Effects of Autonomous Cooperation on the Robustness of International Supply Networks – Contributions and Limitations for the Management of External Dynamics in Complex Systems

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Abstract This paper intends to show possible contributions of the concept of autonomous cooperation (AC) to enable logistics management of International Supply Networks (ISN) to improve dealing with external dynamics caused by environmental complexity and dynamics. The concept of AC as one possible approach to cope with external dynamics of ISN will be analysed either from a theoretical and an empirical point of view.

1 Risks of External Dynamics for the Robustness of Complex International Supply Networks

The phenomenon of real-time economy could be described by timely convergence of order, production and distribution of products and services (Tapscott 1999; Siegele 2002). It evolved from the requirement to fulfil consumers' demands marked by diversified preference structures to a shorter time between order and distribution (Herzog et al. 2003). If an organisation wants to meet these demands it has to adapt its structures and processes constantly in order to meet the real-time-changing consumers' requirements and thereby to ensure its existence and survival on the long run (Hülsmann et al. 2006). A possible way to cope with characteristics of a real-time economy might be to intensify business relationships in order to provide the organisation with a sufficient amount of addressable resources, capabilities and ways of distribution (Geoffrion and Powers, 1995). In turn, this implies an understanding of companies which are interwoven in supply chain networks on global markets. They are legally separate, however economically to a greater or lesser extent dependent on each other (Sydow 2002). Hülsmann and Grapp characterized these global networks terials as International Supply Networks (ISN) (Hülsmann and Grapp 2005). The shown kind of diversity and changeability in customer demands and corresponding variation in organisational structures are assumed to lead to higher complexity and dynamics for the involved management (Hülsmann and Grapp 2005) that has to deal with these phenomenon (Hülsmann and Berry 2004). According to Dörner the existence of multiple interrelations between the elements of a system as well as interrelations between the system's elements and environmental elements, is a characteristic attribute of a complex system (Dörner 2001, p. 60; Malik 2000, p. 186). As ISN are characterised by multiple internal and external relations an ISN can be understood as a complex system. Another factor that characterises a system is "dynamics" that describes the variation of a systems status over time (Kieser 1974). For ISN-Management especially variations in the environment as to say external dynamics of the system are a critical factor because of their number of relations to their environment and the amount of changes in these relations. External complexity and dynamics could also be reasoned by phenomena like hyper-linking, hyper-competition and hyper-complexity (D'Aveni 1995, p. 46; Tapscott 1999; Siegele, 2002; Hülsmann and Berry 2004). Consequently, robustness in ISN might be endangered by a higher amount of information resulting from complexity and dynamics. Because the capacity to handle information is steady (e.g. due to rigidities of organizational competences (Schreyögg et. al. 2003)) the proportion between the amount of information and the capacity to handle information might deteriorate. That could lead to instability of the system.

Organisational flexibility is needed to enable an organisation to respond to changes in environmental conditions like technological progress (e.g. acquiring new technologies for efficient logistic processes in ISN). It is maintained by opening the borders of the system to absorb external complexity (Sanchez 1993). It is necessary for sustaining the integration of the system in its environment. Organisational stability is needed to compensate the absorbed complexity within the system. It is realized by the closure of the respective system. This leads to a definition of the system's identity which is necessary for the internal integration of all system's elements (Luhmann 1973). For adaptivity and therefore to maintain the existence of the ISN both processes (flexibilisation and stabilisation) are needed and have to be balanced (Hülsmann and Grapp 2006; Hülsmann et al. 2006).

From the perspective of logistics the achievement of goals of logistics-management e.g. time, quantity, quality, price etc. (Plowman 1964) is endangered if the level of information availability decreases because a lack of information leads to sub optimal decision-making (e.g. if not every possible offer can be taken into account the products and services might be to expensive).

To enable an ISN to cope with complexity and dynamics and therefore to achieve the goals of logistics-management the adaptivity of the system has to be ensured by its ability to balance flexibility and stability (Hülsmann and Grapp 2006).

One management approach that is currently discussed to balance the adaptivity in ISN is the concept of autonomous cooperation (e.g. Hülsmann and Grapp 2006). The focus of the concept of autonomous cooperation is the autonomous evolution of ordered structures in complex systems (Hülsmann and Wycisk 2005). Therefore, to apply autonomous cooperation in ISN might increase the ability of logistics management to cope with external risks

According to this, the research question of this paper will be: To what extend might the concept of autonomous cooperation contribute to the management of external risks in ISN? To answer this research question the concept of autonomous cooperation will be introduced and theoretically applied to strategic logistics-management in ISN, in order to deduce theoretical findings about the ability of autonomous cooperation to contribute to the management of external dynamics in ISN. The next research step comprises a simulation based empirical analysis in order to proof the theoretical findings. Finally, conclusions will be drawn which lead to implications for strategic logistics-management in ISN.

2 Autonomous Cooperation as an Approach to Increase the Robustness of ISN

Autonomous cooperation is based on the concept of self-organisation and is currently discussed in different fields of research. The concept of self-organisation has its scientific roots in multiple academic fields like physics, biology or chemistry and belongs to the research field of complexity science in the broadest sense (Hülsmann and Wycisk 2005). The different concepts of self-organisation, for example synergetics (Haken 1973), cybernetics (von Foerster 1960), chaos theory (Peitgen and Richter 1986), autopoiesis (Maturana and Varela 1980), and dissipative structures (Prigogine and Glansdorff 1971) have been points of origin for the concept of autonomous cooperation (Hülsmann et al. 2007). In the 70's a basis for an enfolding interdisciplinary theory could be established, due to the fact that the different concepts of self-organisation have a common background in complexity and order (Hülsmann and Wycisk 2005). The aim of this interdisciplinary field of research is to explain and identify how complex system create ordered structures autonomously (Hülsmann and Wycisk 2005). To elucidate the correlations between self-organisation and autonomous cooperation the concepts could be categorized in the following way: Self-organisation as a part of management describes the way in which complex systems autonomously create emergent order in structures and processes (Bea and Göbel, 1999; Probst 1987). Autonomous cooperation has a more narrow perspective than self-organisation. It describes processes of decentralized decision making in heterachical structures. To create a common understanding of autonomous cooperation for this research paper a general definition for autonomous cooperation, which has been formed by Windt and Hülsmann, shall be used:

> "Autonomous Control 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. The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity." (Windt and Hülsmann 2007, p. 8).

According to this definition main characteristics of autonomously cooperating systems are for example autonomy, interaction and non-determinism. To answer the question whether autonomous cooperation is able to contribute to strategic logistic-management of ISN the different attributes can be analysed

A system or an individual is **autonomous** if it forms, guides and develops itself. It is operationally closed, meaning that its decisions, relations and interactions are not dependent on external instances (Probst 1987). As there is no system completely operational closed it is spoken about relative autonomy of a system or an individual in relation to certain criteria (Varela 1979, Malik 2000, Probst 1987). According to theory, an organisation has to have a suitable degree of autonomy to be able to form and develop itself on the one hand and to maintain its identity on the other hand. Therefore a suitable degree of autonomy might preserve the ISN from information overload because it is able to balance between stability and flexibility (e.g. the ability of a load carrier to decide for itself what to transport).

The second attribute is **interaction**. Haken (1987, p. 132) states that open dynamic and complex systems develop a self-organized order through various interactions of the systems individual elements. Due to this processes the system develops new qualitative characteristics through emergence (Haken 1993). The emergent structures might contribute to the capacity for information handling because new structures and processes are developed (e.g. new ways of decision-making by intelligent objects). If the capacity to handle external dynamics rises, the risk of sub optimal decision-making due to information overload falls.

Non-determinism is another characteristic of autonomous cooperation. Non-determinism implies that the behaviour of a system can not be predicted over a longer period of time. With the characteristic of non-determinism, autonomous cooperation aims at higher efficiency for dealing with complexity and uncertainty within processes (Windt and Hülsmann 2007, p. 10). For the management of ISN non-determinism might imply that the processing of information can be handled more flexible. It enables the system to react to changes in the structure of ISN and the resulting problems. For the ISN-Management this could mean that its capacity to cope with complexity and dynamics is increasing. Therefore autonomous cooperation might contribute to the robustness of an ISN because the capacity to handle external dynamics might be increased.

3 Empirical Analysis

To measure the effects of autonomous cooperation on the robustness of ISN a simulation and measurement system has been developed that enables to compare the external risks in ISNs and SCs. In earlier work of the authors, a shop floor scenario has been analysed (Hülsmann et al. 2006). A similar approach will be used to simulate the behaviour of an ISN. Figure 1 shows the different characteristics of ISNs and SCs in order to show the different levels of complexity and resulting external dynamics. The scenario shows a simple supply chain that consist of one source (e.g.

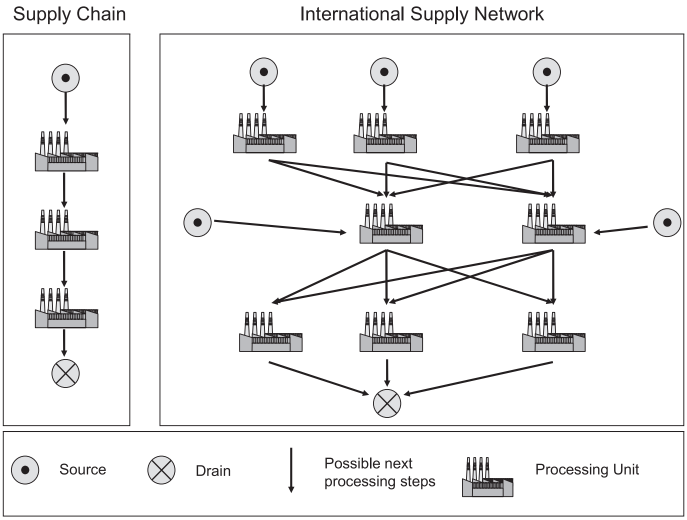

Fig. 1 Different organisational level of complexity

information, resources, orders) and a multi-stage production process. On the other hand, an ISN is depicted that in comparison to the SC consists of diverse sources and interlinked and substitutable production stages. In this model, the supply chain has the lowest level of complexity.

This model inherits the opportunity to evaluate the systems ability to cope with different amounts of external dynamics using different levels of autonomous cooperation. The orders enter the system at the sources and leave it finalised at the drain. 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 centralised 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 behaviour and dynamics.

In the following, the applied autonomous control methods will be described. The first method called **queue length estimator** compares the actual buffer level at all parallel processing units that are able to perform the next production step. Therefore, 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** 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 behaviour 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 behaviour 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 amount 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** 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 systems 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. Therefore, the external dynamics rises with increasing complexity of the ISN. The logistical goal achievement is measured using the key figure throughput time for different levels of complexity and different autonomous control methods.

Figure 2 shows the results i.e. the mean throughput times for the three different autonomous control methods in dependence of the systems complexity. The left side corresponds to the supply chain consisting of three processing units. To the right of

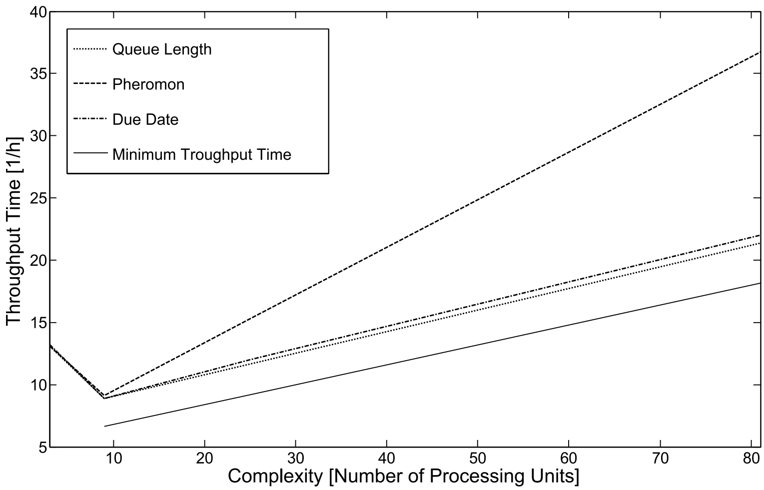

Fig. 2 Logistical goal achievement for different organisational level of complexity and multiple autonomous control methods

the figure the systems 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 level, is shown. In the first part of the figure, the throughput time declines for all three curves. This is caused by the fact that parallel processing units can be used in situations of overload i.e. if the arrival rate is higher than the capacity of the processing unit. In the second part it is shown 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. This means that a constant logistical goal achievement is achieved during rising complexity and rising external dynamics. The pheromone method shows an inferior behaviour. In this scenario, dynamics is too high and the boundary conditions change faster than the pheromones are updated.

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 beeing unstable and to become a locked-organisation. In this simulation the system is called unstable if one of the systems 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 3 shows the results for the three different autonomous control methods. It has been found that the pheromone method shows declining robustness with rising complexity and dynamics while the other two control methods lead to increasing robustness, with a faintly better robustness of the Queue length estimator. The reason for this rising robustness is the higher amount of parallel processing units that are available for the autonomous objects to use in case of overload.

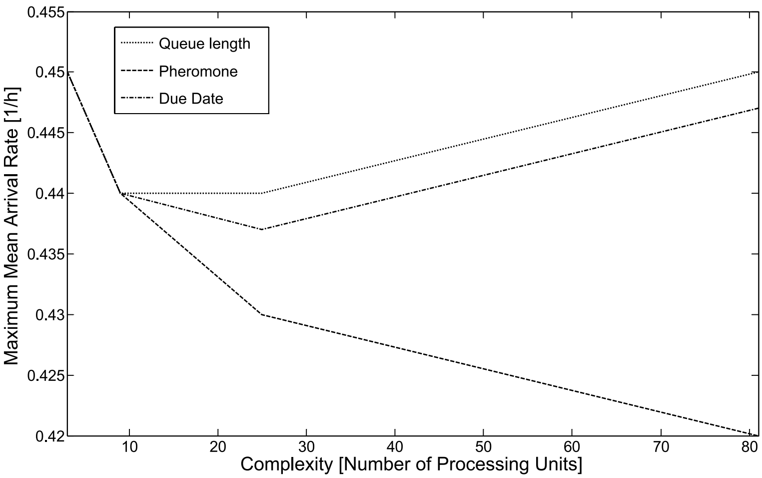

Fig. 3 Robustness measured as the maximum mean arrival rate for different organisational level of complexity and multiple autonomous control methods

The due date method and the queue length estimator show a small difference because only few changes in the sequence occurred and the mean values were not highly affected.

Both simulations have shown that for this kind of scenario, representing different levels of external dynamics, the queue length estimator is the appropriate autonomous control method. Because of the fast changing dynamics, the pheromone method has not been able to adapt to the changed boundary conditions. For the ability of autonomous cooperation to cope with rising external dynamics this means that the adequate autonomous control method has to be chosen depending on the scenarios parameters like complexity, dynamics and reliability of information. If this selection is done properly autonomous cooperation is a possible approach to cope with external dynamics.

4 Conclusions

The aim of this paper was to examine the contributions and limitations of autonomous cooperation on the robustness of ISN especially for the management of external dynamics. From a theoretical perspective it has been outlined, that autonomous cooperation might enable an ISN to enhance its capacity of information handling. For ISN-Management this can lead to a larger capacity to cope with external dynamic that results from changing organisational structures. This implicates that the employment of methods of autonomous cooperation might increase the robustness of the organization. Empirically, it has been shown that autonomous cooperation could be one alternative to cope with rising external risks in ISN but that it depends on the organisational structure and the scenario which level of autonomous cooperation is adequate. In the shown case, the queue length estimator has been the best degree of autonomous cooperation to cope with rising complexity and dynamics. For achieving progress in research other concepts of autonomous cooperation could be analysed. For logistics-management practice in ISN the findings imply that there are concepts of autonomous cooperation like the queue length estimator that might increase the quantity of external dynamics the organisation can cope with but that there is no general method of autonomous cooperation that can be applied in every scenario.

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