## Title:

**Autonomous Cooperation – A Way to Implement Autopoietic Characteristics into Complex Adaptive Logistic Systems (CALS)?**

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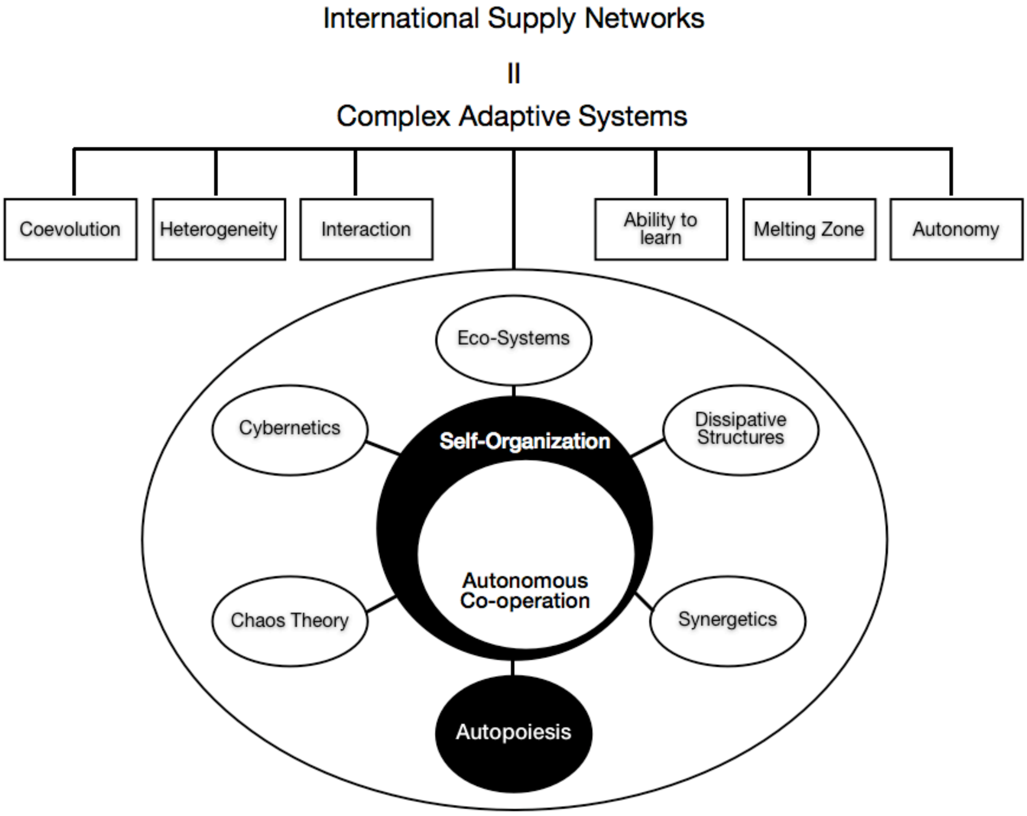
## Abstract:

The intention of this article is to show possible contributions of the concept of autonomous cooperation to enable complex adaptive logistics systems (CALS) to cope with increasing complexity and dynamics and therefore to increase the systems' information-processing capacity by implementing autopoietic characteristics. In order to reach this target the concepts of CALS and autopoietic systems will be introduced and connected. The underlying aim is to use the concept of self-organization as one of their essential similarities to lead over to the concept of autonomous cooperation as the most narrow view on self-organizing systems, which is discussed as a possible approach to enable systems to handle an increasing quantity of information. This will be analyzed either from a theoretical and from an empirical point of view.

### 1. Introduction

From a logistical perspective a tendency from linear supply chains to international supply networks (ISN) can be observed (Surana et al. 2005, Hülsmann et al. 2007, Mason 2007). This tendency includes changes of logistic system structures and environmental conditions. Modern supply network structures can be described as complex adaptive logistics systems (CALS) (Wycisk et al. 2008). One key driver for increasing uncertainty and sensitivity to diverse and changing environmental requirements is the appearance of complexity and dynamics of CALS and their surrounding systems (Wycisk et al. 2008). The understanding of ISN as CALS leads to the realization that the inherent complexity of these systems causes unavoidably nonlinear behavior (Wycisk et al. 2008). In this context a need to analyze opportunities, threads, and impacts for CALS caused by complexity and dynamics can be observed: researchers in this field like Okino (1993) or Ueda (1993) develop such examining concepts for gaining more robustness. Robustness in logistics systems means that a system is stable even in cases of external changes and is able to react to changing environmental conditions. In the context of information systems, robustness means to keep the capacity to handle information at a level that enables a system to make rational decisions (Hülsmann/Wycisk 2005). Therefore, characteristics like flexibility, emergence, and autonomy in logistic systems are needed in order to cope with timely challenges of complexity and dynamics, like the “bullwhip effect” (Forrester 1961; Lee et al. 1997). The fact, that several living systems, that feature suchlike characteristics, have been examined by using the concept of autopoiesis (Varela et al. 1974 as well as other applications like economic systems (Zeleny 1997) or even war as an autopoietic system (Matuszek 2007)), leads over to the question, if the idea of autopoiesis can offer some contributions to an optimal design of logistics systems. Therefore, autopoiesis might on the one hand function as a metaphor to describe logistics systems and its characteristics, which though would include, that there are insurmountable differences between them (Drosdowski et al. (Eds.) 1985). This would reflect an insufficient perspective on the reality of possible prospective technologies and today‘s logistics research. According to Wycisk et al. (2008) (quod vide Surana et al. 2005; Choi et al. 2001; Pathak et al. 2007), logistics systems can be described as complex adaptive systems, which include characteristics like the system‘s self-creation and self-reference. This, in turn, has been factored explicitly into the autopoietic theory (Maturana/Varela 1980) and applied to social systems by Luhmann (Luhmann 1984; Krause 2005). Therefore, the question arises on the other hand, if characteristics of autopoietic systems can be implemented in logistics systems, such as ISN, in order to cope with increasing complexity and dynamics and what instruments are necessary to do so. The theoretic instrument used in this paper, to show respective possibilities, is the concept of autonomous cooperation, which basically states the ability of a system to react to changes in the environment based on own decisions and means of the system‘s single components. The wider concept of autonomous cooperation is self-organisation, which, in turn, has its roots in different concepts, from which one is the autopoietic theory. Therefore, it can be said that autonomous cooperation reflects the idea of autopoiesis and self-organization (e.g. Maturana/Varela 1980; Haken 1973; Prigogine 1969) and allows a system to create ordered structures autonomously (Manz and Sims 1980). Therefore, the concept of autonomous cooperation will be applied to CALS in order to examine its contributions to implement autopoietic characteristics and therefore to increase the system‘s ability to deal with complexity and dynamics. Figure 1 illustrates the coherences between the autopietic theory and ISN, which will be examined in detail in the following sections.

Figure 1: Coherences between Complex Adaptive Logistics Systems and Autopoietic Theory.




The question this paper is going to answer is: Is the concept of autonomous cooperation a reasonable way to implement autopoietic characteristics into logistics systems in order to enable them respective to increase their ability to deal with complexity and dynamics in CALS like ISN? In order to examine this question, the paper is going to proceed as follows. Section two represents the tendency from linear supply chains to international supply networks. This will be used to reveal the increasing sensitivity of international supply networks due to external events. Section three introduces the concept of complex adaptive logistics systems (CALS) and connects it with the properties of autopoietic systems. The underlying concept of complex adaptive systems (CAS) will be described to examine its essential characteristics. One of these properties is autonomous cooperation. Due to the assumption that autonomous cooperation is able to contribute to logistics system's robustness, it will undergo a deeper examination in the following section of this article. Based on these properties the connection between CAS and ISN will be observed. Afterwards, the concept of autopoietic systems will be introduced and connected with the findings of the previous examination. In doing so the autopiesis-concept will be applied to logistical problems whereas it will be focussed on the autopoiesis' possible contributions to the mentioned research question. Following that, the potential abilities of autonomous cooperation to improve the robustness of a CALS that behaves like an autopoietic system, in this case an ISN, will be shown. Section four comprises the simulation due to test empirically the hypotheses on the causal interrelation between different methods of autonomous cooperation and their ability to manage complexity and dynamics of CALS. The simulation model that will be used is a discrete event simulation in the field of production networks. Section five draws conclusions of our findings and gives an overview on future research requirements.

## 2. Tendency from linear supply chains to international supply networks (ISN)

The competitive environment of actors involved in logistic processes is characterized by increasing complexity and dynamics (Hülsmann/Berry 2004). Beside other phenomena (e.g. hyper-competition (D'Aveni/Gunther 1994) and hyper-turbulence (Monge 1995)), hyper-linking (Tapscott 1999) have been discussed as an essential cause for these changes in the environment of logistic actors (Hülsmann et al. 2008). Hyper-linking connotes that the enterprises supply-chains are increasingly interwoven with each other, which means that these actors are not only linked to their direct business partners but as well indirectly to other logistic agents in other supply systems, other countries and other cultures (Tapscott 1999, Hülsmann et al. 2006). This results from the simultaneous integration of one agent in different supply networks and his multidimensional interrelations in combination with the system's immanent openness to other systems in its environment (Tapscott 1999). Therefore, the originally phrased definition of supply chain management that integrates all of the company`s activities and is based on Porters value chain (Porter 1980; Porter 1999) has to be amplified by a view that focuses on the networks lying behind and connecting these value chains with others (Hülsmann/Grapp 2005). Terming this a network instead of a chain is more precise due to its more widely meaning that includes not only material and information flow, but their co-ordination between every single logistic actor in the network (Hülsmann/Grapp 2005). In other words, a tendency from linear supply chains to international supply networks (ISN) can be observed. However Surana et al. came to the same conclusion but integrate the two terms by defining a supply chain as *„a complex network with an overwhelming number of interactions and inter-dependencies among different entities, processes and resources“* (Surana et al. 2005, p. 4235).

In the course of globalization, the number of elements respectively actors in logistics systems increases. On the one hand, this leads to an increasing quantity of information, the information system of an ISN has to handle. Therefore, a necessity for an increasing information-processing capacity can be observed in ISN (Hülsmann et al. 2007).

On the other hand, the more actors are linked to each other, the more potential problem-sources exist. Being linked to many actors in a network means being dependent on many actors, which are in turn accident-sensitive to different external events than other actors in the network. Furthermore, this means that the system's conditions change in increasingly smaller intervals (Hülsmann/Berry 2004). Therefore, new problems can occur from different directions with which companies might have never had to deal before. This leads to an increasing number of potential problems and therefore to a higher sensitivity of the whole supply network. Resulting from this, the butterfly-effect can appear, that states, that minor changes in a complex system can lead to completely different conditions of the system in the future (Lorenz 1972).

In consequence, the management of international supply networks is increasingly confronted with the challenge to adapt to environmental changes.

# 3. ISN as Complex Adaptive Logistics Systems with Autopoietic Behaviour

## 3.1. Description of Used Concepts and their Connection to ISN

### 3.1.1. Complex Adaptive Systems (CAS)

Many kinds of systems, from natural to artificial, can be characterized as complex, e.g. ecologies, social systems or communication networks (Surana et al. 2005). Thereby, the term complexity does not only focus on the number of elements in the system, but particularly on the quantity of relationships between the elements and between the elements and the environment (Dörner 2001; Malik 2000). Due to that, the more elements exist and the more elements are linked to each other in any kind of relationship, the more complex is the regarded system. A biological cell, for example, is a typical complex system, that consists of many proteins that send signals to each other, though they have multiple relationships to other proteins in the cell (Holland 2006).

Furthermore, systems are increasingly confronted with environmental changes, which lead to increasingly dynamic circumstances in which the elements in a system operate and in which the system is situated (Hicks/Gullet 1975; Hülsmann/Berry 2004). Dynamic occurs, when involved elements change themselves or their relationships to other linked elements in the network (Hülsmann et al. 2007). Therefore, dynamics can be described as *„the rate of modification of a system over a specific period of time“* (Windt/Hülsmann 2007, p. 35).

Due to the above-mentioned aspects, it can be assumed that a system's ability to adapt to environmental changes by its own means has an increasing relevance. Furthermore, it can be assumed, that the concept of complex adaptive systems (CAS) can provide this ability (e.g. Surana et al. 2005; Choi et al. 2001; Holland 2002; Wycisk et al. 2008), which leads to the necessity to examine these systems and their properties more precisely.

Its roots can be found on the one hand in biology where systems with living entities were analyzed (Gell-Mann 2002) and on the other hand in the theories of complexity and chaos (Mason 2007). These different approaches have in common, that they all deal with complex systems containing and constituted by a large number of elements, which are linked to each other in a complex structure. (Mason 2007; Gell-Mann 2002).

According to Wycisk et al. (2008) the following properties, mentioned before by Kauffman (1993) and Holland (2002), are essential for CAS and its elements as well for their behavior: (1) Heterogeneity, (2) Interaction, (3) Autonomy, (4) Ability to learn, (5) Melting Zone, (6) Self-organization and (7) Co-evolution. The elements within a CAS in turn can be called agents which may represent e.g. an individual, a team or as well an organization (Choi et al. 2001; Surana et al. 2005; Holland 2002).

First of all, the agents in a CAS are **heterogeneous**. This means that they distinguish themselves from each other through different properties, functions and rules (Holland 2002). In consequence, this results in differentiated behavior within the system because every agent follows *„individual goals under different constraints and different action patterns“* (Wycisk et al. 2008, p. 111).

The agents act as well **autonomously** to a certain degree since their actions are not totally determined by other entities, e.g. from a higher level in a hierarchy (Kauffman 1993; Holland 2002). This results from the existence of the single agents' own rules concerning their behavior (Mason 2007), therefore they are able to make decisions autonomously without the need of any supervision, in other words the system is characterized by **decentralized decision-making** (Windt/Hülsmann 2007; Probst 1987). Decisions can be made decentral if the system provides adequate single elements with necessary resources for it (e.g. relevant information). In contrast to totally hierarchical systems, elements in heterarchical structures have the authorization to make decisions about different action-alternatives autonomously without having to call an entity from a higher level in a hierarchical structure (Windt/Hülsmann 2007). That in turn means, that the management of a system does not have to absorb the complexity that accompanies every single decision-situation in the system. The internal and external complexity, the management of a system has to absorb, decreases because it can be distributed among its multiple elements (Hülsmann/Grapp 2005; Hülsmann/Wycisk 2005). Furthermore, autonomy implies the system's ability to arrange its structure by own means (self-formation), to supervise itself (self-control) and to develop without any impact from the system's environment (self-development) (Probst 1987). However these mentioned characteristics lead as well to a non-predictability about the system's future states, though it is **non-deterministic** (Flämig 1998). This aspect follows in logical consequence the characteristics autonomy- and therewith the decentralized decision-making, which are the reasons for the non-predictability of the single elements' behavior. This means that multiple possible future states of the system exist (Haken 1983).

Due to the agents heterogeneity the agents are as well equipped with heterogeneous resources, e.g. information, which leads to a motivation to exchange them between each other. Therefore, CAS are characterized by **interaction** between the system's elements respectively agents (Holland 2006; Holland 2002; Wycisk et al. 2008). In order to do so, agents have to communicate with each other, which in turn means that agents react on other agent's actions. In the course of a direct exchange of information between them, they do not have to put up with a detour over a hierarchical higher entity. In consequence, the necessary time for decision-making processes abbreviates due to the elements possibilities to communicate directly with each other (Hülsmann et al. 2008). Insofar this can lead to synergetic effects which in turn can result in reaching a qualitative higher level of the whole system (Haken, 1983).

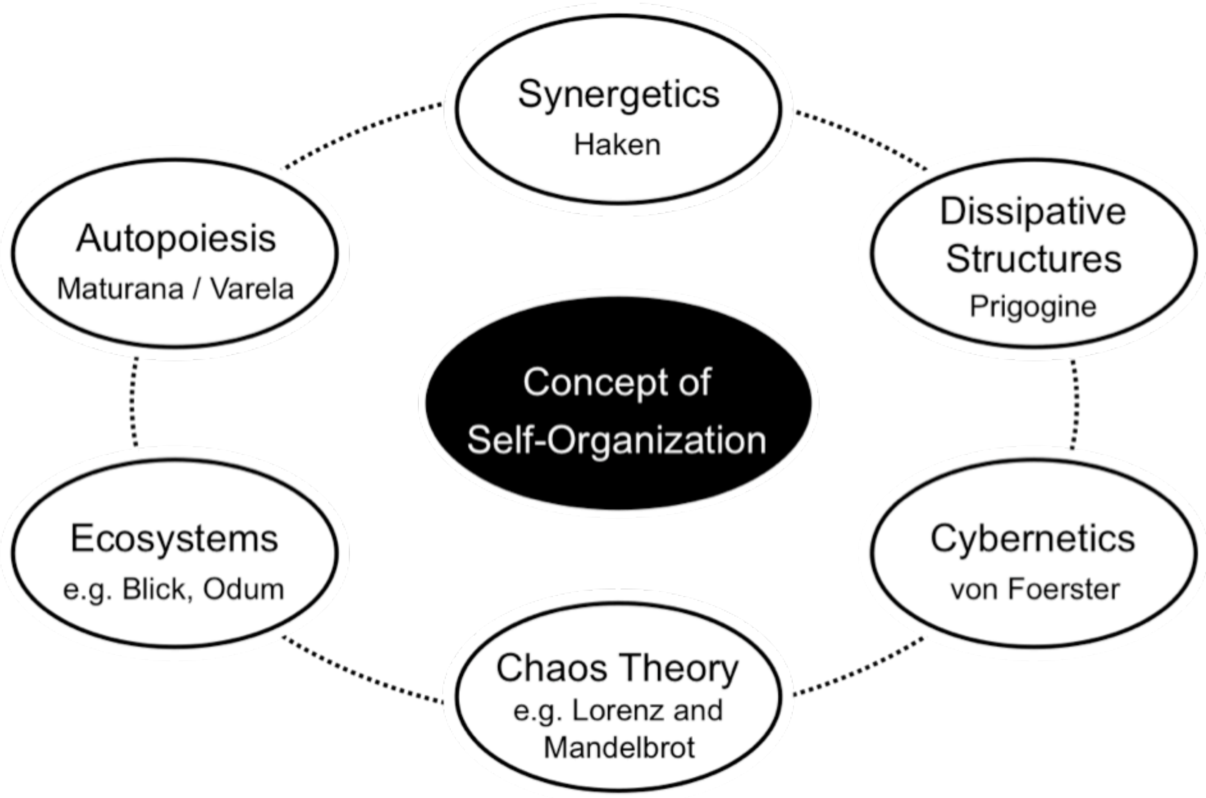
Finally, a CAS is characterized by its agents' **ability to learn** (Holland 2002; McKelvey et al. 2008). According to Holland elements *„...modify their rules as experience accumulates, searching for improvements"* (Holland 2002, p. 25). Thereby CAS achieve the possibility to react on environmental changes, in other words the ability to adopt. In consequence, CAS can be regarded as intelligent systems, whereas the intelligence *„...may be located in its smart parts (...) and their connectivity."* (McKelvey 2008, p. 7).

Besides the properties of CAS there is a need to examine its behavior (Wycisk et al. 2008). First of all, it has **co-evolutionary** characteristics resulting from the agents autonomy- and interaction- properties as well as their ability to learn. On the one hand agents respond to other agents' actions, on the other hand the system is capable to react to environmental changes whereas it in turn can shape its environment through actions respectively responses, which have influences on it (Kauffman 1993; Choi et al. 2001).

Furthermore, a CAS is located in a so called „**melting zone**", which means that it is neither completely ordered, nor completely chaotic, rather it is located in somewhere between these extremes (Kauffman 1993, Surana et al. 2005). According to Surana et al. the elements *„exist in quasi-equilibrium and show a combination of regularity and randomness"* (Surana et al. 2005). That implies that different locations within this melting-zone could be attended by different degrees of contributions to the system (e.g. to the robustness or the flexibility of the system), which in turn means that there could be an optimal location that has to be identified.

Finally, the behavior of a CAS and their agents is characterized by **self-organization** (e.g. Holland 1995; Choi et al. 2001; Surana et al. 2005), which describes an organization-principle, a system uses for its own configuration and organization (Bea/Göbel 1999; Probst 1987). In reference to Windt and Hülsmann (2007) respectively Grapp et al. (2005), its roots can be found, as shown in figure 2, in the following six primal concepts from different disciplines: Synergetics (Haken 1973), Dissipative Structures (Prigogine 1969), Cybernetics (von Foerster 1960), Chaos Theory (e.g. Lorenz 1963; Mandelbrot 1977), Ecosystems (e.g. Bick 1973) and the concept of Autopoiesis, which will be introduced in details later on (Maturana/Varela 1980).

Figure 2: Primal concepts of the idea of self-organization.




Source: Windt/Hülsmann 2007.

Self-organization can be regarded as a part of management and describes the modality, how an ordered structure in a system can arise out of itself, which includes the ability to arrange its own processes and structures without any impact from the outside of the system (Bea/Göbel 1999; Probst 1992; Mainzer 1994; Windt/Hülsmann 2007).

According to Probst (1987) self-organizing systems are characterized by the following four properties: (1) Complexity, (2) autonomy, (3) redundancy and (4) self-reference. The terms **complexity** and **autonomy** were described above and constitute essential characteristics of CAS. The existence of autonomously acting agents, that interact between each other and whose behavior is not determined by other entities, enables a self-organizing system to evolve by own means (Windt/Hülsmann 2007), which in turn leads to unpredictability of future system states (Haken 1987; Prigogine 1996).

**Redundancy** means that there is no difference between organization and execution in self-organizing systems (Probst 1987). Furthermore, the elements are equipped with similar respectively with the same assets and abilities, which means that no functions exist in the system, that can be executed by just one element (Wycisk 2006). Insofar, the system comprises no elements with a permanent dominant impact on the system's development, in other words the elements have similar degrees of influences on it (Probst/Mercier 1992). This aspect shapes the system's **heterarchical structure** (Hülsmann/Wycisk 2006). This leads to an increasing flexibility of the system, because if one element is for any reason not able anymore to execute its function, this function can be taken over by another element. Beside this and as mentioned before, the complexity, the management of a system has to absorb, decreases due to the absence of an entity on a higher level in a hierarchical structure that supervises the single elements' functions. (Hülsmann et al. 2008).

Whereas self-organizing systems are on the one hand open to absorb information and resources, which enables it to adapt to environmental changes (Varela 1979; Malik 2000), they are on the other hand operationally closed (Windt/Hülsmann 2007). This results from its **self-reference**, which describes the system's ability to build its own borders by own means. It offers the elements the information they need to decide autonomously, which is the basis for their actions. Therefore, the system's behavior starts with the existence of this characteristic, as well as the ability to measure environmental changes or to realize possibilities for internal synergies (Probst 1992). In consequence, self-reference enables the system to distinguish itself from its environment (Luhmann 1984).

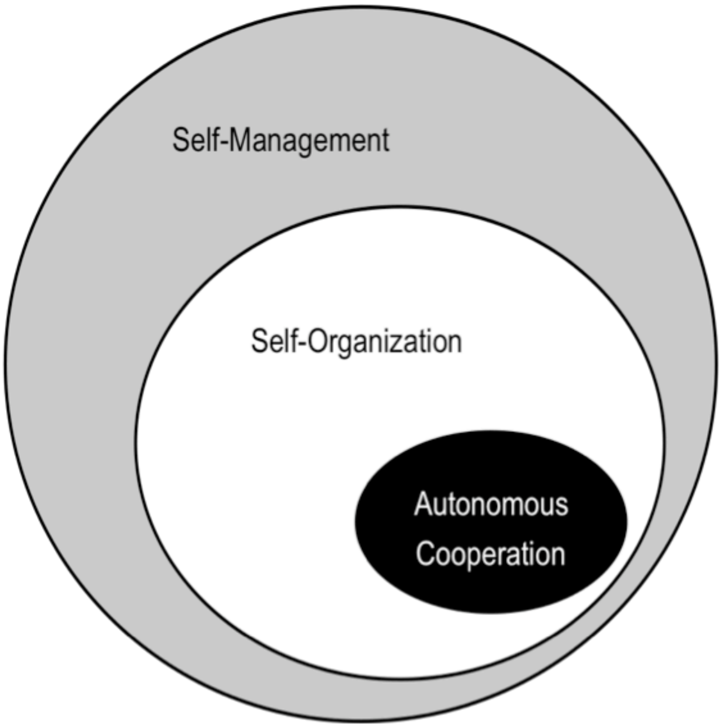
### 3.1.2. Autonomus Cooperation

The concept of self-organization, which is, as shown above, an important property of complex adaptive systems, leads to an approach that is currently discussed as a possible enabler for coping with increasing complexity and dynamics in the system's relevant environment: Autonomous cooperation (Hülsmann et al. 2006; Hülsmann et al. 2007).

The concept of autonomous cooperation is part of a multilevel perception which is based on the ideas of complexity-sciences (Hülsmann/Wycisk 2005). Notwithstanding a clear assignment has not been found in science up to now, it can be distinguished between self-management, self-organization and autonomous cooperation (Hülsmann/Wycisk 2005; Wycisk 2006). The widest notion is constituted by the term self-management, which describes the whole system in its ability to configure itself independently from other systems (Manz/Sims 1980). As mentioned before, self-organization has to be understood as a part of management, more precisely, as a part of self-management (Hülsmann/Wycisk 2005).

The concept of autonomous cooperation focuses on the single system-elements and is, due to that, the most narrow view to self-organizing systems respectively, as shown in Figure 3, can be seen as a part of the larger concept self-organization, which in turn has part of its roots , as shown before, in the concept of autopoiesis.

Figure 3: Classification of the terms ‘self-management’, ‘self-organization’ and ‘autonomous cooperation’.



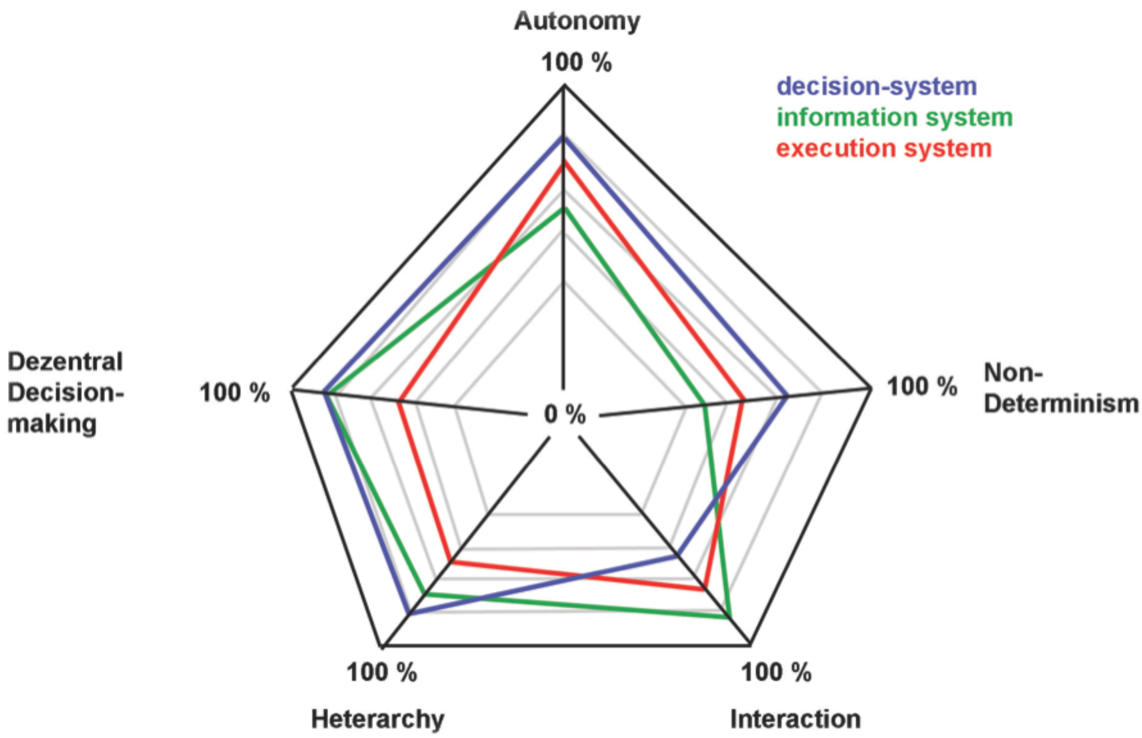

Source: Hülsmann/Wycisk 2005.

Its main goal is to achieve a better ability to cope with increasing complexity and dynamics, though to increase the robustness of a system (Windt/Hülsmann 2007).

According to Windt and Hülsmann autonomous cooperation describes „[ ...] *processes of decentralized decision- making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and* *possibility to render decisions independently"* (Windt/Hülsmann 2007, p. 8). Resulting from this definition processes in complex adaptive systems can be called autonomously cooperating, when the following five constitutive attributes, which were already described above, can be observed: (1) decentralized decision-making, (2) autonomy, (3) non-determinism, (4) heterarchy and (5) interaction (Windt/Hülsmann 2007).

As shown in figure 4, these constitutive attributes of autonomous cooperating processes can adopt different degrees (e.g. within a continuum between 0% and 100%) on different levels (e.g. decision system, information system and execution system), which can vary in the course of time (Hülsmann/Grapp 2006; Hülsmann et al. 2008).

Figure 4: Polarisation Graph.




Source: Hülsmann/Grapp 2006.

### 3.1.3. Complex Adaptive Logistics Systems (CALS)

As shown before, a tendency from linear supply chains to international supply networks (ISN) can be observed (Surana et al. 2005, Hülsmann et al. 2007, Mason 2007). Several authors were arguing that ISN in turn can be regarded as CAS (i.g.

Surana et al. 2005; Choi et al. 2001; Pathak et al. 2007; Wycisk et al. 2008), which leads to the term of complex adaptive logistics systems (CALS). According to Pathak et al. it is self-evident to identify an ISN as a CAS, because *„organizations exhibit adaptivity and can exist in a complex environment with a myriad relationships and interactions."* (Pathak et al. 2007, p. 550).

Complexity in international supply networks results from the *„large amount of involved organizations and relations between these organizations"*, which can be circumscribed by the already mentioned term hyper-linking (Hülsmann et al. 2007). To illustrate this complexity, the example of a multinational textile-company in Hong Kong will be regarded. In a highly globalized world the value chains of companies are not limited to one country, not to mention to one organization. This company can have its customers, its different retailers as well as its different production-locations and suppliers for different parts of their clothes widespread over the world (Natarajan 1999). This leads to the system's inherent complexity and requires therefore a ability to cope with it.

Furthermore, increasing dynamics in ISN can be observed, which is a result of the already mentioned phenomena hyper-linking (Tapscott 1999), hyper-competition (D'Aveni/Gunther 1994) and hyper-turbulence (Monge 1995). Dynamics emerge when, e.g. the contracts with retailers or with extern suppliers expire or organizations linked to the exemplified textile company are not able anymore for any reason to deliver resources. The textile company can as well search for better or cheaper possibilities to get the needed parts like yarn or zippers or for better and cheaper ways to deliver the clothes to the retailers as well as to search for new retailers and/in new markets. Though changes in the ISN can arise from multiple different directions, which reveals the inherent dynamic in ISN.

If organizations do not adapt to these kind of changes, they can lock-in into a suboptimal situation in which they are not able any longer to respond adequately to the resources-requests of their environment, which in turn can lead to negative effects on the continuity of the organization (Schreyögg et al. 2003). In consequence, this leads to the organizations' necessity to adapt to environmental changes, which means to adopt the ability to act flexible without losing stability, though to reach a balance (Hülsmann et al. 2008).

Surana et al. (2005) call a supply network *„[...] higly non-linear,* [*that*] *shows complex multi-scale behaviour, has a structure spanning several scales, and evolves and self-organizes through a complex interplay of its structure and function"* (Surana et al. 2005). Therewith, the most essential CAS-properties can be found in ISN. In the course of describing these properties Pathak et al. (2007) as well as Wycisk et al. (2008) confirm the parallels to supply networks but formulated a few limitations to them, e.g. that CAS properties best fit to living systems whereas logistics systems are only partly alive, e.g. managers (Wycisk et al. 2008). But the validity of this limitation is decreasing due to the current development of new technologies that enable non-living parts of systems to decide autonomously and though to approximate to the acting rules of human parts in the system and become a kind of intelligent. According to Scholz-Reiter et al. (2004) a paradigm shift in supply networks can be observed that leads from centralized planning and control of non-intelligent entities to decentralized planning and control of intelligent entities in the network. In consequence, with consideration of these developments, ISN can be regarded as CALS (Wycisk et al. 2008; Pathak et al. 2007).

### 3.2. Autopoiesis and its Connection to CALS

#### 3.2.1. Autopoiesis as a Theoretical Basis

The properties of CALS connected with the previously mentioned technological developments lead to the assumption, that CALS can, in analogy to the biological roots of CAS, be regarded as living systems at least to a certain degree. Maturana and Varela (1980) dealt in their autopoiesis-concept, which in turn is one of the primal concepts, the self-organization-approach is based on, with the question, by what living systems can be distinguished from non-living systems. Therefore, autopoiesis could be an adequate theoretical basis for further and deeper examination of the effects emanating from CALS and its implications for its management.

The term autopoiesis derives from the greek words autos=self and poiein=making respectively creation or production, therefore it can be circumscribed as well with the terms self-production or self-creation (Maturana/Varela 1980; Drosdowski 1989). This concept was originally created to explain phenomena in biology and describes a system that is characterized by a network of the single elements production-processes, in which they **interact** between each other and create as well as realize the system itself in a recursive way (Maturana/Varela 1980). Furthermore, the single elements are distinct, thus they are **heterogeneous**, and they are able to act without the need of confirming it by another entity, which means, they are **autonomous** (Maturana/Varela 1980) and they act according to a basis of specific behavioral rules (Zeleny 1997; Zeleny 2001). The autonomy of the elements within a system results from its circularity which means, that there is no central reference point in the system from that it develops. According to Flämig (1998) this is a central aspect in the autopoisis-concept. Therewith, the system's elements build the network of production-processes themselves, in other words they constitute it and simultaneously build its borders. The organization of such a system is called an autopoietic organization, in other words a system that **organizes itself by it's own means** (Maturana/Varela 1980; Maturana 1999).

Beside other authors that transferred this approach to new areas of application (Flämig 1998) Luhmann (1984) uses it for certain questions in social sciences, which have relevance for the examination of organizations. The recursive self-production process is illustrated by communication between single actors in a closed social-system, e.g. an enterprise. Therewith, communication functions as the creator of social systems. According to Luhmann (2006) communication does only exist as social systems and in social systems. Due to the impossibility to divide communication, a smaller element does not exist in a social system. Luhmann (1990) describes a chain effect in which every communication produces another following communication without the need of an external entity to trigger the following one; therewith this can be called a self-organizing system.

### 3.2.2. CALS as Autopoietic Systems

Compared with the further described essential properties of CALS, autopoietic organizations show direct similarities.

First of all and as shown above, CALS are **self-organizing** (Surana et al. 2005; Choi et al. 2001; Wycisk et al. 2008), likewise as autopoietic systems (Maturana/Varela 1980). This implies, that autopoietic systems are characterized by the above described properties **complexity, redundancy, self-reference** as well as by **autonomy** (Windt/Hülsmann 2007), which is an essential precondition of autopoiesis (Maturana/Varela 1980). Therewith, just like in autopoietic organizations, no central entity exists in CALS, that coordinates the single elements' actions, therefore a **circularity** can be observed (Flämig 1998). This in turn is a result of the system's inherent characteristic of **decentralized decision-making** (Windt/Hülsmann 2007; Probst 1987). Furthermore, the system's elements are **heterogeneous**, because their behavior is determined by different rules (Holland 2002). A basic necessity for the functionality of a CALS as well as of an autopoietic system is the elements' ability to **interact** between each other (Maturana/Varela 1980; Holland 2006; Holland 2002; Wycisk et al. 2008), which means they exchange information by means of using a certain language (Maturana/Varela 1980), in other words, they communicate (Luhmann 2006).

Because these interactions can result in actions that have influences on the system's structure, which means, the elements react to each other, they **contribute in a recursive way to the creation of the system-structures** in which the interacting elements exist (Maturana/Varela 1980). Therefore, the structure of the CALS as an autopietic system evolves, develops and is being controlled by its own elements, just like a biological cell, that creates its own elements by own means (Flämig 1998), in other words, it is characterized by its **recursive self-production.**

These properties lead in logical consequence to the elements **ability to learn** and to **co-evolution** (Kauffman 1993; Choi et al. 2001). When environmental changes occur, the single elements have to change their rules to keep the system alive due to the absence from an outside impact on the system. That means, that the elements in an autopoietic system as well as in a CALS react on the other elements' actions and to environmental changes. Changes of the elements lead in turn to changes in the system's structures, whereas some of these changes can have influences on the environment of the autopoietic system (Kauffman 1993; Choi et al. 2001). Finally autopoietic systems must have in analogy to CALS a kind of **melting zone** due to a system's impossibility to be completely self-organized as well as being completely organized by an external entity, rather it is situated in a continuum between these two extremity pools (Wycisk 2006).

In summary, it can be said that CALS exhibits the same essential properties like autopietic systems, which in consequence means, that they can be regarded as one of that ilk.

### 3.3. Contributions of Autonomous Cooperation for Coping with External Complexity and Dynamics

As shown above, CALS (e.g. ISN) can be regarded as autopoietic systems, whereas these systems can comprise multiple organizations (e.g. production locations, retailers, suppliers) with multiple elements (e.g. managers, non-living items equipped with technology that enables them to render decisions autonomously). Due to their self-organizing property, which is an essential characteristic of both concepts, they are characterized by their possibility to adopt autonomously cooperating processes (Windt/Hülsmann 2007).

As mentioned before, the environment of CALS is characterized by increasing complexity and dynamics (Wycisk et al. 2008). These are in turn causes for external risks (Hülsmann et al. 2007), which can be described as an impossibility to forecast future developments. This impossibility in turn has its causes in a lack of the information, which would be necessary to decide under secure circumstances (Rosenkranz/Missler-Behr 2005). Caused by increasing complexity and dynamics, the informational basis for secure decision-making is deteriorating (Hülsmann et al. 2007). If the system is not able any longer to handle the incoming information, which means, that it is not able to make rational decisions, the system can become *locked-in* (Schreyögg et al. 2003; Hülsmann/Wycisk 2005). This leads to a necessity to enlarge the capacity to handle the information, the system is confronted with (Hülsmann et al. 2007). The ability to cope with these external risks implies the system's ability to adapt to environmental changes that are in turn causative for the appearance of external dynamics (Hülsmann et al. 2007).

Autonomous cooperation has been discussed as a possible enabler for coping with these challenges and therewith, to increase the system's robustness (Hülsmann et al. 2006). Hence, the question arises, whether the inherent characteristics of autonomous cooperation can contribute to that. These possible contributions, shown in figure 5, are described in the following and will be illustrated by the already mentioned CALS-example of a multinational textile company, which behaves like an autopoietic system.

Figure 5: Possible contributions of autonomous cooperation to a system's ability to cope with external risks.

| Attributes of AC | Technical consequence | Impacts on the management of ISN | Implications on external risks in ISN |
|---|---|---|---|
| Decentralized decision-making | Delegation of decisions to elements of the system | Increase of decision-making capacity | Increase of the ability to handle information |
| Autonomy | Element is responsible for its system design | Enables the system to develop itself | Superior structures to handle complexity and dynamics |
| Interaction | Elements communicate directly with each other | More target oriented exchange of information | Less capacity to handle information is needed |
| Heterarchy | Independence between elements and planning unit | Structure might become more complex and dynamic | More internal complexity and dynamics |
| Non-determinism | Higher efficiency in dealing with complexity | Enables the system to react to changes in the structure | Increase the ability to cope with risks that result from dynamics |

**Decentralized decision-making:** Due to the delegation of decisions to the single elements of the system (e.g. production locations), the **decision-making capacity of the whole ISN increases** (Hülsmann et al. 2007). In consequence, the logistics system's ability to handle information and therefore to adapt to environmental changes can be enlarged. For example, if one location of the textile company stops its production, a decision must be made, which other location has to continue this work. If the headquarter would have to ask first all locations, if they are able to do the same work and then to find the best alternative between all these locations, the decision-making process could take longer than in a case where every location stays in direct contact to the others and are able to render this decision independently. Therefore, the headquarters can be disburdened from its necessity to handle every information about the single system's elements and the decision-making capacity of the whole ISN can be enlarged.

**Autonomy:** If the elements can decide by their own, they are, as shown above, autonomous (Windt/Hülsmann 2007; Probst 1987), which means that the single elements are responsible for the system's design in which they exist. For this reason the development of the system and therewith its direction is as well controlled by its single elements (Probst 1987). This can lead to a **superior system-structure** concerning its ability to absorb complexity and to handle dynamics, in other words, to adapt to environmental changes (Hülsmann et al. 2007). For example, if the production-locations can choose by own means, what kind of clothes they produce and to which retailers in which countries they deliver their products without having to ask the headquarter first, the headquarter would have less decisions to make and therefore less complexity to absorb. Furthermore, if the elements in a logistics system are able to decide, the production locations can as well decide by their own to open up another one (e.g. to increase the production capacity) or to close one of them. Consequently the production- and delivery-structure of the whole ISN would evolve and develop as well as being controlled by its own production locations (Flämig 1998; Probst 1987). This can lead to a superior production structure (which location produces which product and which should be downsized respectively enlarged), concerning its ability to handle dynamics caused by environmental changes (e.g. changes in the demand-structure) compared to a structure that is totally controlled by the headquarter. In this aspect, the resulting recursive self-production of the system through its elements becomes apparent (Maturana/Varela 1980).

**Interaction:** Because the elements in the autopietic CALS are able to **interact** respectively to communicate directly with each other (Holland 2006; Holland 2002; Wycisk et al. 2008; Maturana/Varela 1980; Luhmann 2006) a **more target-oriented exchange of information** can result. The elements exchange only their needed portion of information, so that they need less capacity to handle them (Hülsmann et al. 2007). Picking up the mentioned example, the single production location that stays in direct contact to the other locations does not have to pick up a detour over the headquarter to get some needed information. Instead, they can directly ask other elements in the ISN (e.g. retailers or other production locations).

**Heterarchy:** The heterarchic characteristic of an autopoietic CALS is constituted by independence between the elements and a planning unit. This might lead to a more complex and dynamic system structure and therewith to **more internal complexity and dynamics**; the system has to cope with (Hülsmann et al. 2007). Beside this effect, it has to be taken into account as well, that heterarchy can as well **increase its ability to adapt to environmental changes.** Because the single elements are equipped with similar resources and abilities, one element can undertake another elements function. Therefore, the system's flexibility increases (Hülsmann et al. 2008), which enables an organization to respond to changing environmental conditions (Sanchez 1993). This can be illustrated as well by the already taken example of the textile company: If one of its contractors (e.g. a production location that produces a special kind of trousers) had a production-stop due to any reason, the company could simply switch to another one that has the same assets and abilities to produce this kind of clothes.

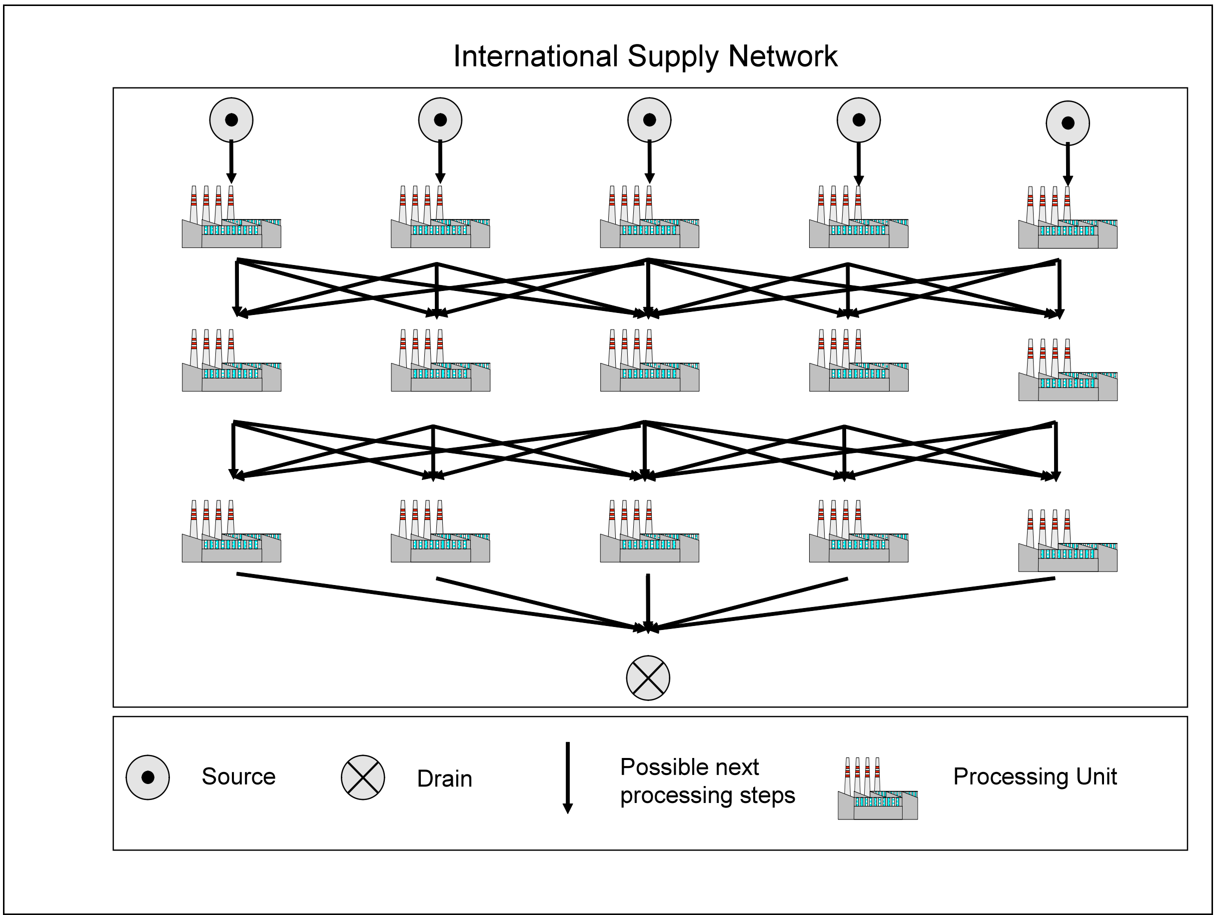
**Non-determinism:** Finally, autopoietic CALS can reach a higher effiency in dealing with complexity due to its non-determinism (Windt/Hülsmann 2007). This results from the fact, that future system states, the elements have to comply with even when environmental changes occur, are not fixed beforehand (Flämig 1998). Hence, uncertainty about the question, weather the system will be able to handle environmental changes and enables it to react to changes in the system structure, can be reduced (Hülsmann et al. 2007). This implies an **increasing ability to cope with risks** resulting from dynamics. In the mentioned example of a textile company, non-determinism would exist, when the production locations, for example, were not bounded to a certain production plan for a fixed time-period. Changes in demands on the market could not be taken into account if they were bounded. Therefore, this non-determinism enables the elements to change plans and therefore it enables the system to react on environmental changes, which can occur as risks for the whole ISN.

## 4. Empirical Test

### 4.1. Test Design

In the previous research it has been identified theoretically that CALS can be seen as autopoietic systems, because the main characteristics of both are similar, respectively identical. According to that, an empirical test of the implications that autonomous cooperation has on the management of CALS could allow to draw conclusions about autonomous cooperation in autopoietic systems as well. To measure the effects of autonomous cooperation on CALS a simulation and measurement system has been developed that allows analyzing the effects of different autonomous cooperation methods on the robustness of production networks with different levels of complexity and different levels of external dynamics. In earlier work of the authors, the simulation model has been used to analyze effects of autonomous cooperation on ISN (Hülsmann et al. 2007; Hülsmann et al. 2006). A similar approach will be used to analyze effects of autonomous cooperation on CALS. Figure 6 shows the simulation model, which has been implemented as a discrete event simulation. The scenario shows a matrix like network of different production stages that are interlinked and able to exchange information, resources and orders to perform a multi-stage production process. On one stage the facilities are able to perform resembling production steps. Each order has a specific processing plan i.e. a list of processing steps that have to be undertaken to produce goods. In the model, the orders are not directed by a centralized control entity but have the ability to render decisions on their next processing step autonomously by using different concepts of autonomous cooperation. Depending on the different autonomous control methods, the overall system shows altered behavior and dynamics.

Figure 6: Matrix-Model of an ISN as an example for CALS.




Source: According to Hülsmann et al. (2007).

This model comprises the opportunity to evaluate the system's ability to cope with different levels of complexity as well as different amounts of external dynamics. The complexity can be varied by using different numbers of production facilities or different kinds of orders and products. The orders enter the system at the sources. Here, the external dynamics can be varied by using different functions that define the arrival rate of different kinds of orders. By implementing different autonomous control methods the ability of autonomous cooperation to influence a system's robustness can be analyzed. Therefore, the system's performance will be measured for different autonomous control methods with varying levels of complexity and external dynamics.

### 4.2. Methods of Autonomous Control

In the following, the applied autonomous control methods will be described. The first method, called Queue Length Estimator (QUE), compares the current buffer level at all parallel processing units that are able to perform the next production step. The buffer content is not counted in number of parts but the parts are rated in estimated processing time and the actual buffer levels are calculated as the sum of the estimated processing time on the respective machine. When a part has to render the decision about its next processing step it compares the current buffer level, i.e. the estimated waiting time until processing, and chooses the buffer with the shortest waiting time (Scholz-Reiter, et al., 2005).

The pheromone method (PHE) does not use information about estimated waiting time, i.e. information about future events, but uses data from past events. This method is inspired by the behavior of foraging ants that leave a pheromone trail on their way to the food. Following ants use the pheromone trail with the highest concentration of pheromone to find the shortest path to food. In the simulation this behavior is imitated in a way that whenever a good leaves a processing unit, i.e. after a processing step is accomplished, the good leaves information about the duration of processing and waiting time at the respective processing unit. The following parts use the data stored at the machine to render the decision about the next production step. The parts compare the mean throughput times from parts of the same type and choose the machine with the lowest mean duration of waiting and processing. The amounts of data sets that are stored define the up-to-datedness of the information. This number of data sets can be used to tune the pheromone method. The replacement of older data sets resembles to the evaporation of the pheromone in reality (Scholz-Reiter, et al., 2006).

The due date method (DUE) is a two-step method. When the parts leave a processing unit they use the queue length estimator to choose the subsequent processing unit with the lowest buffer level. The second step is performed by the processing units. The due dates of the parts within the buffer are compared and the part with the most urgent due date is chosen to be the next product to be processed (Scholz-Reiter et al. 2007).

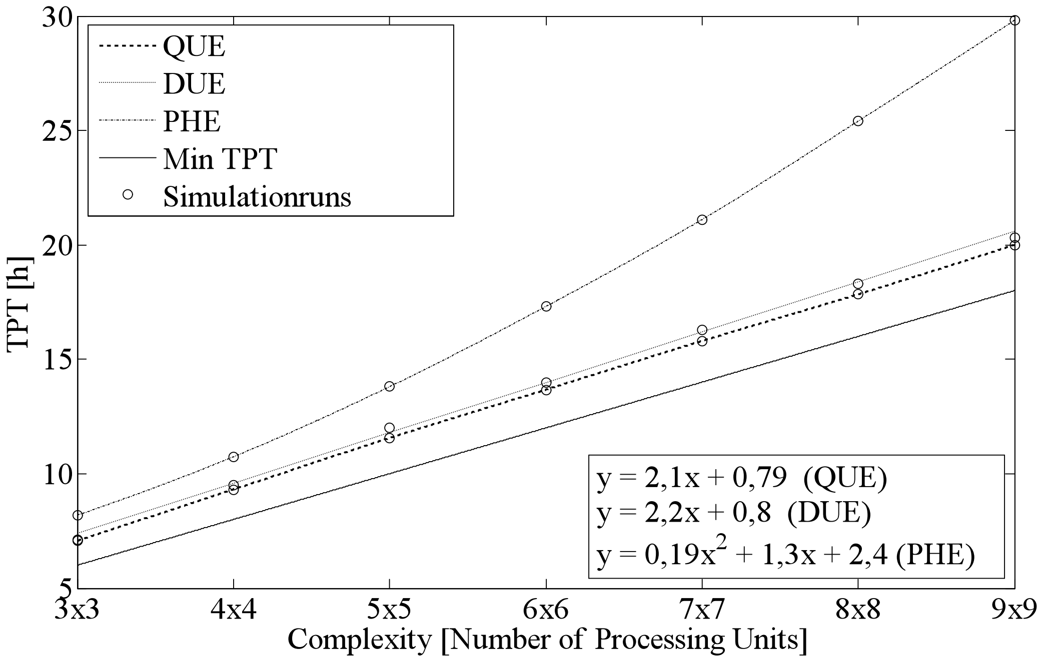
The following simulation analyses the overall system’s ability to cope with rising structural complexity and rising external dynamics using different autonomous control methods. At each source the arrival rate is set as a periodically fluctuating function. The logistical goal achievement is measured using the key figure throughput time for different levels of complexity and different autonomous control methods.

Therefore, the simulation model is able to represent the main characteristics of CALS. The agents within the model have different characteristics e.g. different due dates or different production steps, therefore they can be assumed to be **heterogeneous**. Additionally **interaction** between the system's elements is implemented, due to the agents' ability to communicate with each other (e.g. the different orders communicate with the processing facilities furthermore the order agents communicate with each other using the stigmergy concept i.e. communication via the environment by leaving information for following agents). As well the agents are able to act **autonomously** since the orders are able to render their decisions concerning the next processing step. Up to now the learning ability within the simulation model is limited due to the fact, that the agents are modeled relatively simple so that they themselves do not have any learning abilities. In contradiction to that, the methods of autonomous control enable the system to react flexibly to changes and to **learn** about changes in the system's structure, for example if a machine breaks down the control methods enable the agents to avoid this machine in the production plan and therefore enable the overall system to learn how to react on unexpected changes. The **melting zone** is part of the analytical aim of the simulation. As different grades of autonomous control are compared to each other via different control methods, they can be seen as different grades in a continuum between 100% decentralized decision-making and 100% centralized decision-making (Hülsmann/Grapp 2006). Therefore, the different methods of autonomous control might represent different locations in the melting zone. Finally, **self-organization** is implemented into the simulation model by applying the ability to the agents to organize their processing autonomously.

### 4.3. Test Results

Figure 7 shows the results, i.e. the mean throughput times for the three different autonomous control methods in dependence of the system's complexity. To the right of the figure the system's complexity is increased by enlarging the amount of processing units as well as the number of sources. Furthermore, the minimal throughput time, which is rising with increasing complexity, is shown. It can be observed, that the curves for the due date method and the queue length estimator show almost the same results. The due date method shows a slightly worse performance because of sequence reordering, while the pheromone method shows inferior goal achievement. The first two curves are almost parallel to the minimal throughput time and can be fitted by linear functions, which are shown in the inset of figure 7. This means that a constant logistical goal achievement is gained during rising complexity. The pheromone method shows an inferior behavior, which is proved by the fact that the curve can be fitted by a 2nd degree polynomial. In this scenario, the dynamic is too high and the boundary conditions change faster than the pheromones are updated.

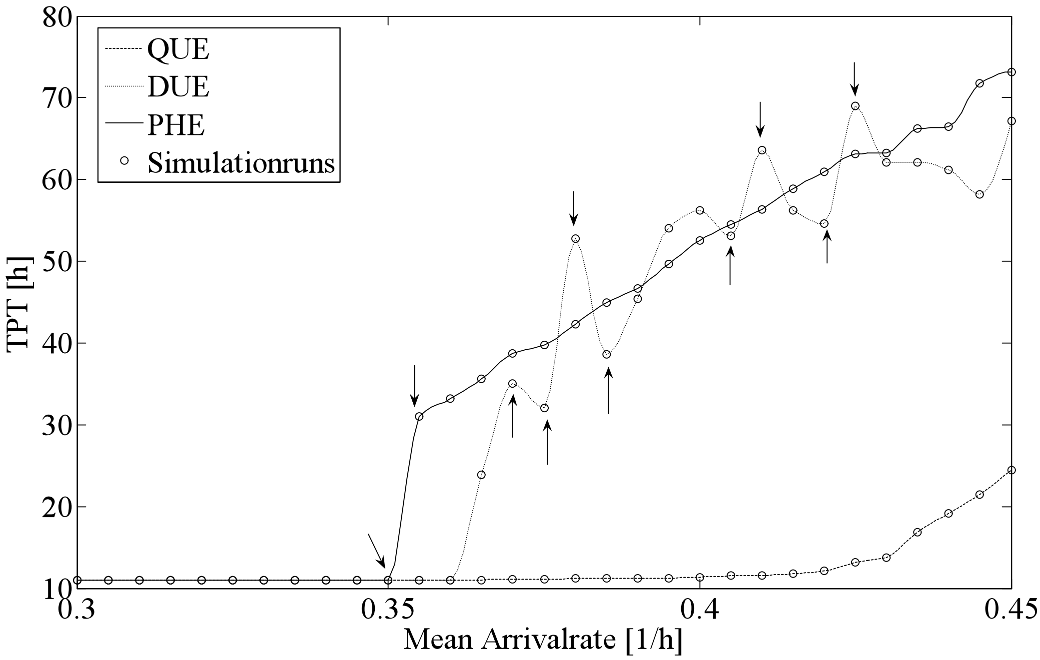
Figure 7: Logistical goal achievement for different organizational level of complexity and multiple autonomous control methods.




Therefore, the pheromone method is not able to adapt to changing conditions and this effect seems to cause more problems the more complex the scenario gets. With rising complexity of the model the pheromone shows declining performance, which is caused by the fact that the pheromone method is not able to use the higher amount of degrees of freedom during frequently changing boundary conditions.

In a second simulation, external dynamics is varied to determine the system's robustness, i.e. the system's ability to cope with external dynamics without being unstable. In this simulation the system is called unstable if one of the system's parameters increases without restraint. To determine this boundary of stability, the mean arrival rate at all sources has been increased and the highest possible arrival rate before the system starts to be unstable is measured. Figure 8 shows the results. The Queue Length Estimator shows the highest robustness. The model shows stable behavior until a mean arrival rate of 0.43 parts per hour is reached. The other two methods show unstable behavior at much lower workload. They begin to destabilize at 0.35 respectively 0.36 parts per hour. This is caused by reordering in case of the Due Date method and the above-mentioned inertia of the Pheromone method respectively.

Figure 8: Logistical goal achievement for different mean arrival rates and multiple autonomous control methods.




The arrows in figure 8 highlight the interesting measurement points in this simulation study from the dynamics perspective. The system shows altering phases of worse and improved behavior although the external dynamic is continuously enlarged. This is caused by the fact that the system shows different characteristics of internal dynamics at the different parameter constellations, which cause different performance rates. This strong interrelation between certain parameter constellations, dynamics and performance is typical for complex systems and especially those with elements of autonomous cooperation. Those systems tend to show chaotic-like dynamics including extreme events and their behavior strongly depends on initial conditions.

It has been shown that different autonomous cooperation methods i.e. different levels of autonomous cooperation cause different robustness and internal dynamics which result in different performances. This has been shown for different levels of complexity and external dynamics. The key finding of the simulation study is that the question of finding the adequate autonomous cooperation method is context sensitive i.e. it depends on the boundary conditions which autonomous cooperation method is the adequate in terms of performance improvement. Nevertheless it has been shown that autonomous cooperation could be an opportunity to cope with rising complexity and dynamics but is has to be taken into account that autonomous cooperation could lead to unforeseen dynamics. In this case it depends on the external dynamics which method to chose to reach the desired behavior of the overall system and the system is strongly sensitive to changing boundary conditions.

## 5. Conclusions and Future Research Requirements

The question, this article is aiming to answer is, weather the concept of autonomous cooperation can be seen as a reasonable way to implement autopoietic characteristics into logistics systems and therewith, to increase their ability to deal with complexity and dynamics.

For the management of organizations and information systems (e.g. in logistical contexts), the analysis in this article was able to show that the quantity of information, that organizations and their information systems have to process, increases. This is due to the tendency from linear supply chains to ISN, that has been confirmed during this analysis (Surana et al. 2005, Hülsmann et al. 2007, Mason 2007). Therefore, it has been outlined that the environment of actors within logistics processes is characterized by increasing complexity and dynamics

(Hülsmann/Berry 2004). This lead to one of its inherent problem-sources: Due to a larger number of involved actors and to a larger number of relationships between these actors in ISN, it can be stated that they are more accident sensitive than linear supply chains. In consequence, new challenges, concerning the ability of systems to cope with increasing complexity and dynamics and therefore to handle an increasing quantity of information, arise (Hülsmann et al. 2007).

Furthermore, it has been shown, that the concept of autonomous cooperation could be an appropriate instrument to implement autopoietic characteristics like self-creation into logistics systems. This contributes to its robustness on each of its levels, e.g. decision system, execution system as well as the information system (Hülsmann/Grapp 2006). It has been shown, that ISN can be regarded as CAS as well and therefore, the possibility arises to use CALS and its underlying theories as a framework to analyze their structures as well as their inherent complexity and dynamics. CALS' inherent self-organizing characteristic leads to apparent similarities to the autopoiesis-concept (e.g. Holland 1995; Choi et al. 2001; Surana et al. 2005; Maturana/Varela 1980; Maturana 1999). Therewith, autopoietic systems have potentials for implementing autonomously cooperating processes and therefore increase the information-processing capacity (Windt/Hülsmann 2007). Hence, regarding an ISN as a system with autopoietic behavior, can contribute to enable the organizations within an ISN and the information systems within the organizations to handle the increasing quantity of information (Hülsmann et al. 2007) caused by increasing complexity and dynamics and therefore to keep its ability to make rational decisions (Hülsmann/Wycsik 2005).

The simulation model confirmed the theoretical assumption, that autonomous cooperation is a possible instrument to enable an organization, an information system or CALS as autopoietic systems, to cope with the discussed challenges. By examining different methods of autonomous cooperation it has been pointed out that different systems require different methods and different degrees of autonomous cooperation to get the best resulting system performance. Therefore, in the context of information systems, it has to be evaluated which autonomous cooperation methods and which degree of autonomous cooperation has to be chosen to generate the desired effects on the system's ability to handle the increasing quantity of information and therefore, the highest robustness and in summary the best performance.

Further research requirements result on the one hand from the question, which degree of the single constitutive attributes of autonomous cooperation (e.g. autonomy, interaction, etc.), on which level and which combination between the degrees and the levels should be aspired, especially in autopoietic systems (e.g. CALS). On the other hand it is still unclear which impacts the single degrees and the single attributes have on each other. Beside this, problems in measuring the degree of the single attributes of autonomous cooperation, can be observed, that have not been under closing research up to now. Furthermore, the transfer of the autonomous cooperation idea as well as the findings from research in autopoietic systems has not been completely transferred into a practical logistics context yet (Hülsmann et al. 2008).

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