A Reference-Model for Holonic Supply Chain Management

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Abstract. IT systems are getting more connected, more network-like and hence more complex. The question arises, how such systems with steadily increasing complexity could be managed? Therefore new innovative approaches like Arthur Koestler's Holon approach are needed. This method arose in the 60´s of the past century as a philosophical work based upon a collection of parables, but not much tested and used yet. This paper describes how this approach is deployed for the Supply Chain domain as a reference model for Supply Chain Networks. It can be shown, that based on better methods for the complexity management better efficiency as well as effectiveness can be achieved.

1 Introduction

In general systems are getting more connected, more network-like and even more complex. As one of those this paper presents a reference-model the supply chain network domain. Therefore it makes use of the philosophical thought about system theory from Arthur Koestler [12]. His idea of systems helps to manage the increasing complexity of those systems. The paper is structured as follows: first a short overview about Koestler's main idea and conception of a holon is given. Furthermore already existing approaches are addresses, which make also use of the holonic concept, and are compared with the here presented approach. It follows a brief description of the Supply Chain Networks and especially of the SCOR-model. Then the holon-based reference model is introduced. In the end the static and dynamic behaviour of this model are discussed and evaluated by scenario example concerning the well known bullwhip-effect.

2 The Holon Approach

Koestler has designed a system-theoretic model of Self-regulated Open Hierarchical Order (SOHO), which instead of mathematical symbolics is originally based upon parables. From Koestler's point of view there did not exist a sufficient mathematical theory for his thoughts at that time [11].

V. Mařík, R.W. Brennan, M. Pěchouček (Eds.): HoloMAS 2005, LNAI 3593, pp. 221 – 232, 2005.

Koestler realized that all complex structures and stable processes present a hierarchical structure, like living organisms, social societies and non-living systems. Complex systems evolve in much shorter time out of simpler systems, with stable character shapes between the complex and the simple ones [22]. Systems that start up simple and than turn from stable character shapes to complex systems are inevitably hierarchical systems [11].

Hierarchies. The establishment of a hierarchy is the base for structuring and the control within a system. Typically hierarchies have top-down-flow of orders (output-hierarchies) and a bottom-up-flow of information (input-hierarchies). In hierarchies the principle of feedback exists immanent – like in the control loop – where the outcomes from changes are compared to the goals. Most of the time hierarchies are looked at as rigid and inflexible shapes. However, some approaches are not following this like the approach for "Dynamical Hierarchies of Artificial Life" and the "Holonic Ansatz" according to Rasmussen [18].

From the hierarchical principle to the holonic approach. The evolutionary stability of complex systems build out of simpler subsystems in nature reflects their remarkable autonomy and independence. Every subunit could operate as a quasi-autonomic whole. They are sub-wholes facing their subordinated units as a whole, and in relation to their superordinated system as a dependent part [11]. This could also be an approach to integrate systems based on swarm algorithms which usually show emergent behaviour into a huger and more complex system. Even this whole-part dualism is important for Koestler. By definition 'part' is something fragmented and incomplete, that has no justification to exist for its own. To be the part of something complies the requirement for integration. The term 'whole' stands for something complete, which needs no further explanations. For a whole-parted system Koestler has invited the term 'holon', derived from the greek word holos = whole with the suffix –on (like neutron or proton) pointing out the part characteristic [11].

Tendency of autonomy and integration. A base for the stability of a holon - one of it's specific design pattern - are the internal rules or more precise a canon out of them. The rules describe the content, the structural configuration and the function-patterns. While the rules define possible actions, a strategy chooses the current action inline with the environmental requirements. A holon could compile a strategy out of it's rules, which fits to its intentions, goals and the interpretation of the environment.

The second feature of a holon is the tendency to integrate into a more comprising wholeness. The communication and cooperation skills of a holon emerge from this tendency to integration. Still not any complex is a holon. The complex must have a hierarchical order, rules and strategies. Without communication and reaction abilities it cannot be called a holon. Accumulations of artefacts are not holons, but they could be part of them.

Self-regulation. The principle of self-regulation is also fundamental for the concept of autonomy. If a holon is a semi-autonomic whole-part, then it must have plans for self-regulation. Put it briefly, an action must on one hand be conform to the inner rules of the holon and on the other hand depends on the observed environment variables. A permanent flow of information from the action – being executed – has to

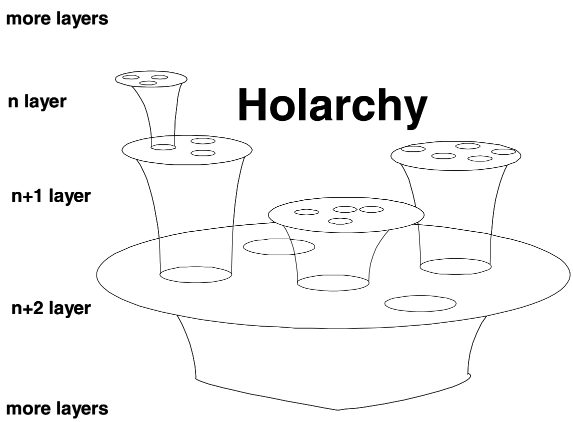

Fig. 1. Picture of a hierachical order of holons called holarchy [16]

exist to the part, which controls it. The actions have to be permanently regulated, which corresponds to the principle of feedback-control [12].

Holarchy. Hierarchies of complex systems containing not only simple connection structures, but also including heterarchic subsystems are called holarchies by Koestler. The latter are orders of holons, which have hierarchic dependences. Every holon could have an other internal structure (cmp. figure 1).

The higher layers of a holarchy are normally not in direct contact with the lower ones and vice versa. Signals pass established channels from one layer to the next, one step at a time, up or down in the hierarchy. A short circuit of the information flow above more layers could lead to unpredictable disturbances of the whole system (cmp. [12]).

With every step upwards in the holarchy, holons are getting more complex, flexible and unpredictable in their behaviour structures, but with every step downward the holons become more mechanical, stereotype and predictable in their behaviour structures.

Other holonic approaches. So far existing holonic applications or models apply mostly to the inner production processes of a company, called holonic manufacturing systems (HMS). Similar to all these approaches is that they are modelled domain specific. Mentioning a few of them: a holonic reference architecture for production systems, called PROSA, developed at the PMA-KULeuven by Wyns [24]. A second approach from Fischer [8] uses an agent platform to develop an HMS. Also HMS are build by Goua et al. [10], Adelberg [1] and Silva/Ramos [21]. Instead Bussmann [4] builds not a HMS but a holonic transportation management system. The here proposed reference model is related to all these approaches as a framework. Hence all the above mentioned systems but also legacy systems could be integrated into a holonic supply web, each of them as a concretisation of a specific holon, but mostly at the operative level of the model. You could also use different HMS at the same time in different holons.

3 Supply Chains

The holonic view served the handling of complex systems. According to Deloitte supply networks are complex systems and their complexity will even grow in the next time [7]. To explain the character of a supply chain, we give two example definitions:

A supply chain described from the macro-perspective corresponds to the stepwise transformation from raw material to end products and their distribution and selling to the customer. From the perspective of a single company (micro-perspective) it described the cooperation with its supplier and customer by the creation of value (cmp. Delfmann/Albers [6], p.42]).

A supply chain is a compound of activities, which contains planning-, coordination- and controlling-tasks. These activities are subordinated to the goal to produce the end product. Seuring points out, that the supply chain contains not only the physical motion of the good, but also the delivery management, the supply management, the production management, the material planning, the location planning, the customer service and the information flow [20].

For the building of the reference model it is resorted to quasi-standards in the supply chain domain. It is used the SCOR-model from the Supply Chain Council and an expansion of it, the task model from the SCM-CTC (Supply Chain Management–Competence & Transfer Center from the Fraunhofer Institut [13]) as starting points.

The SCOR model describes all enterprise activities, which are related with the satisfaction of the demand. With regard to figure 2 it subdivides into a four-layer structure, refining down to more detail layers. The first three-layers are of more

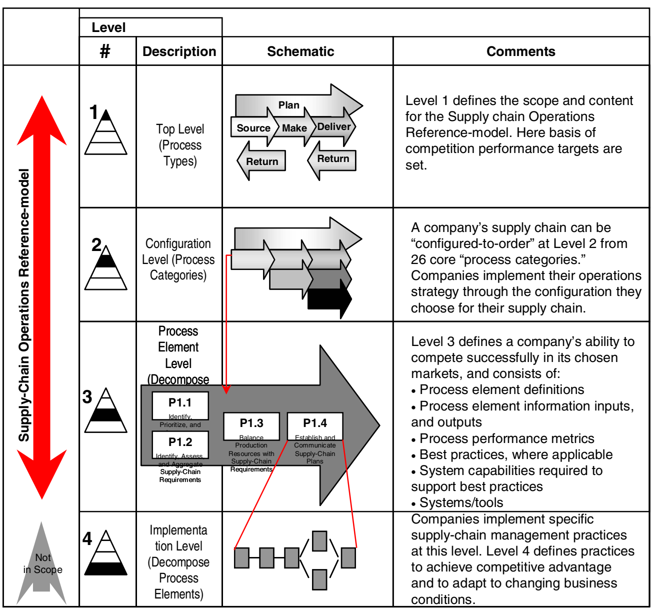

Fig. 2. Process layers of the SCOR model (Source: SCOR5.0 2001 [19], p.7])

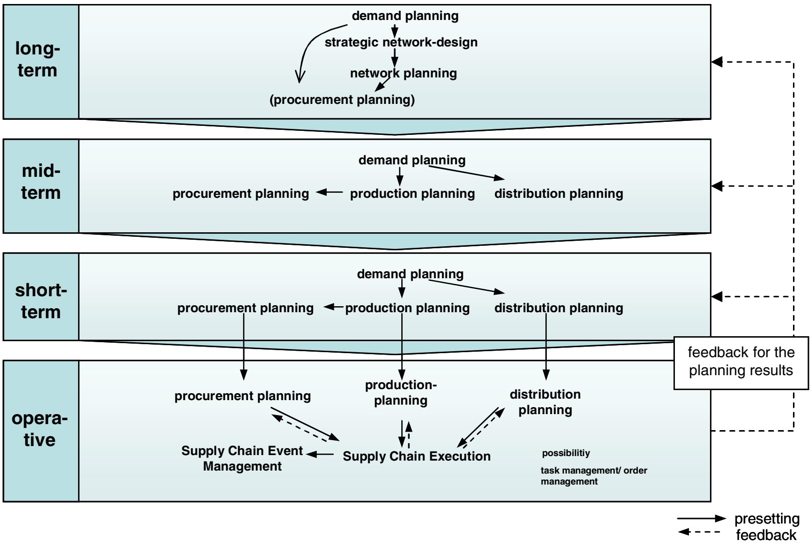

Fig. 3. Task model of the SCM-CTC (Source: Peters 2004 [17], p.31)

conceptual character, the lowest layer represents the implementation layer, which depends on the individual enterprise to enterprise and is not further explained in the SCOR model. The reference model refined here on a holon basis does not make use of all layers in the SCOR model, hence only specific functions are integrated. The task-model of the SCM-CTC can be seen in figure 3.

4 The Holonic SCM Reference-Model

The model separates into a static and a dynamic view. In figure 4 nearly every holon as designed for the reference model can be seen. In opposition to the static view holons could also change within time, e.g. the distribution holon could be coupled out and become an enterprise holon on its own. This is the reasons, why dynamic behaviour is of that special interested. Before specifying this, a short overview above the designed holon of the reference model should be provided. First all terminable holons had to be identified. Also subsequent expansions should be supported by them. Every holon has to fit into the holonic structure, meaning that every holon has to fulfil the grounding paradigms of the holonic structure: every holon has to be able to communicate (the integration-paradigm) and acts by its own driven by rules and strategy (the autonomy-paradigm).

The enterprise holon represents location point of a firm as a whole. The location is simply a node of the supply network. The enterprise holon consists out of following subholons: the sourcing holon, the production holon, the distribution holon, a central service holon and finally a supply net planning holon. The first three of them are also called process holons and have been derived from the SCOR model. This holon building block set should be sufficient to model every thinkable company structure.

The major task of the enterprise holon is to coordinate it's subholons respectively to give them the platform for their own self-coordination. In favour of the task fulfilment the enterprise holon defines the directive structure of subholons from the next lower holarchy level. An additional task of the enterprise holon is to conduct changes: the enterprise holon stimulates for capacity expansion and reduction. If necessary it could replace subholons and give the impulse for the change of the internal structure of a subholon. At the outer interface the enterprise holon communicates with other enterprise holons to optimize the supply chain network.

The supply net planning holon comprises for all skills necessary for the long-term planning. The process holons are responsible for the mid- and short-term planning. The operative holons of the process holons and the security-/monitor holons take over the operative planning tasks. The supply net planning holon is responsible for the integration of a company into the overall planning of the supply net, which complies to the tasks of the strategic network design, cooperative demand planning and the network planning. The planning task is solved in cooperation with the other network nodes. Results are then forwarded to the process holons.

The sourcing holon is namely responsible for all aspects of sourcing. It consists of a planning holon, an operative holon and a security/monitor holon. The planning holon takes all planning tasks, the operative holon takes all process task while the security/monitor holon supervises the planned processes. The production holon is responsible for all aspects of production and the distribution holon for all aspects of distribution. Their internal build-up is same like the sourcing holon.

The central service holon provide services that the process holons will needed, like bill of cost, internal transportation and storage.

Only the dynamic behaviour of supply chain networks could let you have a presentiment of the true complexity of such systems. You could compare it to circular flow of a higher organism. The problem is not to design any complex system, but to design it such that it shows up emergent behaviour. Bonabeau exemplifies this [3]:

"… using a swarm-intelligent system to solve problem requires a thorough knowledge not only of what individual behaviour must be implemented but also what interactions are needed to produce such or such global behaviour."

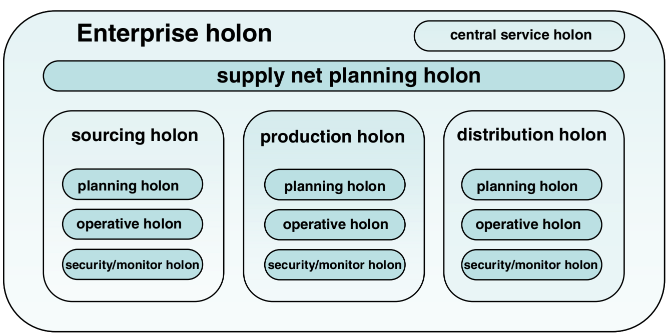

Fig. 4. Static view on an enterprise holon (Source: Peters 2004 [17], p.47)

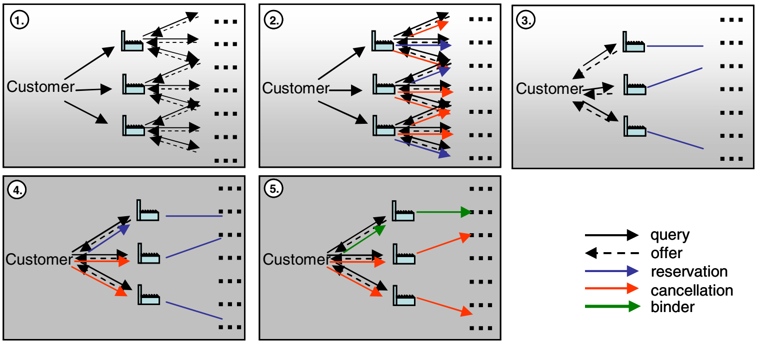

Fig. 5. Short-time negotiations (Source: Peters 2004 [17], p.64)

In the holonic reference model the supply chain network nodes interact with each other on different layers. The activities of the supply network have different structures. Some of the information flows are pyramidal from the customer to supplier and back, while others pass through all parts of the net. Accordingly the complexity of supply systems the dynamical behaviour for negotiations, the material flow including the collocated information flow, the order management, the control- and monitor-functions and finally the cooperative planning have been designed (cmp. figure 5).

The negotiations could be divided into long-term and short-term ones. The results of the long-term negotiations are of more timely stability. The procedure for the short-term negotiations can be seen in figure 5 and explained as enlisted in the following:

- Point 1: The customers query
- Point 2: The first nodes ask their suppliers
- Point 3: Answer
- Point 4: Reservation of the best offer, the others get refusals
- Point 5: Offer to the customer
- Point 6: The best offer is chosen, the others get refusals
- Point 7: The reservation of the best alternative is transformed into a concrete order, the reservations of other vendors get refusals

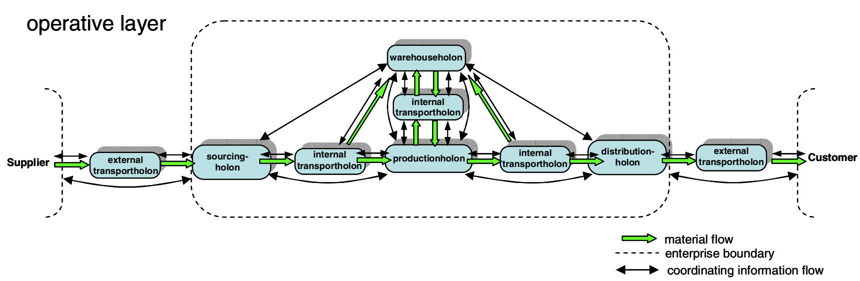

Fig. 6. Drawing of the material flow including the collateral information flow (Source: Peters 2004 [17], p.75)

The material flow as depicted in figure 6 is attended with an agile information-exchange, like mail conformations, planning data, error messages and so on. The tasks that occur during the material flow are taken over by the operative holons, like the transformation, the transportation and the storage of the goods.

Order management. The order holons are the lowest entities in the holarchy that is designed in this reference model. They are placed within the operative holons of the process holons. Every order gets an order holon, so the order holons forms order pyramids depended on the first order or the end-customer order. In a network so many order pyramids exist like end-customer orders exist. So this order pyramids could interact with each other or alone to coordinate the order fulfilment. If an order gets late, the depended orders could higher their negotiation might for the resources and try to catch up the lost time. This could be an adequate mean against the ripple-effect.

"…the variation of leadtimes at any stage will affect the execution of the other stages and result in uncertainties for the overall order cycle time. This is called the ripple effect." – Lin et al. 2000 [15], p.234 –

The monitoring of the material flow is one part take over by the order holons in a permanent self-control and the other part by the security/monitor holons. The security/monitor holon is responsible for identification and forwarding of error messages from one process holon to the next. It activates new planning (reactive planning) and tries to embank the error causalities. The philosophy is to embark the errors as early as possible, so that many of the supply chain partners will hold their planning security.

In figure 7 the coherence of the different planning holarchies could be seen, like the overall coordination in the network, the coordination in view of an order holarchy, enterprise holon internal directive structure, feedback-loops. The overall network coordination is in the simplest case the forwarding of prognosis, at the time data and enterprise data, but it can also show swarm behaviour, so that the neighbours give input to expand or reduce capacities.

Building a system with central or decentral coordination based on this reference model is a modelling task. This reference model should be seen as a construction set for complex systems that support both central as well as decentral solutions. It is

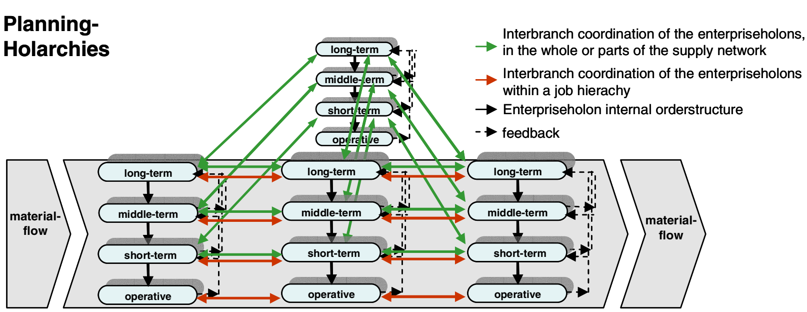

Fig. 7. Cooperative planning (Source: Peters 2004 [17], p.89)

possible to model one layer of the holarchy centrally but another one decentral, if needed. Just since many supply chain systems use agent technology for implementation, according to Dangelmeier agent technology could also be used for holonic applications [5]. This technology will support your design decision no matter if central or decentral. For more information about agent technology is referred here to Glückselig [9] and Peters [16].

5 Evaluation for the Bullwhip-Effect

Since the here proposed reference model has not been practically implemented, its usefulness has been evaluated by executing scenarios of practical relevance. One of this regards the well-known bullwhip-effect and is exploited in more detail. If significant fluctuations occur within a supply chain, but the end-consumer demand is relatively constant, this phenomenon is called the "bullwhip-effect". According to Delfman/Albers [6] the reason for this is, that the actualisation of sales prognoses, packaging of orders, price fluctuation and rationing-and-shortage gaming lead to incremental amplification. Lee pronounced that each of the four forces in conjunction with the chain's infrastructure and the order managers' rational decision making create the bullwhip effect [14].

Table 1. Bullwhip-effect (Source: Störk 2003 [23], p.4)

Time	0	1	2	3	4	5	6
customer-demand	100	100	103	100	100	100	100
dealer-inventory stock	100	100	97	103	103	100	100
dealer-calculated assets		200	203	203	200	200	200
dealer-order size	100	100	106	100	97	100	100
wholesaler-inventory stock	100	100	94	106	109	97	97
wholesaler-calculated assets		200	206	206	197	197	200
wholesaler-order size	100	100	112	100	88	100	103
distributor-inventory stock	100	100	88	112	124	88	85
distributor-calculated stock		200	212	212	188	188	203
distributor-order size	100	100	124	100	64	100	118
producer-inventory stock	100	100	76	124	160	64	46
producer-calculated assets		200	224	224	164	164	218
producer-order size	100	100	148	100	4	100	172

The example chosen from Störk [23] concentrates on consequences caused by package of orders along a supply chain. In figure 8(Left) and table 1 increase of the inventory by the disturbance of 3% of the demand can be observed. In figure 8(Right) and table 2 the changed demand will be passed collaboratively along the supply chain partners and the bullwhip-effect does not occur. The example is simplified, but shows the difference between collaborative planning and not coordinated inventory policies. The following equations are the basement for the bullwhip-effect (see table 1):

$$\text{demand} = \text{order size of the following step} \tag{1}$$

inventory stock(t) = inventory stock (t-1) – demand (t) + order size (t-1) (2)

calculated assets (t) = demand (t) + demand (t-1) (3)

order size (t) = calculated assets (t) – inventory stock (t) (4)

In table 2 it can be observed, how simple coordination of the information flow could stop the bullwhip-effect in this example. The difference between table 1 and table 2 is that the information of the customer demand is passed through the supply chain, so every company could calculate the overall demand:

demand = for every node the customer demand (5)

inventory stock(t) = inventory stock (t-1) – demand (t) + order size (t-1) (6)

calculated assets (t) = demand (t) + demand (t-1) (7)

order size (t) = calculated assets (t) – inventory stock (t) (8)

Table 2. No bullwhip-effect, (Source: Peters 2004 [17], p.97)

Time	0	1	2	3	4	5	6
customer-demand	100	100	103	100	100	100	100
dealer-inventory stock	100	100	97	100	100	100	100
dealer-calculated assets		200	203	203	200	200	200
dealer-order size	100	100	103	100	100	100	100
wholesaler-inventory stock	100	100	97	100	100	100	100
wholesaler-calculated assets		200	203	203	200	200	200
wholesaler-order size	100	100	103	100	100	100	100
distributor-inventory stock	100	100	97	100	100	100	100
distributor-calculated stock		200	203	203	1200	200	200
distributor-order size	100	100	103	100	100	100	100
producer-inventory stock	100	100	97	100	100	100	100
producer-calculated assets		200	203	203	200	200	200
producer-order size	100	100	103	100	100	100	100

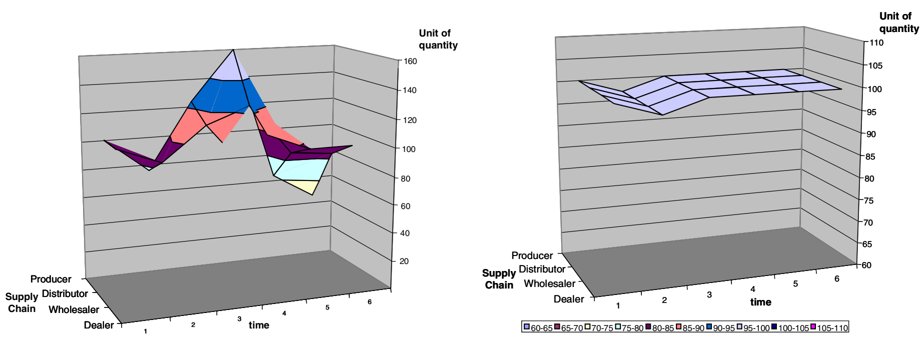

Fig. 8. Left: Inventory with bullwhip effect(Source: Peters 2004 [17], p.93) Right: No bullwhip-effect via collaborative planning (Source: Peters 2004 [17], p.98)

6 Summary and Outlook

The reference model for the supply chain management as presented here has been designed using Arthur Koestler’s holonic approach. In favour of a more throroughly analysis especially in cases of great system complexity, the next step is to develop a prototype, where such systems could be simulated and strategies be developed. Especially the de-escalation problem of increasing complexity in the management of supply networks using holon-structuring is one of the great advantages of this approach. In order to manage a complex system which contains many different systems and hence several sub- and sub-sub-systems, automatically leads to the phenomena of emerging systems. The domain of supply chain networks is a excellent research field for this phenomena. A transfer of the results and strategies from this research field into practical domains is the major goal following Bertalanffy’s general system theory [2].

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