-Complexity</td><td>Human-based:
- Culture
- Language
- Increased customers expectations
- Changing skill requirements
- Over specialization

Operation & Process-based:
- Work Elements
- Layout & work-station design
- Accelerate technology; new technologies
- Globalization
- Different locations of suppliers & customers
- Process complexity
- Demand uncertainty
- Non-accurate forecasts
- Awkward design
- Changes in schedules
- Non-compatible tools and machines

Product-based:
- Complex design & specifications
- Shorter products lifecycle
- Products obsoleteness</td><td>- Large number of individual entities
- Number of products
- Number of consignments
- Number of destinations and addresses
- Number of parts for producing a product
- Number of interfaces</td></tr>
<tr><td>Inter-Complexity</td><td>Poor Flows:

- Asymmetric information
- Unmatched resources and goods
- Different aspects of resource utilization
- Currency Change rates
- Reverse flows</td><td>- Huge stream of flows
-Large number of distribution channels
-Large number of shipments</td></tr>
<tr><td>Outer-Complexity</td><td>- Complex rules:
  - Governmental
  - Managerial: different perspectives
  - Environmental
- Market Complexity
- Time Complexity: time restrictions
- Smuggling and fake products
- Upstream uncertainty (Late delivery of supply, poor quality of supply)
- Economic trends</td><td>- Large number of rules

- Number of market segments</td></tr>
<tr><td>Intangible Complexity</td><td colspan="2">- Emergence, Evolution, chaos</td></tr>
</table>

Table 5.9 – Root causes of complexity

5.5.2.1. Intra-Complexity

Root causes of intra-complexity could be divided to qualitative and quantitative.

- Qualitative ones can be divided further to human-based, operational and process–based as well as product-based.

Human-based causes

-*Culture:* differences in culture is one of the drivers of complexity in supply chains specially the ones which operate globally.

Genelot (1998, p.195 cited in Browaeys & Baets 2003) stresses that men are products of their culture: "their representations, their visions of what is good and what is wrong, their behaviors in work, their concepts of organizations are the fruit of the representations carried by their ancestors". Can one thus state that a change of culture would only be a change in representations?

According to Berlin (2006), culture has two parts: one which can be seen and one which is hidden.

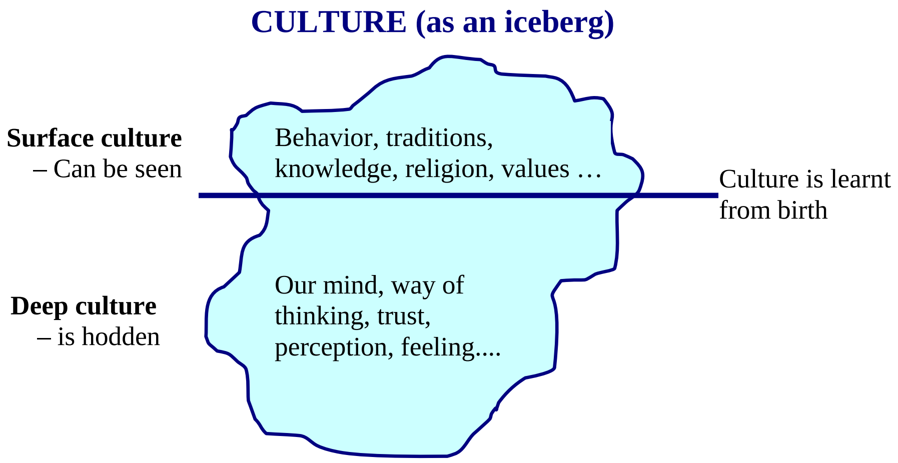


Figure 5.18 – Culture as an iceberg (Source: Berlin 2006)

Cultural complexity could be simplified by adaptation, adjustment, respect and trust.

-*Language:* differences between languages are another cause of complexity which is more obvious in global supply chains. A word in one language may have a different perception in another language. Syntax, semantics and pragmatics of a language are other aspects of the problem.

This complexity could be simplified by implementing semantic web or profound learning and implementing of an international language like English for universal businesses.

-Changing skill requirements: Progress of technology and upgrades of systems and machines, demand novel human skills. In this regard, new skilled staffs ought to be employed and former employees should be educated properly.

-Increased customer expectations: Final customers are indeed pivotal entities of supply chains as they are sources of revenue-making. In increasing competitive markets, customer expectations mount alongside. Ignorance of up-to-date expectations and future trends will lead to uncertainty, complexity and risk in the supply chains.

In this regard, continues feedbacks and receiving voice of customers sound essential.

Operation & Process-based causes:

These roots of complexity are driven from several operations and processes in a supply chain like:

- Work elements: Every operation is constituted of different work elements and therbligs. Simplification of non-value added motions, movements and work elements conduce to superior outcomes.

- Location & layout design: Poor location and layout design will have long-term effects on efficiency of operations. It leads to higher costs and investments, difficult transportation, dissatisfied employees and customers, frequent interruption of production, delays and denied advantages of geographical specialization.
For sake of simplification, a robust design is essential. Furthermore, implementation of proper related software can lead to optimum or at least reliable location and layout design.

- Work-station design: A sturdy work-station design requires proper equipments and tools, proper hand or elbow height relative to tasks, proper seating facility, adequate task lighting, adequate space for materials and tools, proper location and positioning of tools and proper distance and orientation of monitoring equipments and input data. (Arora 2004)

- Accelerate technology (new technologies)
- Globalization

- Different locations of suppliers and customers: Expansion of supply chains markets usually lands more suppliers and customers and as result diverse locations of consignors and consignees. Optimization of transports with proper software can fairly increase efficiency of transshipments and transportations.

- Process complexity: As mentioned in section 4.2.2, several processes are tied-up in a supply chain. Berlin (2006) suggests the following remedies for amending processes' management.

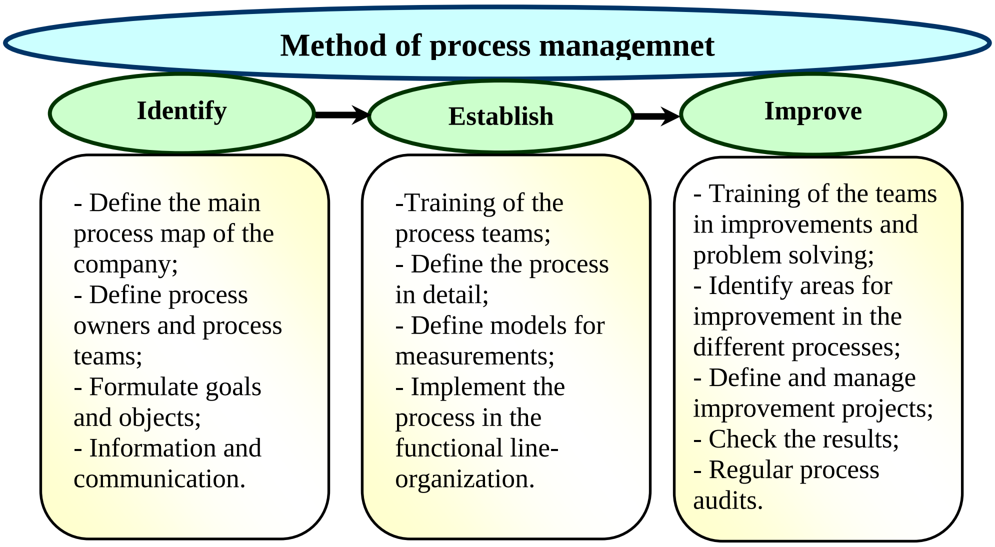


Figure 5.19 - Method of process management (Source: Berlin 2006)

Furthermore, implementation of ISO 9000, 14000 and so on can simplify management of different processes in the system.

- Demand uncertainty: Demand uncertainty and bullwhip effect have considerable impacts on inventory management, risk and complexity of supply chains. According to Datta (2006) 'bullwhip effect' distorts the demand signals, resulting in costs in the form of excess capacity and inventory, need for increased storage, increasing transportation costs (due to less-than-truckload or LTL) and so on.
Datta (ibid) stats that such inefficiencies may be reduced, in theory, by centralizing information related to supply and demand. In a centralized supply chain model, information is made available to all participating businesses at various stages of the supply chain or network of partners. Advances in information and communication technologies in the past decade has made it easier to acquire, share, access and analyze data in manner that is increasingly feasible for ' sense and response' systems. In the context of SCM, the idea is to enable intermediaries in the supply chain process to act as infomediaries or serve as agents for sharing and accessing the real-time data flow through common interfaces, such as web-based services.

- Non-accurate forecasts & Changes in schedules: Forecasts are always wrong. Changes in forecasts and non-accurate methods of forecasting are some reasons of demand uncertainty. They conduce to permutation of tactical and operational schedules (like manufacturing, transportation, capacity, work shifts) in the firm.
Implementing proper forecast methods can modify the mentioned issues. The holy grail of simplification of demand uncertainty and non-accurate forecasts is using Agent-Based Models (ABM) which is discussed in chapter 6.

- Non-compatible tools and machines

Product-based causes
- Complex design, specifications

- Shorter products' lifecycles: In order to cope with short life-cycle of different products, supply chains should be resilient and agile.

- Products obsoleteness

➢ Quantitative causes of complexity can be defined as:
- Large number of individual entities: It is supposed that each the number of agents and entities in a supply chain be more, complicatedness and complexity of the chain would be more.
- Number of products
- Number of interfaces
- Number of consignments
- Number of destinations and addresses
- Large number of constituent components of products.

Eftekhar (2007) suggests 'function delivery' as a method of simplification of such complexity. Function delivery reduces the number of first tier suppliers/ customers in the chain.

5.5.2.2. Inter-Complexity

The word 'inter' demonstrates ongoing flows in a supply chain.

➢ Qualitative causes of inter-complexity can be results of the following issues:

- Asymmetric information: diverse data and information from different resources. Political issues are one of the most important causes of information asymmetry especially in supply chain specially ones which operate globally.
One tool for simplification of information flow is the potential use of real-time information to catalyze or trigger autonomous decision steps capable of re-planning and execution (Datta 2004).

- Unmatched resources and goods: represent complexity of flow of resources which move in different directions in the chain.

- Currency exchange rates: exchange rates are a critical cause of complexity in global supply chains.

- Reverse flows

- ➢ Quantitative causes of inter-complexity can be due to dignity of flows in the chain or channels in which they move like:

- Huge stream of material, resource, information and monetary flows
- Large number of distribution channels
- Large number of shipments

A global manufacturing supply chain usually involves heterogeneous environments. Such a supply chain network is much more complex than that for the procurement, production and delivery of a simple commodity, not only for the volume and complexity of transactions, but also due to its dynamic and heterogeneous manufacturing environments.

5.5.2.3. Outer-Complexity

Outer-complexity is due to external causes, rules, and laws like governmental, managerial, environmental, and so on.

- ➢ Qualitative drivers of outer-complexity can be due to following factors:

- Complex administrative laws and rules from environmental organization, government, managerial boards and so on: Standardization could be powerful remedy for such causes.

- Market complexity: complexity derived from competitors, economic trends, and fashion and so on.
- Time complexity: time restrictions and due-dates on different activities of the chain.
- Smuggling and fake products.

- Upstream uncertainty: like late delivery of raw-materials, poor quality of suppliers and so on. Solid collaboration among entities of the chain can be considered as a powerful remedy.

- ➢ Quantitative drivers of outer-complexity can be due to following factors:
- Large amount of rules,
- Large number of market segments which supply chain acts in it.

5.5.2.4. Intangible-Complexity

Intangible complexity is due to emergence, evolution and chaos in the system. These issues make management of supply chains impossible.

Priya Datta (2007) states that since supply networks often display unpredictable behaviors, they can never be completely controlled through top-down planning however collaborative it might be. Also since supply networks are ever changing dynamic webs of linkages; it is pointless for each individual entity to optimize their functions by reducing or simply disregarding the interactions by assuming linearity. First of all, the space of possibility will be too large and secondly, there is no practical way to find an optimum as every moment the situation changes in today's dynamic environment.
Intelligent agents are assured tools for simplification of dynamic complex supply chains.

Choi et al (2001) delineates: "if a Supply Network (SN) operates non-linearly, it is then not possible for one firm to control its operation in deterministic fashion. This is an important realization for many firms whose management has developed an unfounded belief that the ultimate goal of supply chain management is to control the entire supply networks. We would argue, in contrast, the ultimate goal should be to develop a strategy on how much of the SN to control and how much of it to let emerge. For instance, Honda controls its SN through several tiers deep for a few critical items, but for most other items, it empowers its top-tier suppliers to manage their suppliers, in essence letting the SN emerges".
According to Zsifkovits & Sereinigg (2005), only 20 % of the scope of logistics activities is within the direct control of a company's logistics function.

According to Lumsden (2008), all the mentioned remedies of supply chains simplification can be summarized in five general hints:

1) Excess Time: Time restriction is a significant cause of complexity. Excess time and converting non-value added time to value-added one render to simplification of supply chains;
2) Optimum Resources: Too much resources as well as shortage of them make the supply chains complex. Finding the optimum number of resources yields to simplification of the system;
3) Optimum Inventory, materials and products;
4) Diminishing length of supply: Decreasing length of supply to demand, leads to simplicity of the system. This can be done by robust design, optimum movement and transshipment routs, finding correct transportation modes and vehicles and so on;
5) Shrinking number of non-value added as well as illegal actors, entities and actions of supply chain.

5.5.3. Complexity remedies from other literatures

Hoole (2005) states: “It is only common sense that if a business process can be simplified, it will usually enhance overall performance, leading to more consistent quality, lower operation costs, and inherently greater responsiveness. That powerful combination will most certainly yield more satisfied customers”.

Complexity reduction has become an important aspect of supply chain management in many industries (Zhou 2002); (Meijer 2002); (Muses 2000). In this regard; a bunch of remedies could be found in several literatures as:

JIT manufacturing and supply, Lean production (Scott et al 2000), vendor-managed inventory in supply chain, product and process modularization and standardization, business process restructuring, supply chain reconfiguration, postponement, Genetic Algorithms (Stewardson et al 2002) and so on.

Hoole (2006) demonstrates that companies can learn to manage supply chain complexity. Specifically, they can:

- Use metrics that reveal and track complexity;
- Control the number of product offerings and prioritize them in terms of market strategy and customer requirements;
- Design products in such a way as to simplify planning, supply, manufacturing, and distribution. That is, companies can make sure the supply chain is aligned with the product platform—the process for conceiving, developing, and launching new products.

Kearney (2002) states: “the first step of complexity management is to understand that complexity is not necessarily a pejorative term. Simply focusing on reducing complexity is a mistake. There is such a thing as good complexity for companies- complexity that is necessary and value-adding. And just like with good and bad cholesterol, companies need to treat good and bad cholesterol; companies need to treat good and bad complexity differently. In other words, companies should aim to reduce the cost of good complexity and the level of bad complexity.”

Kearney (ibid) adds: “From our analysis, we have determined that six characteristics, common to all leaders, will help to effectively manage complexity:

- Understand the requirements of customers and consumers;
- Make trade-offs based on an understanding of the cost effects of change;
- Eliminate over-specification and complexity creep in design and development;
- Align goals and objectives at the executive level;
- Provide visibility into complexity levels and required trade-offs;
- Develop and leverage new capabilities on a continuous basis.”

Companies also can improve their ability to take on complexity through the following actions:

- Standardizing material requirements and reducing the number of suppliers to help ensure consistency and quality of supply;
- Standardizing manufacturing and distribution processes to allow products to be made and shipped from alternate locations;
- Eliminate non-value-adding activities in supply chain processes with customers and suppliers;
- Sharing information on usage, forecasts, capacity, inventory and shipments to customers across internal departments and with suppliers;
- Developing supply chain strategies that build in flexibility and resiliency.

According to Michael & Wilson (2004), for sake of supply chain simplicity three main issues should be considered:

(1) Eliminate complexity that customers will not pay for:

Most businesses today find themselves carrying more products and services (or variations on them) than their customers really want. Getting rid of that complexity not only removes a source of wasted costs, but can also lead to an enviable competitive position.

A good real example in this regard is Southwest Airlines. They recognized that their market would not pay any of the typical costs of complexity seen in the air travel business. So they designed out the complexity that customers won't pay for.

Southwest operates only Boeing 737 aircraft. American Airlines, in contrast, have historically supported a lot of internal complexity-operating as many as 14 aircraft types-to address what it thought were different markets with different needs. As a result, the operating costs arose tremendously from supporting 14 types of aircraft, which means 14 spares depots, 14 sets of mechanic and pilot training, 14 kinds of certification, and the cost of an information factory to schedule and maintain it all; None of which is value-adding to the customer.

(2) Exploit the complexity that customers will pay for:

"I have this simple law of economic redemption- and it suggests that if you do something that's valuable, you should be able to make a profit," said Michael Dell at a conference in 2003.

One key message of this essay is that conquering complexity does not always mean eliminating it. In some cases, businesses can get a market edge by preserving or even adding complexity.

(3) Minimize the costs of the complexity you offer:

Michael & Wilson (ibid) states: "Whether you are getting rid of complexity or adding it, you have to make sure whatever complexity you keep is provided at the lowest possible cost. This mandate requires a rigorous analysis of every element of your service or product: Does it add value that the customer will pay for? Is the value worth the cost?"

A major advance in complexity achievements was made by Toyota in the 1960s when they created a system to simultaneously achieve Ford's high process velocity (which yields low cost) with Sloan's product complexity and market appeal. Toyota used a complexity reduction strategy known as standardization to eliminate waste in their internal products and processes, which enabled them to easily produce nearly one million vehicle variants to meet every customer's needs.

At the other end of the volume spectrum is Scania Trucks of Sweden. They have the same truck lineup as Mercedes-Benz, but with fewer than half the part numbers. Their internal design processes ensure that use of common parts is driven through engineering. European-based Scania dominates sales in countries as far flung as Brazil. They have achieved an unrivaled world record of 34 years of continuously profitable operations.

Anderson et al (2006) have designed a roadmap for identifying and eliminating complexity which is shown in figure 5.20. They add that IT can help a company to reduce its complexity in three areas: Products, Architecture and Services.

(1) Products: Information technology can help reduce complexity by taking a product-platform approach. Products or services are based on a common platform so companies can add or delete features depending on the customer.

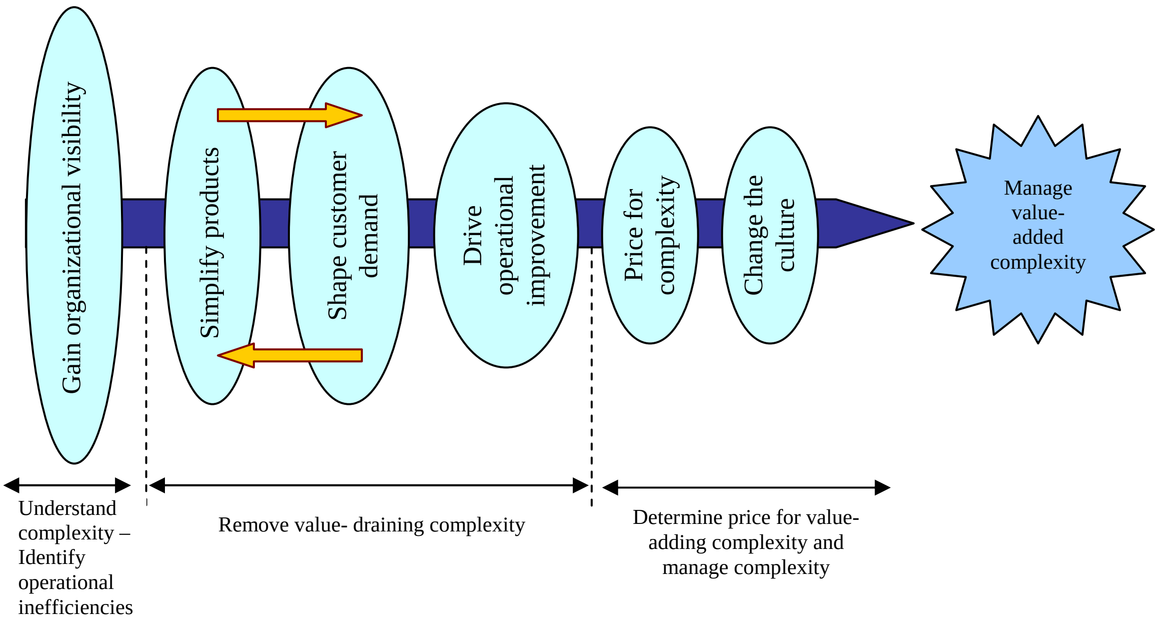


Figure 5.20 – Roadmap for identifying and eliminating complexity (Source: Anderson et al 2006)

(2) Architecture: Another area in need of complexity reduction and standardization is IT architecture. Throughout the IT architecture there are opportunities to both modularize and standardize certain areas. For example, common solutions in areas such as databases, applications, and servers will help a company improve its overall delivery capabilities and cost structure, and could lead to substantial savings and greater flexibility
(3) Services: To effectively match the services that IT provides with demand from the business, IT must be standardized and aligned with the company's business, product, and customer strategies. Historically, IT organizations deliver a defined set of capabilities and services to the business. However, these services often proliferate and expand, leading to unwanted ''shadow costs.'' To avoid these extra costs, companies should work with IT to first define the needed services and then determine how IT will meet the demand. In fact, some firms develop an IT services catalog that defines the service, estimates the cost to the business, and outlines how the service is prioritized and delivered.
According to Anderson et al (ibid), the best companies in the financial-services industry treat complexity as a business issue and adapt their cultures and organizational structures accordingly. Rather than focusing on a tactical complexity reduction – eliminating a few slow-moving products or services – they think about how to achieve and maintain profitable growth by adding complexity only where it increases profits or learning.

Hoole (2005) has designed a framework for complexity reduction. The Complexity Reduction Framework breaks down supply chain complexity into its component parts. Since the supply chain is a "process view" of a company's logistical activities, it is appropriate that the supply chain first be broken into its process elements. The process elements, in turn, can be defined by a number of other attributes, or "performance levers" that can be modified to increase supply chain performance.
The Supply Chain Operations Reference-model® (SCOR®), endorsed by the more than 750 member companies of the Supply-Chain Council, breaks the outbound supply chain into four process elements:
1) plan;
2) source;
3) make; and

4) deliver.
‘Plan’ includes all the supply chain activities related to demand management, sales and operations planning (S&OP), and overall supply chain strategy planning. ‘Source’ covers the identification of supply sources and the execution of material and services sourcing on an ongoing basis. ‘Make’ covers all the conversion activities performed internally.
Finally, ‘deliver’ includes taking of customer orders and their fulfillments, including the management of the distribution infrastructure and outbound transportation.
Five critical performance levers have the greatest impact on supply chain performance:
1) configuration;
2) management practices;
3) external relationships;
4) organization; and
5) systems.
‘Configuration’ addresses the physical assets and material flows of the supply chain. The ‘management practices’ lever covers the specifics of how the supply chain is managed. External relationships deal with how the company leverages the capabilities of its partners and suppliers. ‘Organization’ identifies who in the company is responsible for what and, perhaps more importantly, how performance objectives are aligned. Lastly, the ‘systems’ lever refers to the retrieval of information needed to make decisions and support leading practices.
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. By creating a matrix, a comprehensive toolkit of simplification techniques is developed as illustrated in table 5.10.

		Supply Chain Processes			
		Plan	***Source***	***Make***	***Deliver***
Performance Levers	***Configuration***	Product/Configuration/ Package Rationalization	Part Rationalization Vendor Rationalization	Plant Rationalization	Reduce distribution layers Drop Ship
	Management Practices	Postponement	Design for sourcing Rationalize terms	Lean Mfg.practices	Reduce self-induced volatility: • Promotions • Hockey Stick
	External Relationships	Customer & Market segmentation	Supplier collaboration: • VMI etc. • JSA Term codes	Outsourcing	Customer collaboration • JSA Rationalize term codes
	Organization	S & OP	Demand management Outsource procurement	VMI	Outsource (3PL) Call center consolidation
	Information Systems	Customer sell-through data: • CPFR • VMI	E-Procurement tools	Lean Mfg. IT e.g. ‘backflush etc’.	E-Commerce portals

Table 5.10 - Complexity reduction techniques (Hoole 2005)

6. INTELLIGENT AGENT-BASED SUPPLY CHAINS

The technology of intelligent agents and multi-agent systems seems set to radically alter the way in which complex, distributed, open systems are conceptualized and implemented (Wooldridge 1997).

Advances in IT, the growing complexity and decentralization of the utility markets and the increasing pressure to lower costs have pushed the demand for new tools or systems to remove the burdens of human decision makers from tedious and repetitive tasks. One application is the software agent (Yan et al 2001). Agents and agent-based modeling are important tools for simplification of complexity.

Jennings (1996) states that the most natural way to view the business process is as a collection of autonomous, problem solving agents which interact when they have interdependencies. In this context, an agent can be viewed as an encapsulated problem solving entity

In this chapter, at first several definitions of agents and their structures and types are introduced. Later, agent-based modeling and multi-agent systems as well as agent-based supply chains are explained.

6.1. Concept of Agents

The term “agent” is an elusive one to define. An agent can be a person, a machine, a piece of software, or a variety of other things. The basic definition of agent in dictionary is one who acts. An agent must be automatic, social, reactive and pro-active (Zhang & Xie 2007).

According to Gershenson (2007), an agent is a description of an entity that acts on its environment. Examples of this can be a trader acting on a market, a school of fish acting on a coral reef, or computer acting on a network. Thus, every element, and every system, can be seen as agents with goals and behaviors aiming to reach those goals.

Russell & Norvig (1995) demonstrate that an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors. A human agent has eyes, ears, and other organs for sensors, and hands, legs, mouth, and other body parts for effectors. A robotic agent substitutes cameras and infrared range finders for the sensors and various motors for the effectors. A software agent has encoded bit strings as its percepts and actions.

A helpful description of agents and agency has been provided by Wooldridge & Jennings (1995) based on weak and stronger notions of them. In the following, characteristics of agents are explained based on Wooldridge & Jennings’ (ibid) work:

- **A Weak Notion of Agency**

Perhaps the most general way in which the term agent is used is to denote a hardware or (more usually) software-based computer system that enjoys the following properties:

• ***Autonomy***

According to one notion of autonomy "The more I can do, the more autonomous I am” (Gadomski & Zytkow 1995). Agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state (Castelfranchi 1995; Wooldridge 1997; Jennings 1996; Franklin & Graesser 1996). Autonomy depends on individual power of an agent.

• ***Social ability***
Agents interact with other agents (and possibly humans) via some kind of *agent-communication language* (Genesereth & Ketchpel 1994; Pavon et al 2007; Jennings 1996).

• ***Reactivity (Responsiveness)***
Agents perceive their environment (which may be the physical world, a user via a graphical user interface, a collection of other agents, the INTERNET, or perhaps all of these combined) and respond in a timely fashion to changes that occur in it.
Pavon et al (2007) state that depending on the degree of complexity that agent's behavior requires, their architecture may be reactive, where actions are triggered when certain events occur, or cognitive, where agents reason, even learn, to adapt or create new solutions in a changing environment.

• **Pro-activeness**
Agents do not simply act in response to their environment; they are able to exhibit goal-directed behavior by taking the initiative (Jennings 1996; Franklin & Graesser 1996).

➢ **A Stronger Notion of Agency**
For some researchers—particularly those working in AI (Artificial Intelligence)—the term 'agent' has a stronger and more specific meaning than that sketched out above. These researchers generally mean an agent to be a computer system that, in addition to having the properties identified above, is either conceptualized or implemented using concepts that are more usually applied to humans. For example, it is quite common in AI to characterize an agent using *mentalistic* notions, such as knowledge, belief, intention, and obligation (Shoham 1993). Some AI researchers have gone further and considered *emotional* agents.

➢ **Other Attributes of Agency**
According to Gershenson (2007), there are various other attributes which are sometimes discussed in the context of agency. For example:

• ***Mobility***
Mobility is the ability of an agent to move around an electronic network;

• ***Veracity***
Veracity is the assumption that an agent will not knowingly communicate false information;

• ***Benevolence***
Benevolence is the assumption that agents do not have conflicting goals, and that every agent will therefore always try to do what is asked of it; and

• ***Rationality***
Rationality is (crudely) the assumption that an agent will act in order to achieve its goals, and will not act in such a way as to prevent its goals being achieved — at least insofar as its beliefs permit.

According to Desouza (2001), attributes of agents can be divided to internal and external ones. Internal attributes are Autonomy, Reactivity, Goal driven, Intelligence, Mobility and Continuity. External attributes include cooperation and communication. Furthermore, Personality is a common attribute (Figure 6.1).
Continuity means that agents operate in continuum; upon achievement of their goals they continue to run in the background and monitor the environment.

An agent-based application is never supposed to terminate.
Personality is both an internal and an external characteristic and is considered by many to be a gray area. As intelligent agents represent humans, it is often desirable that they exhibit human-like traits. Just as people's personalities tell a lot about how they deal with the environment, similar rules apply to intelligent agents.
Desouza (ibid) states that agents need to be able to communicate with other agents and humans. Agent–human communication can be via terminal input such as keyboards, or more sophisticated technologies such as natural language processing and speech recognition. Multi-agent communication can take place using standard or defined protocols.

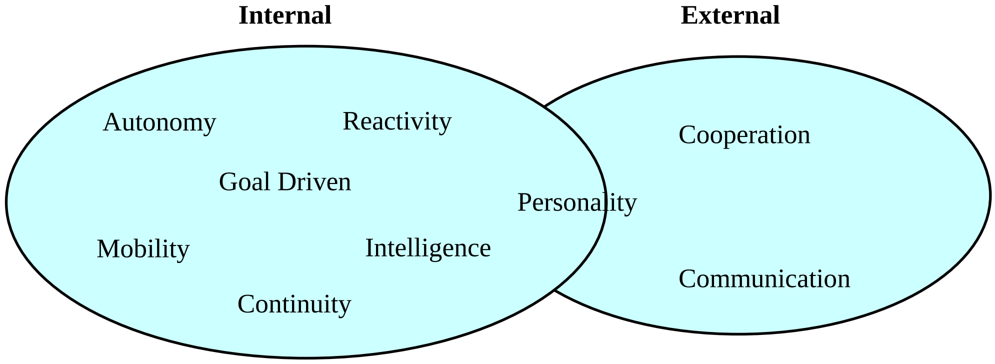


Figure 6.1- Internal vs. External attributes of agents (Source: Desouza 2001)

Nwana (1996 cited in Anumba et al 2002) defines an agent in terms of three behavioral attributes which are similar to week notions of agents introduced by Wooldridge & Jennings (1995). These attributes are: autonomy, co-operation and learning.
Among these three attributes, learning requires to be more sifted.
For agent systems to be truly 'smart,' they would have to learn as they react and/or interact with their external environment. Agents are (or should be) disembodied bits of 'intelligence.'
According to Gadomski & Zytkow (1995), intelligence is a capability of a system to achieve a goal or sustain desired behavior under conditions of uncertainty. Intelligent agents have a capability of coping with poorly structured and changing environment, learning from others and from their own experience.
An important attribute of any intelligent being is its ability to learn. The learning may also take the form of increased performance over time.
This ability of learning makes agents an important tool for studying, modeling and simplification of complex systems.
The mentioned attributes are shown as a Venn diagram (Fig 6.2).

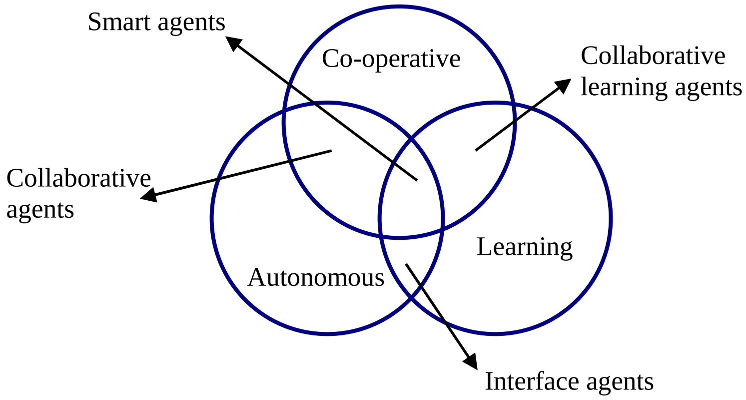


Figure 6.2- Taxonomy for agents (Source: Nwana 1996 cited in Anumba et al 2002)

Desouza (2001) defines an intelligent agent as software that assists users and acts on their behalf. Intelligent agents perform predefined task delegated by their users. Agents can automate repetitive tasks, remember events, summarize complex data, learn, and make recommendations.

Intelligent agents continuously perform three functions: perception of dynamic conditions in the environment, action to affect conditions in the environment, and reasoning to interpret perceptions, solve problems, draw inferences, and determine actions (Hayes-Roth 1995 cited in Desouza ibid).

Nissen (2000) has depicted technological framework of intelligent agents (Figure 6.3).

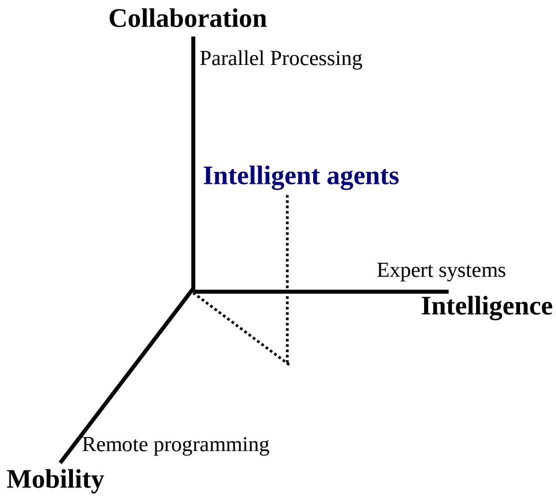


Figure 6.3- Agent technological framework (Source: Nissen 2000)

6.2. Architecture of Agents

According to Jennings et al (1998), agent's architecture is realized as a number of software layers. This architecture is a *hybrid* approach, which marry the best aspects of both deliberative and reactive approaches (Please refer to section 6.3).

Typically, the layers may be arranged vertically (so that only one layer has access to the agent's sensors and effectors) or horizontally (so that all layers have access to sensor input and action output); see Figure 6.4.

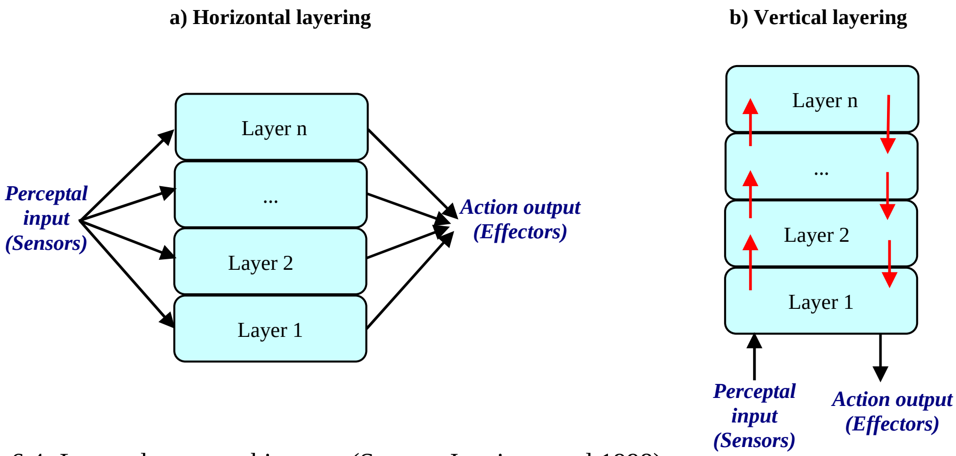


Figure 6.4- Layered agent architecture (Source: Jennings et al 1998)

Jennings et al (ibid) state that in the subsumption architecture (Figure 6.4), layers are arranged into a hierarchy, with different levels in the hierarchy dealing with information about the environment at different levels of abstraction. Most of architectures find three layers sufficient.
At the lowest level in the hierarchy there is typically a *reactive* layer which makes decisions about what to do based on raw sensor input.
The middle layer typically abstracts away from raw sensor input and deals with a *knowledge level* view of the agent's environment typically making use of symbolic representations. The uppermost level of the architecture tends to deal with the *social* aspects of the environment (it has a *social knowledge level* view). Thus, typically representations of other agents are found in this layer (their goals, beliefs, and so on).
In order to produce the global behavior of the agent, these layers interact with each other.
The specific way that the layers interact differs from architecture to architecture.

ZEUS (1999 cited in Anumba et al 2002) demonstrates different layers of an agent as the follow (Figure 6.5).

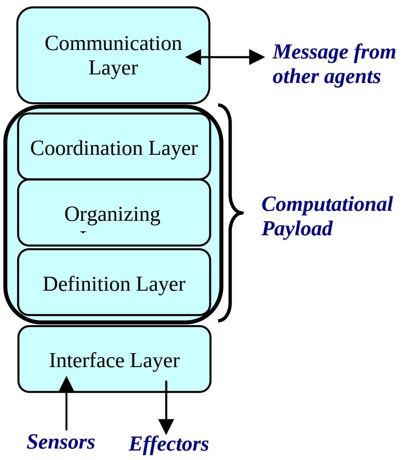


Figure 6.5- Conceptual model of a Zeus agent (Source: Anumba et al 2002)

- Interface layer: enables the agent to be linked to the external programs that provide it with resources and/or implement its competencies;
- Definition layer: where the agent is viewed as an autonomous reasoning entity;
- Organization layer: where the agent is viewed in terms of its relationships with other agents;
- Co-ordination layer: where the agent is viewed as a social entity that interacts according to its known protocols and strategies; and
- Communication layer: implements the protocols and mechanisms that support inter-agent communication.

According to Pavon et al (2007), sensors can be active, if they can process the information they capture, classify it and decide what to do according to their relevance; or passive, if they just send the information they capture to some sensor manager agent, which will take care of integrating and processing the received information.

6.3. Classification of Agents

According to Zhang & Xie (2007), there is a general classification of agent types as shown in Figure. 6.6.

According to an agent's behavior, the agent can be classified into reactive agent, deliberative agent, and hybrid agent which is a combination of reactive agent and deliberative agent. Based on the functionality of agent, it can be classified into an interface agent, information/internet agent, etc. Based on the mobility of an agent, it can also be classified into mobile or stationary agent.

Deliberative agents have domain knowledge and the planning capability necessary to undertake a sequence of actions with the intent of moving towards or achieving a specific goal. The problem with deliberative agent based planning systems is that they don't scale very well when the complexity of the problem increases and they cannot react well in real time.

Reactive agents respond in an event-action-mode. Reactive agents simply retrieve pre-set behaviors similar to reflexes without maintaining any internal state. They respond solely to external stimuli and the information available from their sensing of the environment.

Neither a purely deliberative nor a purely reactive, agent can cope with every requirement of a dynamic environment. To overcome the weaknesses of the deliberative agent and reactive agent, a combination of them is used, called hybrid agents.

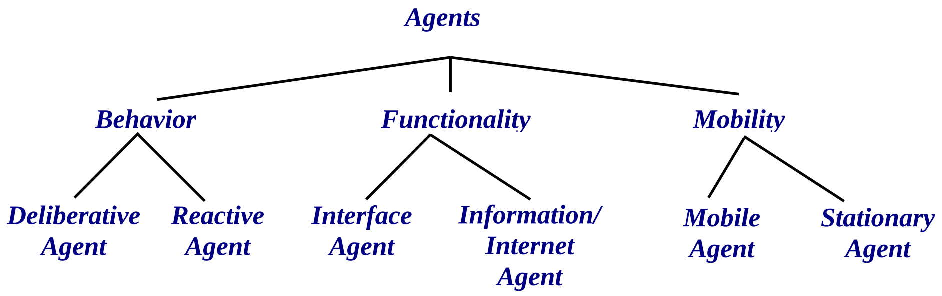


Figure 6.6- A general classification of agents (Source: Zhang & Xie 2007)

Nissen (2000) has grouped extant agent applications—both single- and multi-agent systems—into four classes:

1) Information filtering agents;
2) Information retrieval agents;
3) Advisory agents; and
4) Performative agents.

This classification scheme is developed specifically to compare various agent capabilities that are applicable to supply chain processes.

Most information filtering agents are focused on tasks such as applying user-input preferences to screen and sort e-mail, network news groups, frequently asked questions and arbitrary text.

Information retrieval agents address problems associated with collecting information pertaining to commodities such as compact disks and computer equipment, in addition to services such as advertising and insurance. The ubiquitous Web indexing robots are also included in this class along with Web based agents for report writing, publishing and assisted browsing.

Advisory agents are oriented toward providing intelligent advice. Examples include recommendations for CDs and movies, an electronic concierge, an agent 'host' for college campus visits and planning support for manufacturing systems. Agents for strategic planning support, software project coordination and computer interface assistance are also grouped in this class, along with planned support for military reconnaissance and financial portfolio management.
Performative agents in the fourth class are generally oriented toward functions such as business transactions and work performance. Examples include a market-space for agent-to-agent transactions and an agent system for negotiation, in addition to performance of knowledge work such as automated scheduling, cooperative learning, and automated digital services.

Gadomski & Zytkow (1995) have classified agents into three categories:

1) **Programmed agents**: Conventional robots and computer controlled machine tools are examples of such systems.
2) **proto-intelligent agents**: They can be artificial or biological, and react to the state of their environments. Thermostats and auto-pilots are extreme examples of such systems.
3) **Intelligent agents**: These agents also have a capability of coping with uncertainty.

According to Liu (n.d.) agents can be categorized based on figure 6.7.

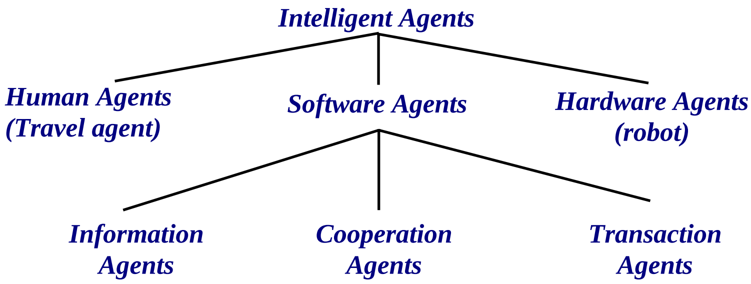


Figure 6.7- Types of agents (Source: Liu n.d.)

6.4. Ancestors of Agents

As Wooldridge (1997) states, the concept of an intelligent autonomous agent did not appear in a vacuum. It is a natural development of various other trends in Artificial Intelligence and computer science. In the subsections that follow, some ancestors of agents are discussed, and the attributes that make them distinct from their forbears are identified.

6.4.1. Agents and Expert Systems

Expert systems were the AI technology of the 1980s. An expert system is one that is capable of solving problems or giving advice in some knowledge-rich domain.

An expert system is a system that uses human knowledge captured in a computer to solve problems that ordinarily require human expertise. In fact they are computer programs that are derived from a branch of computer science research called *Artificial Intelligence* (AI). AI's scientific goal is to understand intelligence by building computer programs that exhibit intelligent behavior. It is concerned with the concepts and methods of symbolic inference, or reasoning, by a computer, and how the knowledge used to make those inferences will be represented inside the machine.

Of course, the term *intelligence* covers many cognitive skills, including the ability to solve problems, learn, and understand language; AI addresses all of those. But most progress to date in AI has been made in the area of problem solving; concepts and methods for building programs that *reason* about problems rather than calculate a solution.

AI programs that achieve expert-level competence in solving problems in task areas by bringing to bear a body of knowledge about specific tasks are called *knowledge-based* or *expert systems*. Often, the term expert systems is reserved for programs whose knowledge base contains the knowledge used by human experts, in contrast to knowledge gathered from textbooks or non-experts. More often than not, the two terms, expert systems (ES) and knowledge-based systems (KBS) are used synonymously. Taken together, they represent the most widespread type of AI application. The area of human intellectual endeavor to be captured in an expert system is called the *task domain*. *Task* refers to some goal-oriented, problem-solving activity. *Domain* refers to the area within which the task is being performed. Typical tasks are diagnosis, planning, scheduling, configuration and design.

An expert system essentially consists of three basic components: the knowledge base, an inference engine, and a user interface.

The **knowledge base** contains factual knowledge, like textbook facts that nearly everyone agrees on and heuristic knowledge, such as speculative or hypothesized judgment calls. This information is organized in a systematic way using a process called knowledge representation. There are several different types of knowledge representations. *Production rules* and *units* are two ways in which this information can be represented. *Production rules* consist of a series of if-then statements (Wooldridge 1997).The conditions for acquiring the information (for example, a specific query input by the user) is used as an argument in the ‘if’ section, while the corresponding answer, or requested information goes into the ‘then’ section. *Units*, *frames*, *schemas*, or *list representations*, tend to group similar areas of knowledge by common traits and associated values (See also McPherson & White 2006).

The **inference engine** (also called the *cognitive engine*) tries to draw answers from the knowledge base. It is often considered to be the “brain” of the system since without it, the expert system would not be able to analyze the user’s question nor infer answers nor draw conclusions from the knowledge base. The cognitive engine is logic that manipulates the procedural knowledge and the declarative knowledge to obtain a solution. The problem-specific information is contained in the knowledge base, whereas the cognitive engine logic usually is sufficiently general to work with different knowledge bases. Cognitive engine logic is separated into two major categories—state-space searches and problem reduction. State-space searches either search forward or backward. The forward search starts at the current state and tries to find a set of procedures that obtain the final goal state, whereas backward searches do the reverse. Problem reduction methods attempt to decompose the problem into smaller sub-problems which, when solved together, obtain the overall solution. Methods which combine these approaches also have been developed (McPherson & White 2006).

The **user interface** is the medium through which the user interacts with the expert system. Thus, a typical user interface allows a user to input questions and commands as well as respond to the expert system's answers and queries for clarification.

Building an expert system is known as *knowledge engineering* and its practitioners are called *knowledge engineers*. The knowledge engineer must make sure that the computer has all the knowledge needed to solve a problem. The knowledge engineer must choose one or more forms in which to represent the required knowledge as symbol patterns in the memory of the computer; that is, he (or she) must choose a *knowledge representation*. He must also ensure that the computer can use the knowledge efficiently by selecting from a handful of *reasoning methods*.

Perhaps the most important distinction between agents and expert systems is that expert systems are inherently *disembodied*. It means that they do not interact directly with any environment: they get their information not via sensors, but through a user acting as middle man. In addition, expert systems are not usually required to operate in anything like real-time. Finally, we do not generally require expert systems to be capable of co-operating with other agents.
According to Nissen (2000), one key difference is that individual agents are generally quite small and limited in terms of knowledge and capability, with respect to a traditional expert system. Other key differences stem from agent mobility and the ability of agents to collaborate through federations to solve problems. In contrast, expert systems typically operate on a single processor and as standalone entities.

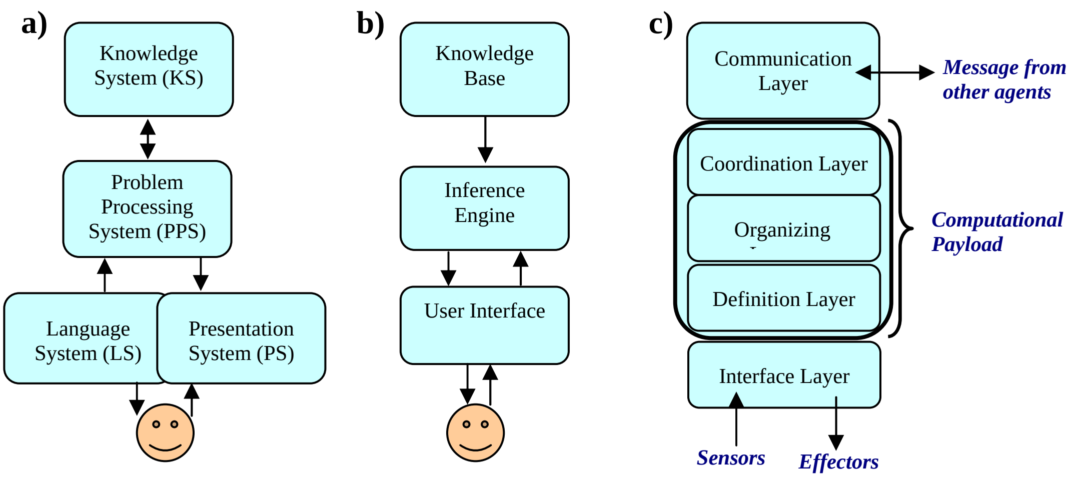


Figure 6.8- Structure of a) a decision support system, b) an Expert System, and c) an Agent

6.4.2. Agents and Objects

The most obvious difference between the 'standard' object model and our view of agent- based systems is that in traditional object-oriented programs, there is a single thread of control.

In contrast, agents are process-like, concurrently executing entities. An agent is a *rational decision making system*: we require an agent to be capable of reactive and pro-active behavior, and of interleaving these types of behavior as the situation demands. The object-oriented research community has nothing whatsoever to say about building systems that are capable of this kind of behavior.

The main difference between the two concepts of objects and agents is the *autonomy* of agents. In fact, while objects encapsulate some state on which their methods can perform actions **(**Tatara et al 2007), and in particular the action of invoking another object's method, an object has control over its behavior. That is, if an object is asked to perform an action, it always does so, while an agent may refuse. Concerning this point, Wooldridge (2002) recalls the slogan *"Objects do it for free; agents do it because they want to"*. Of course, some sophisticated objects may be very similar to agents. In fact, Wooldridge (ibid) noted that there are clear similarities, but obvious differences also exist.

Object state is much simpler than agent state. In fact, an object state is only a data structure, i.e., an aggregation of variables of different types (integers, Booleans, character strings. . .) in a common structure, while an agent state consists of components such as beliefs, decisions, capabilities, preferences and obligations.

6.5. Multi-agent systems (MAS)

6.5.1. Background

Jennings et al (1998) state that traditionally, research into systems composed of multiple agents was carried out under the banner of *Distributed Artificial Intelligence* and has historically been divided into two main camps: *Distributed Problem Solving* (DPS) and *Multi-Agent Systems* (MAS).

More recently, the term “multi-agent systems” has come to have a more general meaning, and is now used to refer to all types of systems composed of multiple (semi-) autonomous components.

Distributed problem solving (DPS) considers how a particular problem can be solved by a number of modules (nodes) which cooperate in dividing and sharing knowledge about the problem and its evolving solutions. In a pure DPS system, all interaction strategies are incorporated as an integral part of the system. In contrast, research in MAS is concerned with the behavior of a collection of possibly pre-existing autonomous agents aiming at solving a given problem.

According to Jiao et al (2005), a multi-agent system is a loosely coupled network of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver. The agent-based technology has emerged as a new paradigm for conceptualizing, designing, and implementing software systems. Multi-agent systems (MAS) enhance overall system performance, in particular along such dimensions as computational efficiency, reliability, extensibility, responsiveness, reuse, maintainability, and flexibility. They are also capable of solving the problem of matching supply to demand and allocating resources dynamically in real time, by recognizing opportunities, trends and potentials, as well as carrying out negotiations and coordination.

Multi-agent systems have several properties that make them particularly attractive for use with large, complex systems. The first, and usually most important in critical systems, is a high level of reliability. Modularity and scalability are also attractive features of multi-agent systems.

Software agents often produce different solutions to the same problem. Solution multiplicity arises when several agents, using completely independent methods, arrive at different conclusions based on the presented data. Negotiation between agents, in the form of sharing state and decision information, is therefore required to resolve the situation (Tatara et al 2007).

The design of a multi-agent system is an iterative process which aims at the identification of the parties involved (i.e., human agents, system agents, external worlds), and the processes, in addition to the types of knowledge needed (Brazier et al 2002).

6.5.2. Architectures and characteristics of MAS

The multi-agent system architectures can be expressed as the relationships of information and control among agents. That is, how individual agents are organized together and how to solve problems by working together. From the viewpoint of control, MAS architectures can be categorized into: centralized architectures, distributed architectures, and hybrid architectures that are a combination of centralized and distributed architectures. The centralized multi-agent architectures share many of limitations of the master-slave architectures. The distributed architectures are much more complex because of huge information flow and complicated information control. The hybrid architectures combine the advantages of these two types of architectures. In manufacturing systems, Shen et al (cited in Zhang & Xie 2007) classified MAS architectures into three categories: hierarchical architectures, federated architectures and autonomous system architectures (Zhang & Xie ibid).

According to Datta (2006), characteristics of MAS can be summarized as follow:

- Agents should correspond to 'things' in the problem domain rather than to abstract functions;
- Agents should be small in mass, time (able to forget) and scope (avoid global knowledge action);
- Multi-agent systems should be decentralized (no single point of control/ failure);
- Agents should be neither homogeneous nor incompatible but diverse;
- Agent communities should include a dissipative mechanism;
- Agents should have ways of caching and sharing what they learn about their environment;
- Agents should plan and execute concurrently rather than sequentially

According to Johnson (2006), a characteristic of most multi-agent systems is that no agent knows everything. This is a strong reason to avoid top-down control. In many situations, the agent "on the ground" has better information than a centralized controller, and is best equipped to make decisions.
Managing human systems can be seen as the need to enable appropriate bottom-up self-organization to achieve desirable emergence, rather than to give agents precise top-down instructions on how to organize. In this sense, management can be seen as deciding objectives and controlling resources, and making and communicating policies, rather than giving orders.
It comes as no surprise that it is not possible to predict the behavior of multi-agent systems into the long-term future. However, multi-agent system simulations are used extensively in the analysis of complex systems and give useful insights into possible patterns of system behaviors.

6.5.3. MAS communication

Communication is one of the critical aspects in multi-agent systems because it enables agents to exchange information and coordinate their activities. Bieszczad et al (1999) state: "coordination is needed in multi-agent systems to prevent chaos, satisfy global constraints, explore distinctive expertise, and synchronize individual behaviors of agents".
Multi-agent systems are designed to have the capability to collaborate, for example decompose a problem and jointly solve the problem, or compete, such as searching for best deals for the users (Yan et al 2001).
According to Zhang & Xie (2007) and Sycara & Zeng (1996), to achieve communication, coordination and cooperation in a multi-agent system, the need for a medium of communication or protocol consequently arose. An agent communication language (ACL) is developed to facilitate communication. Knowledge query and manipulation language (KQML) and FIPAACL are two of the most widely used ACLs in multi-agent systems.
KQML is both a message format language and a message-handling protocol to support run-time knowledge sharing among agents (Yan et al 2001).
Barbuceanu & Fox (1995) have also introduced a language for describing coordination in multi-agent systems which is called COOL (stands for COOrdination Language).

6.5.4. Advantages of MAS

Autonomous agents and multi-agent systems represent a new way of analyzing, designing, and implementing complex software systems. The agent-based view offers a powerful repertoire of tools, techniques, and metaphors that have the potential to considerably improve the way in which people conceptualize and implement many types of software. Agents are being used in an increasingly wide variety of applications — ranging from comparatively small systems such as personalized email filters to large, complex, mission critical systems such as air-traffic control. At first sight, it may appear that such extremely different types of system can have little in common. And yet this is not the case: in both, the key abstraction used is that of an *agent*. It is the naturalness and ease with which a variety of applications can be characterized in terms of agents that leads researchers and developers to be so excited about the potential of the approach. Indeed, several observers feel that certain aspects of agents are being dangerously over-hyped, and that unless this stops soon, agents will suffer a similar backlash to that experienced by the Artificial Intelligence (AI) community in the 1980s (Jennings et al 1998).

According to Zhang & Xie (2007), the properties of agents meet the requirements of the next generation manufacturing systems which are needed to be open, dynamic, agile, scalable, and fault tolerant. Nowadays, agent technology is recognized as a promising approach for intelligent manufacturing systems. The unique features of agent technology have shown a great potential in developing distributed manufacturing systems. It leads to applications in manufacturing areas, such as manufacturing planning, scheduling and control, supply chain management, and enterprise integration. In traditional manufacturing environment, information systems mimic organizational structures, utilizing a top-down, command-and-control structure.

Communicating decisions and information down through the organization is time consuming—making it impossible to respond and adapt quickly to the external environment. Traditional manufacturing relies on schedules as means of forecasting what needs to be produced. One of the problems with traditional schedulers is that they try to anticipate and plan for every possible change that may occur.

Abraham et al. (1985 cited in McPherson & White 2006) in particular note the limited usefulness of static models for production planning and scheduling.

In practice, plans must be executed in a dynamic environment. Within planning and scheduling cycles, production and scheduling decisions must be developed that yield robust recommendations that endure under changing production scenarios.

Bigus & Wiley (2001) state: “it is apparent that a natural way to modularize a complex system is in terms of multiple, interacting, autonomous components that have particular objectives to achieve”; this issue is done with MAS.

According to Magedanz et al (1996), in principle, the following chances of emerging agent technology can be identified:

- ***Asynchronous and cooperative processing of tasks***

  The possibility of delegating specific tasks by means of mobile agents to one specific or even multiple nodes allows for highly dynamic and parallel computations. Particularly this supports disconnected operation of tasks and weak client computers.

- ***Customization and configuration of services***

In the light of an electronic market place, agent technology allows to instantly provide new services either by customization or (re)configuration of existing services. In this case, agents act as "service adaptors" and could be easily installed.

- ***Instant service usage and active trading***

Mobile agents realizing service clients travel to potential customers providing spontaneous access to new services. This feature enabling easy distribution of service clients can be exploited to perform active trading.

- ***Decentralization of management***

Mobile agents allow decreasing pressure on centralized network management systems and network bandwidth by delegating specific management tasks from the central operations system to dispersed management agents. Mobile agents representing management scripts enable both temporal distribution (i.e. distribution over time) and spatial distribution (i.e. distribution over different network nodes) of management activities.

- ***Intelligent communications***

Agents provide the basis for advanced communications. They support the configuration of a user's communications environment, where they perform control of incoming and outgoing communications on behalf of the end user. This includes communications screening, intelligent adaptation of services (i.e. conversion of information formats) to network access arrangements and end user devices, as well as advanced service inter-working and integration.

- ***Information retrieval and support of dynamic information types***

Mobile agents provide an effective means for retrieving information and services within a distributed environment and support for dynamic information types within electronic mail and advanced networked information systems.

Gil (2006) demonstrates that agents' architectures offer valuable techniques to provide the autonomy and flexibility required in highly dynamic and heterogeneous environments.
According to Gadomski & Zytkow (1995), more and more frequently, the complexity of industrial and social systems under human management leads to serious unexpected consequences, caused by human errors or by deficiency in planning. To alleviate these faults, it becomes increasingly realistic to support human reasoning and human execution of complex tasks by intelligent computer systems. Models of artificial intelligent agents can provide theoretical base for construction of such systems.

According to Vázquez et al (2007), since agents provide modularity and decentralization, changes in an agent only affect the agents that are directly related, not the rest of the system. This allows us to construct a more robust system that can be adapted to any future requirements. In this regard, agents reduce the complexity of the system.

Mele et al (2007) declare that multi-agent system is suitable for supply chains that are either driven by pull strategies or operate under uncertain environments, in which the mathematical programming approaches are likely to be inferior due to the high computational effort required.

6.6. Agent-based modeling

6.6.1. Background

According to Merali (2006), there are two main ways in which complexity concepts have been deployed to study complex systems and their dynamics. The first is through the direct use of complexity concepts and language as sense-making and explanatory devices for complex phenomena in diverse application domains. The second is through agent-based computational modeling to study the dynamics of complex systems interactions and to reveal emergent structures and patterns of behavior.

Traditional modeling techniques (like: optimization, mathematical models, system dynamics, game theory) are quite suitable for modeling supply chain decisions within a single enterprise. Organizations have been applying these techniques for several decades leading to higher efficiencies. Given that intra-enterprise modeling helped improve the efficiencies a great deal, modeling of inter-enterprise issues for SC integration is crucial for further large-scale improvements. Considering the fact that most of the supply chains involve enterprises with independent ownerships (requiring the ability to model information asymmetry and distributed/decentralized mode of controls), applicability of the traditional modeling approaches is quite limited and indeed unrealistic. The latest developments in the modeling technology, agent-based systems, and multi-agent systems for example, are quite promising for such modeling situations. They are best suited to handle issues of information asymmetry, decentralized and distributed decision-making, and modeling inter-enterprise issues (Govindu & Chinnam 2007).

Agent-based modeling is a way of studying complex systems. An agent-based model consists of a virtual world filled with agents. Agents are like creatures that follow simple rules. They can represent any kind of individual like people, cars, atoms, cells etc or functions. Complex systems can be modeled by giving the agents a set of rules for how to behave and interact. The results are often surprising (Johnson 2006).
Datta (2006, p.70) states: “Computer-based modeling has largely used system dynamics based on ordinary differential equations. However, a multitude of industries and businesses, including SCM, are struggling to respond in real-time. […] The ‘sense and respond’ type solutions will demand agent-based software that functions continuously and autonomously without human intervention to ‘understand’ the process environment in order to respond appropriately or alert human operators.
Eventually this transition may emerge as real-time adaptable business network. This paradigm shift will make it imperative to model software based on agents and equations. The question is no longer whether to select one or the other approach but to establish a mix of both and develop criteria for selecting one or other approach, that can offer real-time solutions”.

6.6.2. Agent-based models (ABM) vs. Equation-based models (EBM)

According to Datta (ibid), commercial supply chain software (like SAP, Garp, and Oracle) defines process in the traditional terms of rates and flows (consumption, production). System variables (cost, rebates, transportation time, out-of-stock) evaluate or integrate sets of algebraic equations (ODE, ordinary differential equations or PDE, partial differential equation) relating these variables to optimize for best results (best price, shortest lead time, minimal inventory). The process based on equation-based modeling (EBM) assumes that these parameters are linear in nature and relevant data are available.

In the real world, events are non-linear, actions are discrete and information about data is distributed.
On the other hand, in Agent-based modeling (ABM) the focus is on agents and their relationships with other agents or entities (Nilsson 2005). ABM draws clues from natural behavior of biological communities of ants, wasps, termites, birds, fish and wolves, to name a few. The 'natural' use of continuity and autonomy indicates that agents are able to execute processes or carry out activities in a flexible, intelligent manner that is adaptive and responsive to changes in the environment (without requiring constant human guidance, intervention or top-down control from a system operator). An agent that functions continuously in an environment over a period of time may 'learn' from experience (patterns). Agents that inhabit an environment with other agents are expected to communicate, cooperate and possess mobility between environments (Datta 2004, 2006).

Nilsson (2005) explains ABM in the context of science of complexity as well as logistics. It is one way of making logistics processes more adaptive and thus increasing its effectiveness. In this regard, the following assumptions in ABM are supposed:

- Heterogeneity: Agent populations are heterogeneous. In ABM there is no any need to aggregate different agents' behaviors into average variables.
- Autonomy: There is no central, or 'top-down', control over individual behavior in ABM. (Author: Lyons et al 2003)
- Local interactions: Typically, agents interact with neighbors in their operating space. Uniform mixing is generically not the rule.
- Distributed decision making: ABM takes decision making, dispersed both in time and space, into consideration. Each agent can be designed to act according to its goals. For example, the production agent aims at high operational efficiency while a stock agent aims at lowest possible stock levels.
- Bounded rationality: The agents do not possess global information, and they do not have infinite computational power which makes them rationally bound.
- Emergent behaviors: Complexity theoretical research shows often that unpredictable behavior on an aggregated (system) level arises from simple rules in the agent's individual behavior, and that slight changes in these rules can have radical impacts on the behavior of the system. Explaining and understanding the dynamic behavior of a group's or organization's behavior is beyond human capabilities. However, with the use of simulations, such behavior can often be rendered identifiable and understandable.

According to Datta (2004, 2006), both ABM and EBM approaches simulate the system by constructing a model and executing it on a computer. The differences are in the form of the model and how it is executed. In ABM, the model consists of a set of agents that encapsulate the behaviors of the various individuals that make up the system and execution consists of emulating these behaviors, which is essentially dynamic. In EBM, the model is a set of equations (pre-determined static) and execution consists of evaluating them. Thus 'simulation' is a general (umbrella) term that applies to both methods, which are distinguished as agent-based emulation and equation-based evaluation.
In the following table a comparison between ABM and EBM is presented (Table 6.1).

Agent-based model (ABM)	*Equation-based model (EBM)*
Better suited to domains where the natural unit of decomposition is the individual rather than observable or equation and where physical distribution of computation across multiple processors is desirable.	Better suited to domains where the natural unit of decomposition is the observable or equation rather than the individual.
Naturally represents the process as a set of behaviors, which may include features difficult to present as rates and levels, such as step-by-step processes and conditional decisions.	Represents the process being analyzed as a set of flow rates and levels. ODEs are well-suited to represent purely physical processes. However, business processes are dominated by non-linear, discrete decision-making.
Easier to construct. Certain behaviors are difficult to translate into rate-and-level formalism.	Includes 'black boxes' for specific entities (such as conveyors or ovens) whose behavior is difficult to represent in a pure rate-and-level system.
Distinguishes physical space from interaction space. Permits the definition of arbitrary topologies for agent interactions.	ODE methods, such as system dynamics, have no intrinsic model of space. PDE's provide a parsimonious model of physical space but not of interaction space.
Validated at the system level and at the individual level, since the behaviors encoded for each agent can be compared with local observations on the actual behavior of the domain individuals.	Only validated at the system level by comparing model output with real system behavior.

Table 6.1 – ABM versus EBM (Source: Datta 2006)

Macy & Willer (2002) presented a historical development of agent based models as a tool for social simulation. They stated that ABMs defy classification as either micro (bottom-up modeling approach to simulate the evolution through time of each decision maker) or macro (holistic approach in dynamical systems models) levels of simulation but instead provide a bridge between levels. Agent based approaches offer increased robustness against unpredictability of supply chain operations.

Disadvantages of EBM result largely from use of averages of critical system variables over time and space. EBM assumes homogeneity among individuals but individuals in real systems are heterogeneous. When the dynamics are non-linear, local variations from the averages can lead to significant deviations in overall system behavior. In business applications driven by 'if-then' [fuzzy] decisions, non-linearity is the rule. (Datta 2006)

6.7. Agent-based supply chains

6.7.1. Background

Supply chain management represents a critical competency in today's fast-paced, global business environment. However, in the current transition from EDI to Web-based supply chain technologies, much of the capability for process integration is being lost. Integration of buyer and seller supply chain processes is critical for speed and responsiveness in today's hypercompetitive product and service markets.

Intelligent agent technology offers the potential to overcome many limitations of current supply chain technologies (Nissen 2001).

Agent technology views a supply chain as composed of a set of intelligent agents, each being responsible for one or more activities and interacting with other related agents in planning and executing their responsibilities in complex dynamic environments. It provides methods of integrating the entire supply chain as a networked system of independent echelons, each of which utilizes its own decision-making procedure (Fung & Chen 2005).

Multi-agent application in supply chain management mainly covers building multi-agent architecture of demand–supply procedure and modeling a communication or cooperation mechanism between agents (Lu & Wang 2007).

The supply chain network problem is characterized by complexity and inherent decentralization. The application of multi-agent systems techniques to this problem seems promising (Gjerdrum et al 2001).

According to Govindu & Chinnam (2007), autonomous agents and multi-agent systems represent a new way of analyzing, designing, and implementing complex software systems. They are expected to pioneer a revolutionary paradigm shift in software systems modeling and engineering. Multi-agent systems can be used to model any phenomenon, scientific or behavioral, in order to study the underlying dynamics of complex systems such as supply chains very effectively. Agents can be modeled to represent organizations, functions, resources, and even human beings.

Weiss (1999) specifies a couple of reasons for the popularity of multi-agent systems (systems with multiple interacting agents): (i) modern computing and information environments are distributed, large, open, and heterogeneous, and (ii) multi-agent systems have the capacity to play an important role in developing and analyzing models and theories of interconnectivity in human societies. In terms of the application potential, they are best suited and hold a great promise for a large spectrum of complex real-world systems, in particular, supply chains.

Because agent technology is inherently scalable, agent-based supply chain integration offers good potential for both cost and cycle time reduction in the enterprise. This augments the noted increase in flexibility and process integration over extant supply chain technologies (Nissen 2001).

6.7.2. Literature review

Several articles, especially in recent years, have been written about agent-based supply chains. Application of multi-agent technology in supply chain management, especially supply chain coordination, has become a strongly emerging research area. In the following table, some reviewed articles and literatures are summarized.

Author	Year	Type of Model
Barbuceanu & Fox	1995	Coordinating multi agents in the supply chain
Swaminathan et al	1998	Modeling supply chain dynamics: a multi-agent approach
Lin et al	1998	Modeling supply chain networks by a multi-agent system
Weiss	1999	A multi-agent supply chain framework (MASCF)
Sadeh et al	1999	MASCOT: An agent-based architecture for coordinated mixed-initiative supply chain planning and scheduling
Sauter & Parunak	1999	ANTS (Agent Network for Task Scheduling)
Chen et al	2000	A negotiation-based multi-agent system for supply chain management (Introduction of functional agents)
Fox et al	2000	Agent-based software architecture for supply chain based on four issues (Distribution of activities, coordination, responsiveness, and availability)
Wu	2000	An artificial agent-based approach for the design of shop-floor production lines
Nissen	2001	Agent-based supply chain integration
Gjerdrum et al	2001	A combined optimization and agent-based approach to supply chain modeling and performance assessment
Cohen & Stathis	2001	Strategic change stemming from e-commerce: implications of multi-agent systems on the supply chain
Julka et al	2002	Agent-based supply chain management-framework (introduction of Emulation agents, Query agents & Project agents)
Wagner et al	2003	T ÆMS agents: enabling dynamic distributed supply chain management
Chiu & Lin	2004	Collaborative supply chain planning using the artificial neural network approach
Jiao et al	2005	An agent-based framework for collaborative negotiation in the global manufacturing supply chain network
Janssen	2005	The architecture and business value of a semi-cooperative, agent-based supply chain management system
Tah	2005	Towards an agent-based construction supply network modeling and simulation platform
Zhang et al	2006	An agent-based approach for e-manufacturing and supply chain integration
Liang & Huang	2006	Agent-based demand forecast in multi-echelon supply chains
Lu & Wang	2007	A multi-agent supply chain framework based on network economy
Chatfield et al	2007	A multi-formalism architecture for agent-based, order-centric supply chain simulation
Mele et al	2007	An agent-based approach for supply chain retrofitting under uncertainty
Ming et al	2007	Study on the agile supply chain management based on agent
Labarthe et al	2007	Toward a methodological framework for agent-based modeling and simulation of supply chain in a mass customization context
Wang et al	2008	On-demand e-supply chain integration: A multi-agent constraint-based approach
Lau et al	2008	Real-time supply chain control via multi-agent adjustable autonomy
Nagarajan & Sosic	2008	Game-theoretic analysis of cooperation among supply chain agents
Knoblock & Minton	n.d.	Aents for internet-based supply chain integration (Ariadne)

Table 6.2 – Reflection of multi-agent supply chains in several articles and literatures

7. CONCLUSION

“He laughs best who laughs last”.

This thesis struggles to reflect increasing complication and complexity of logistics and supply chain systems from different angles. In the following, some of its achievements are mentioned:

1) Logistics and supply chain systems are inherently complicated and complex. Solid management of such systems necessitates thorough understanding of what make them complicated and complex.

2) Studying supply chains in context of science of complexity will precisely clarify their characteristic and attributes.
Self-organization is a powerful drive to make the supply chains robust and adaptive.
Supply chains adapt to their environment by adapting their structures by adding or deleting relations between agents (e.g. connecting with new suppliers, serving new customers, etc.), changing their physical abilities (e.g. implementing new technologies) and adapting their behavioral processes, i.e. shifts in strategies. In doing so, a supply chain reacts to environmental demands and at the same time creates a new environment for its competitors. Processes of adaptation take place in different levels of the supply chain at different times and different dimensions.
Adaptation necessitates resilience and robustness of supply chains. In fact, supply chain must resist to its probable changes and revision.
Perceiving the emerged behavior of a supply chain system is one of the most decisive elements of supply chain risk and quality management.
One of the main reasons for studying emergence is to find ways of designing systems that have desirable emergence.
Agents and entities of supply chain need to constantly observe what emerges from a supply network and make adjustments to organizational goals and supporting infrastructure. Further, they should realize that it is quite normal for them to behave in a deterministic fashion based on few salient rules and performance measures. Key is to stay fit and agile and be willing to make appropriate adjustments in the face of changing environment and not be apologetic about making structural changes over a course of time.
Supply chain management plays a critical role in making the network evolve in a coherent manner.
A complex supply network can be thought of as a system of attributes. These attributes combine in some manner to form a “fitness” or goodness value to the product. For example, an automobile may be judged by its cost, its speed, its handling, and its reliability. In most cases, making the product or offering a service better means attending to these underlying features.
Finally, application of chaos theory to various supply chain issues and key functional areas is a necessity. The results may produce an increase in the level of understanding of supply chain ambiguity and how chaos theory may provide valuable insight into the effective management of supply chain networks.

3) In order to reduce complexity to simplicity, a boundary between the part of the world that we want to “understand” and the rest should be defined. In other words, we assume first that there is a “System” and an “Environment”. Later, we should have rules for the

classification of objects that lead to a relevant taxonomy for the system components, which will enable us to understand what is going on. This is often decided entirely intuitively. Several classification procedures of supply chain complexity as well as hundreds remedies of complexity have been suggested.

4) Implementations of smart logistics systems (Lumsden & Stefansson 2007) as well as intelligent agents are significant tools for complexity reduction. Intelligent agents are the best tools for embodiment of characteristics of complex adaptive systems (Self-organization, Adaptation, Emergence and so on).
The considered intelligent agents have the following attributes (Wycisk et al 2008):

(1) Heterogeneous:
Agents can be distinguished by different "rules" defining and/or governing abilities, fitness, goals, patterns of actions, rules of actions, etc. Owing to differences among their governing rules, most agents comprising a Complex Adaptive System (CAS), like supply chain network, are heterogeneous.
Homogeneous agents do not behave in the manner of CAS. In complex supply networks, higher-level agents may represent firms, such as suppliers, manufacturers, distributors, retailers, customers, and other firms constituting the entire supply network. Lower-level agents may be single physical entities within a firm, such as piece goods, machines, containers, or applicable materials for the production of goods. Owing to their different functions within the supply network (distribution and allocation functions), agents may follow individual goals, under different constraints and different action patterns – they are heterogeneous.

(2) Interaction:
CAS intelligent agents may be highly interactive. The form of interaction depends on the nature of the system. For example, with laser light, interaction takes place through the exchange of energy; in social systems interaction might be different modes of human communication.
As long as agents remain motivated to exchange information and/or resources, a stable degree of interaction is assured. Heterogeneity is one driver that sustains the motivation of interaction between agents: if, for example, all agents possess the same knowledge, they would have no motive to exchange information among themselves.
Within supply chain systems, individual objectives of agents provide motives to interact in order to match timely, qualitative, quantitative, cost-oriented or flexible-based logistics goals. Interaction takes place within the whole supply network in form of flows of information, resources and/or finances. In this context, Choi et al. (2001) talk about a "critical level of connectivity" that exists among companies within a supply network and that is a presumption for a firm to be a part of it. Also, at a lower level of a supply chain system, a high degree of interaction between employees and between physical entities may be found. In the case of physical entities, this is possible, if they are enabled to interact directly through communication and information technologies.

(3) Autonomy:
Agents within a CAS act autonomously; meaning that their actions may be self-initiated without any external influence steering or controlling them, though there are usually a few imposing influences.
Firms, subunits, and even physical entities (if enabled) are empowered to a certain degree, via delegation and decentralization, to plan, decide and act without direct supervision.

(4) Ability to learn:
Owing to their ability to learn, agents are able to adapt by modifying their individual capabilities by changing their rules of action so as to improve their performance as experience accumulates. In doing so, agents search for so-called “building blocks,” a set of plausible rules enabling them to interact within a CAS.
Mostly, current research articles explicitly discussing the treatment of logistics systems as CAS, do not mention learning ability. However, where agents represent higher-level organizational entities within a supply network, organizational learning may be present. In contrast, at lower levels, where agents represent physical entities, a general ability of learning can not be ascertained at this time. The learning ability of physical entities requires the newest information and communication technologies (e.g. multi-agent-based models, RFID tags, etc.), but their development is still in progress and not completely implemented in general practice.

According to Datta (2006), there are two advantages in agent-based supply chains:
First, in an ABM, each firm has its own agents. The internal behaviors of agents are not required to be visible to the rest of the system. Firms can maintain proprietary information about their internal operations. Groups of firms can conduct joint modeling exercises (Marketplace) while keeping their agents on their own computers, maintaining whatever controls are needed.
Second, in many cases, simulation of a system is part of a larger project whose desired outcome is a control scheme that more or less automatically regulates behavior of the entire system. Agents correspond one-to-one with individuals (firms or divisions of firms) in the system being modeled, and their behaviors are analogs of the real behaviors.
These two characteristics make agents a natural locus for the application of adaptive techniques that can modify their behaviors as agents execute, so as to control emergent behavior of the overall system. This control of emergent behavior makes intelligent agents as powerful tools for simplification of supply chain intangible complexity.

7.1. Future intelligent adaptive supply and demand networks

In traditional paradigm, the focus of value creation was on the “focal company”. Later on, this focus transferred to “supply chain management” which reflects the fact that the chain should be driven by suppliers (from upstream to downstream). In recent paradigm it is argued that it should really be termed “demand chain management” which reflects the fact that the chain should be driven by the market (from downstream to upstream) not by suppliers. Equally the word “chain” should be replaced by “network” since a company may have several tiers of suppliers and customers (Lumsden 2001; Christopher 2005).
Here, it is argued that the future paradigm will shift to “intelligent adaptive supply and demand networks” which reflects the fact that the supply will be intelligently synchronized by demand.
The holly grail of intelligent adaptive supply chain networks is tied-up in implementation of intelligent agents as well as intelligent flows (Figure 7.1).

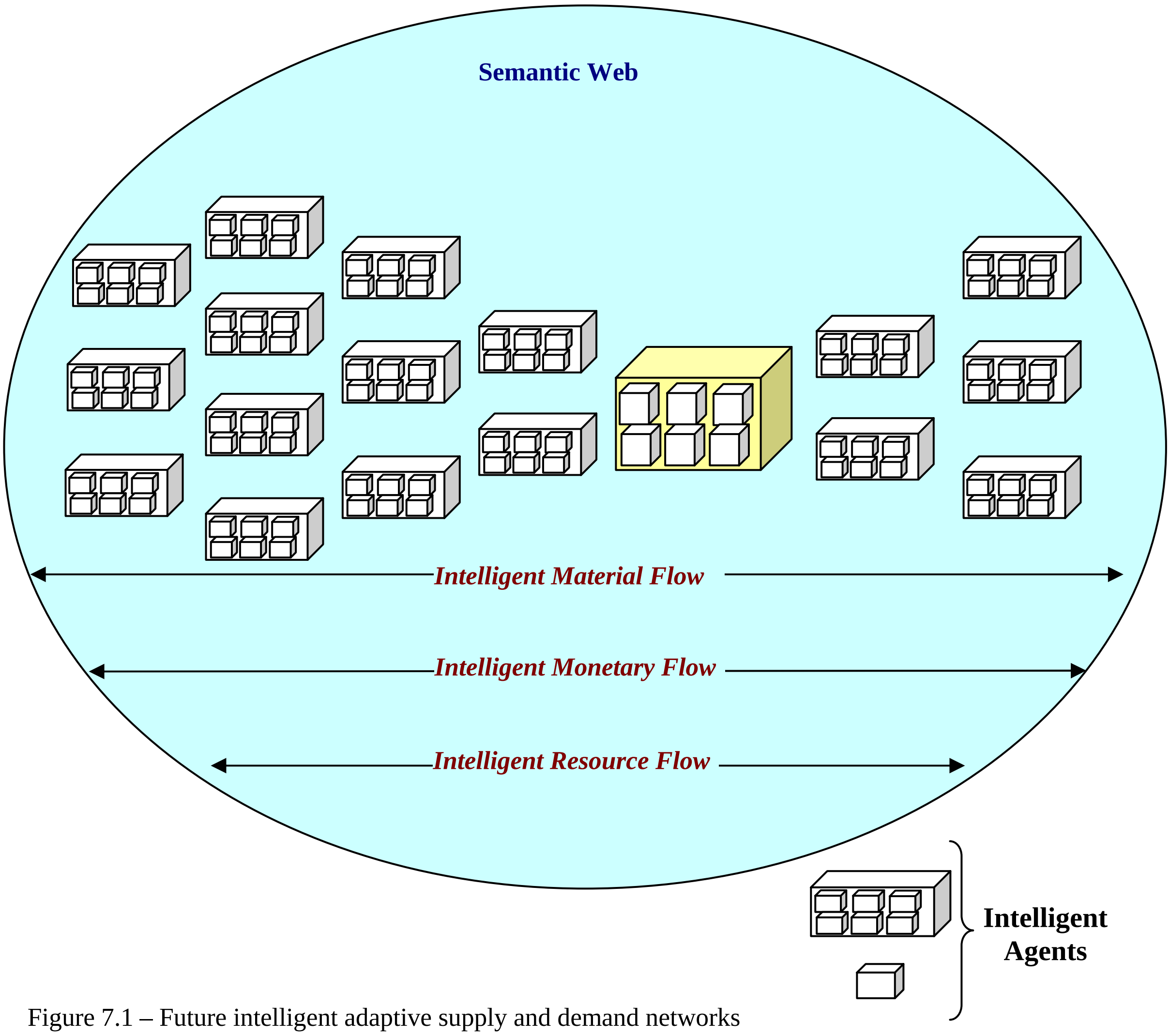


Figure 7.1 – Future intelligent adaptive supply and demand networks

Real-world smart parts supply networks do not yet exist, but Scholz-Reiter et al. (2004 cited in Wycisk et al 2008) observe that there is an ongoing paradigm shift from centralized control of "non-intelligent" items in supply networks towards decentralized operations by "intelligent" items (smart parts) in logistic structures – so-called "autonomous cooperating processes." These smart parts could be raw materials, components or products as well as transit equipment (e.g. pallets or packages) or transportation systems (e.g. conveyors and/or trucks).
According to Sternberg (2008), smart freight, smart goods and intelligent goods are used interchangeably in the literature and are partly synonyms. The concept of smart freight was introduced by Lumsden & Stefansson (2007). They suggest the following capabilities of smart freight:

- Processes a unique identity;
- Is capable of communicating effectively with its environment;
- Can retain or store some data about itself;
- Deploys a language to display its features, production requirements, etc;
- Is capable of support local decision making.

The main characteristic of smart parts is their ability to control themselves, which means that they can make autonomous planning and production choices. Reichl & Wolf (2001) describe such intelligent items as "things that think." Windt & Hulsmann (2007) define autonomous cooperation as decentralized decision-making processes within logistics structures, that is, interacting parts possess the ability to render decisions independently. The objective of such complex adaptive intelligent systems is achievement of robust and effective emergent behaviors that are efficaciously adaptive in the face of uncertain, changing, and frequently non-linear environments.

To establish intelligent flows (figure 7.1), tools like *Jini*, *Bluetooth*, *Semantic Web*, *RFID*, *Barcodes*, *GPS* and techniques like *Fuzzy Logic* could be implemented.
Design of intelligent supply chains based on intelligent agents and flows will revolutionize the future of supply chains. In fact it will lead to automation and synchronization of all activities and processes in supply chains. This can be even a gateway for "robotic supply chains" where every activity of the chain is done by robot(s).
Probably in one century later on or less, instead of "one laptop for everyone", we will have such mottos as "one robot for everyone". So, in such scenario all robots in a chain (network) from Customers' customers' ones to Suppliers' suppliers' ones will be connected to each other and all interactions and flows in the chain are synchronized intelligently.

In figure 7.2, connection of intelligent agents to presented structure of complexity studying is depicted.

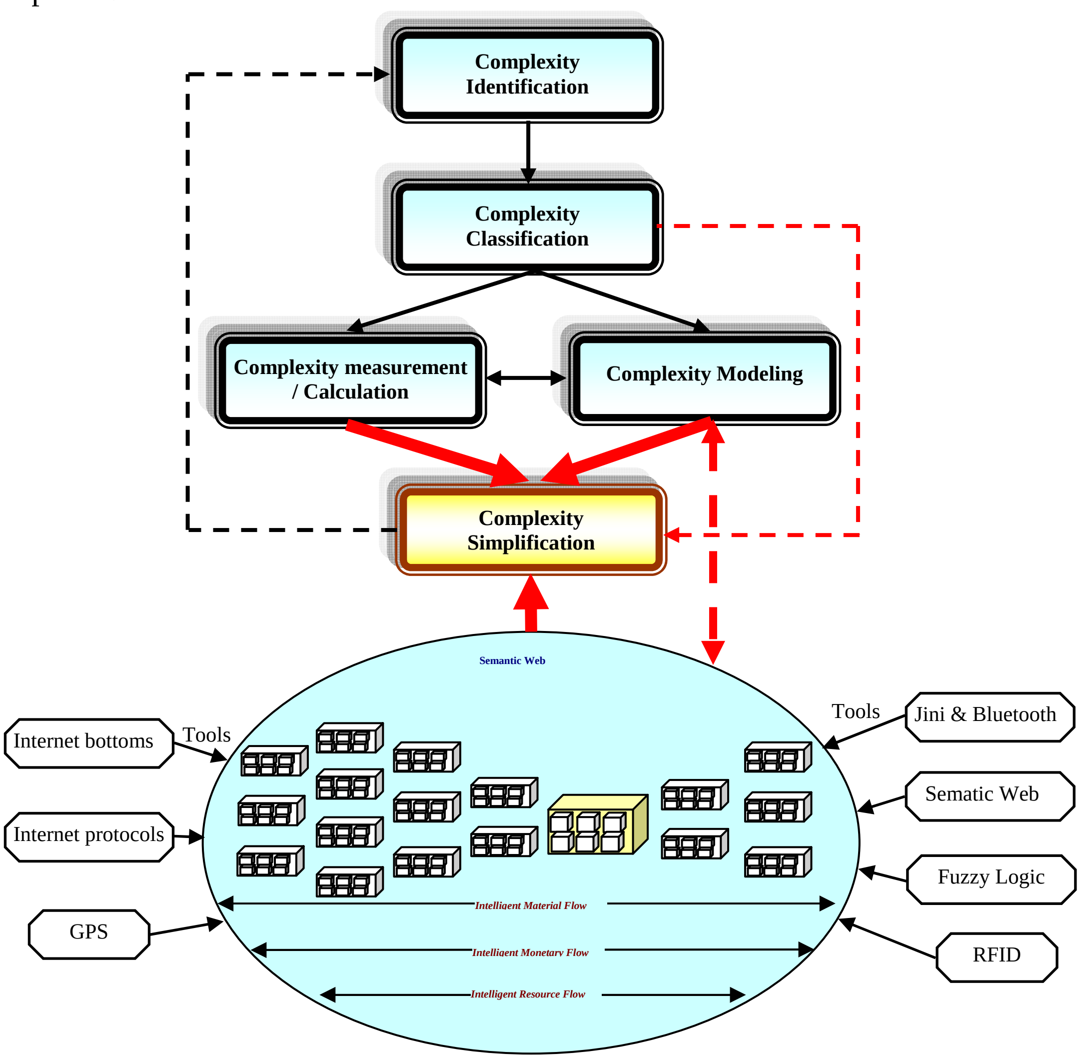


Figure 7.2 – From Complexity to Intelligence

8. FURTHER RESEARCH

"Intelligence is not 'making no mistakes'; but quickly to see how to make them good." (Bertolt Brecht)

As mentioned before, this final thesis is too theory-laden. It would be interesting for the author to increase reliability of several parts of the work by executing the rendered models and frameworks in practice.
In the follow, potential parts, in different chapters of the thesis, for further research are notified:

In chapter 4, discussing different effects of complication and complexity on supply chains based on figure 4.3 would be interesting. Furthermore, plotting effects of supply chain complexity against cost, demand, inventory, process, risk, agility and so on would be challenging.
The author, in a near future, will introduce a novel characteristic and theme of complex systems which is called "Rehabilitation". Moreover, embodiment of rehabilitation in supply chains and logistics will be explained.
The author of this thesis has a good mind to combine science of complexity with science of logistics and supply chains more and more. Recent achievements in dealing with complex and chaotic systems should be also valid for complex supply chains.

In chapter 5, figure 5.1 is a good model for dealing with complex systems but certainly is not the best. Accomplish of this model to an utter one would be interesting.
Literatures review evidence that supply chain measurement and modeling have been much less paid attention than supply chain classification. Measurement of supply chain complexity and connecting complexity to numbers are important tools for benchmarking.
Offered remedies for simplification in section 5.5 are not still mature. Finding recent methods of amending the complexity would be interesting.
In a later work by the author, the concept of 'complexity-based process mapping' would be introduced. Here, different processes in the supply chain would be studied based on their complexity and some simplification hint would be suggested.

Chapter 6 is the holly-grail of future and further research. Intelligent supply chains based on agent-based systems and intelligent processes and flows in the system are powerful tools for simplification of complexity. They are also gateways of 'robotic supply chains'.
In section 6.3, determination of an utter classification of agents in supply chains would be interesting.
Development of agents' communication and interaction, semantic web as well as fuzzy intelligent agents would be intriguing.
Analysis and traverse of different parts of intelligent agent-based supply chains sound essential. In a future research, the author would study production and manufacturing systems of intelligent agent-based supply chains (Figure 8.1).
In intelligent production systems, all entities and flows adapt with each other and decide autonomously. In this scenario, demand is synchronized intelligently with supply. Based on on-line and on-time demands, the optimum required capacity, row materials and inventories, and human resources are calculated.

This intelligence can also affect speed of different flows in the system. In this regard, rate of resources flow (man, machine (like robots, conveyors)) as well as material flow is synchronized intelligently with rate of demand.

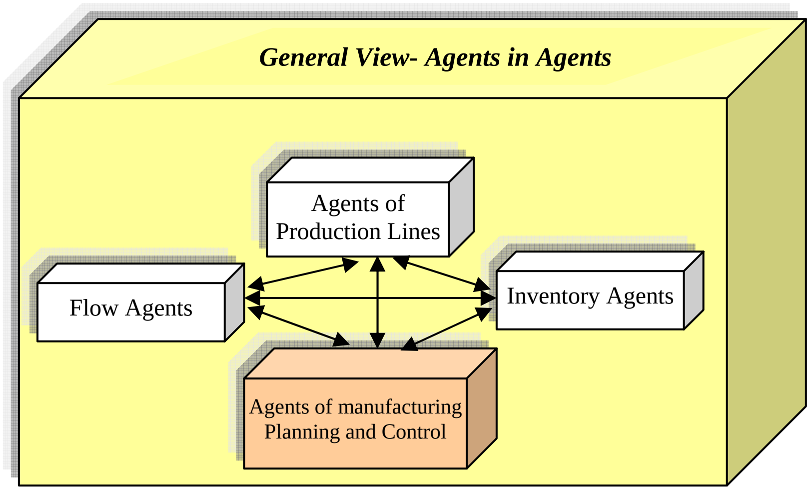


Figure 8.1 – Intelligent agent-based production systems

Furthermore, intelligent agents of manufacturing planning and control would be analyzed thoroughly. Figure 8.2 suggests a rough schema of agent-based manufacturing planning and control (AMPC).

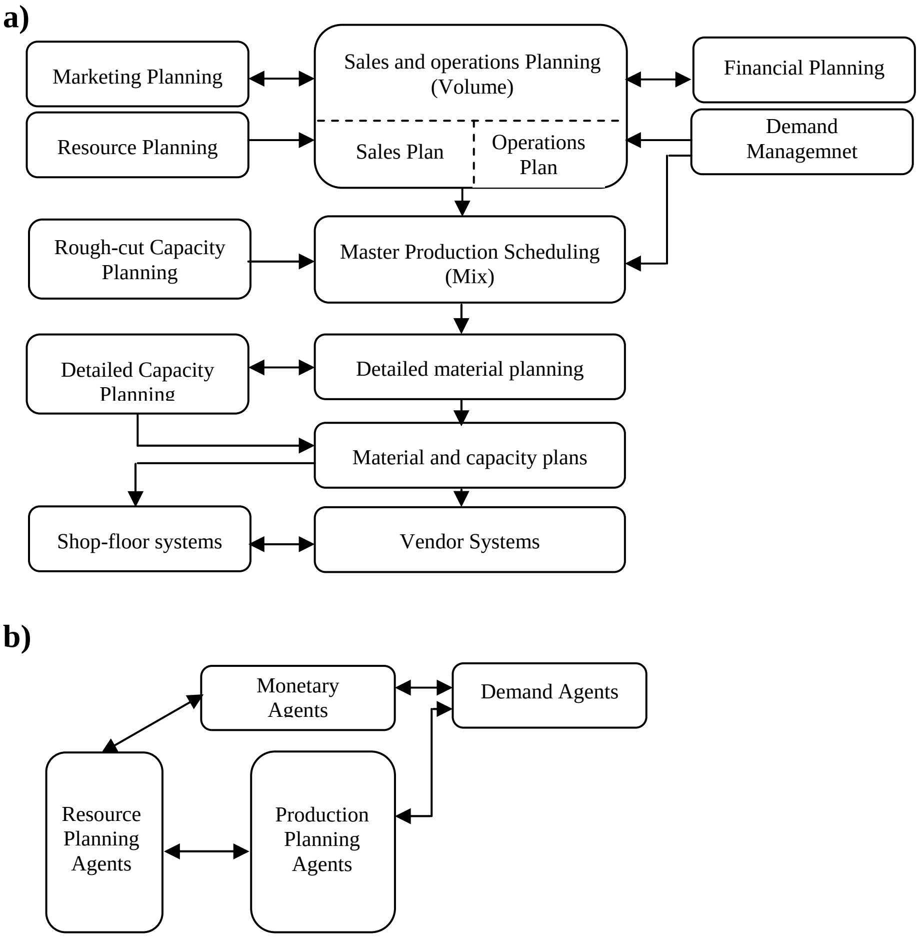


Figure 8.2 – a) Present Paradigm - Manufacturing Planning and Control Systems according to Vollmann et al 2005; b) Future Paradigm – Agent-based Manufacturing Planning and Control (AMPC)

Based on intelligent agent-based manufacturing planning and control systems, different exchanges of traditional systems would be analyzed as shown in table 8.1.

Manufacturing Planning and Control Systems				
Planning and Control Level	***Approaches***			***Intelligent Fuzzy Agents***
Sales and operations Planning	Level		Chase	Fuzzy Leveling
Master Production Scheduling	MTS	ATO	MTO	Decoupling Customer Orders Intelligently
Detailed material planning	Rate-based		Time-based	Fuzzy-based
Shop-Floor Planning	JIT-type		MRP-type	Synchronous type

MTS: Make To Stock; ATO: Assemble To Order; MTO: Make To Order

Table 8.1 – Intelligent manufacturing planning and control systems

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