Toward Adaptive Logistics Management

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Abstract

The aim of this paper is to discuss the implications of a complex adaptive systems approach to the management of logistics operations. The research is a result of the need for managers of logistics operation to be able to adapt to the ever-changing demands of their environment and customer demands. The identified emphasis of mechanistic assumptions in traditional modeling of logistics is discussed and it is suggested that a change towards adaptive models and tools is needed. This means that the models have to be able to consider more complex behavior such as self-organization and emergent phenomena. A complex adaptive system (CAS) approach is applied by the use of agent-based modeling (ABM). Two cases are provided in which the CAS approach has been applied through ABM simulations. It is concluded the CAS approach implemented by the use of ABM can provide valuable insights for both researchers and practitioners within the field of logistics management.

1. Introduction

Supply networks are becoming more complex and the need for managers of logistics operation to be able to adapt to the ever-changing demands of their environment and customer needs is increasing. Two major reasons for the increased complexity are; I) greater demands from customers and II) increased competition from competitors, both of which compel firms to focus on delivering greater value to the customers, in less time. Traditionally, the value logistics contributed to business was in lowering the transportation costs for firms in the supply chain when they pushed products toward the market. Today, the value is shifting towards adding service dimensions; in addition to the product features required, these give the customer accessibility to the product based on the customer's own requirements.

All in all, this means that the situation for managers is becoming more complex and increasingly demanding. Consequently, the approaches, methods, and models provided for logistics managers as well as researchers, must be able to consider and treat more complex constellations of interactions and behaviors within and among firms.

Currently, firms put lot of money, time, and resources into approaches, methods and models which are based on Newtonian assumptions and beliefs of certainty and mechanistic principles i.e. perfect rationality, determinism, and linear causality (e.g. spread sheet tools, linear programming, etc.). However, the reality managers confront in their efforts to manage tasks e.g. logistics processes in supply networks, is mostly perceived as uncertain, nonlinear, and increasingly complex. Furthermore, with increased competition and changing demands, the marketplace will be even more turbulent i.e. the landscape on which firms operate is not fixed or static and cannot therefore be treated using only mechanistic principles. In other words, as stated by Robertson; "*if the business world is viewed as being complex, it is inappropriate to consider models developed under paradigms of equilibrium, stability, and linearity to produce an analysis of a turbulent environment*"[1 p.61]. Consequently, handling the logistics operations in the supply network will place new demands on logistics management, which means that 1) new approaches are needed for managers to understand logistics processes and 2) new methods and models to deal with logistics operations and activities in a more effective way are needed.

In this paper it is argued that by allowing more complexity in the models constructed and theoretical frameworks used, increased understanding and better insights may be gained by management to cope with present and future logistics challenges. In particular, greater insights can be achieved concerning system-wide effects over several business processes e.g. transportation, inventory, production, sales, etc. Another insight which can be provided is the nonlinear effects rather small changes in behavior or policies can have i.e. they can escalate to high costs or leverage into high performance. In this regard, one beneficial theory is the complexity theory, especially that regarding complex adaptive systems (CAS), which is based on assumptions of a more adaptive character i.e. fewer mechanistic assumptions. The complexity theory has been used to enhance understanding of several other phenomena such as

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knowledge management [2;3], organization science [4;5;6], strategy [7;8;9], and manufacturing strategy [10], to mention but a few, and Sutherland and van den Heuvel state that *"business entities are good examples of complex adaptive systems"* [11 p.3].

However, while insights from CAS provide increased understanding for logistics processes and a helpful framework for modeling, some kind of method is needed in order to implement such an approach into tangible and understandable results, from a management perspective. The reason for such a method is that our research has pointed to the need for managers to be able to test and evaluate different what-if scenarios, simulate policy changes or change in behavior in order to understand and even consider a new way of thinking. In this regard, one modeling and simulation approach influenced by the complexity paradigm is Agent-Based Modeling (ABM), which is derived partly from object-oriented programming and distributed artificial intelligence [12], and partly from insights found in the science of complexity [13;14;15]. ABM provides a modeling and simulation approach which can be beneficial for a CAS approach and a usable method for creating tangible and understandable results for managers.

The purpose of this paper is to discuss the implications of a complex adaptive systems approach as a new approach for understanding logistics complexity, with the use of ABM as a method and modeling tool as the application to enable and facilitate the implementation of effective ways to deal with logistics issues. The paper aims to provide a framework to help logistics management to become more adaptive to market changes and contextual constraints in order to enhance customer value.

The remainder of this paper is organized as follows: The next section discusses complexity in logistics management today, followed by the introduction of a complex adaptive system approach to logistics management. ABM is then introduced as a method used to apply the CAS approach and to implement increased adaptive understanding, thinking and acting in logistics contexts. In the subsequent section two cases are described which illustrate the application of the CAS approach with ABM as the application at a fast-moving consumer goods company and a packaging company. Both cases demonstrate positive results, both regarding increased understanding from management, as well as in operational changes leading to lowered costs and increased customer service. Finally, a concluding discussion of the CAS approach with ABM in the context of logistics management is provided, and further research is outline.

2. Complexity in logistics Management

To address the complexity of logistics management a logistics framework has been used [16]. The framework includes three properties which have been identified within the logistics area as having a significant impact on the management of logistics operations. These are *the structure property, the dynamics property*, and *the property of adaptation* (see figure 1 below).

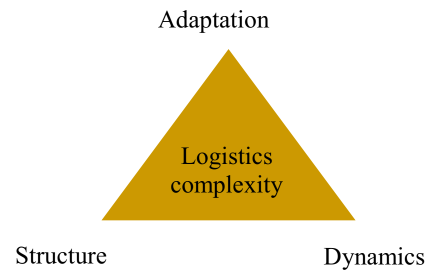

Figure 1. Key properties which have significant impact on the management of logistics.

The structure property is related to the infrastructure in the context of logistics, and covers physical as well as information and communicational structures. The dynamic property is related to the processes performed on the network i.e. the flow of goods, money and information within the structure and hence the dynamics in these processes. The property of adaptation is related to the organization and the decision-making i.e. the management, of the structure and the dynamics, in order to realize the processes of satisfying customer demands in an effective way.

Since logistics management is, to some extent, similar to other kinds of management there are of course similarities in how different types of problems are being treated. However, logistics is by nature a discipline where a mechanistic approach has been successful since the major benefits firms exhibit from logistics are time and place utility of products [17]. Time can easily be divided into time intervals and measured quite easily. The spatial dimension is also fairly easy to divide into parts because there is a measurable distance from, for example, Sweden to Hawaii. Both these measurements are of a mechanical character and suit the property of structure as well as the property of dynamics, since distance is related to structure and time is related to dynamics. With a perspective of reality as being objective it is then quite easy to deal with these properties by means of a mechanical and summative approach. Axelrod and Cohen provide a good explanation for the success behind the mechanical approach when they state: *"No doubt, machines and hierarchies provide easier metaphors to use than markets and gene pools. So it is no wonder that most people are still more comfortable thinking about organizations in fixed,* *mechanical terms rather than in adaptive, decentralized terms"* [18 p.29].

There are, of course, several logistics operations taking place in supply networks i.e. operations related to structure and dynamics, which can be simplified on an aggregated level into mechanical terms. However, since logistics management covers management of socio-technical processes the dominant mechanical approach in modeling logistics processes is questioned by the authors. Instead, it is argued in this paper that logistics researchers and managers should consider the third element in figure 1, namely adaptation. The process of adaptation is often neglected in theories and modeling approaches used in the logistics context and has not been greatly emphasized in logistics management, neither in research nor in practice. Our research has shown that there is an apparent need for an increased focus from logistics managers on adaptation. By using theories and modeling approaches based on assumptions more suited to a complexity perspective, increased compliance to real-life logistics operations can be achieved and the first steps towards adaptive logistics management can be taken.

3. A CAS approach to logistics

What is proposed in this paper is a new approach for logistics management based on an extensive set of assumptions which are more suited to real-life logistics operations, i.e. where considerations are taken to the socio-technological processes involved. An extensive set of assumptions means that those of linearity, reductionism, determinism, rationality etc. are still apparent and useful; however, they are of limited use when it comes to logistics operations involving several people, functions, and processes, where the situation is characterized by conflicting demands and multiple goals. Instead, assumptions of nonlinearity, heterogeneity, subjective and bounded rationality, self-organization, emergence, subjectivism, to mention but a few, are central to the CAS approach and highly apparent in real-life logistics operations.

The implications the CAS approach has on logistics management will be illustrated by a discussion of one of the main purposes of logistics management i.e. "*conforming to customer requirements"*[1] especially with the value adding features of time and place utility. This is by definition related to the property of adaptation since it demands interpretation by people concerning customer requirements, and is especially vital for logistics management concerning their efforts in planning and controlling activities needed for customer fulfillment. Since the market is becoming increasingly interconnected and available data and information are increasing, there are several factors which might influence not only customer requirements, but certainly also the actual handling, flow, and storage of products as well as information. This complexity results in great interpretation consequences for logistics management since emergent phenomena are unpredictable and the managers are not in the position of an observer or designer standing outside the logistics system. Nevertheless, they are still supposed to plan and control the flows of products and information in increasingly interconnected supply networks. What is needed to handle this paradox is a more balanced view of the mechanical assumptions in planning and control with considerations to the CAS assumptions i.e. adaptation, self-organization, emergence, etc.

For logistics management to realize the paradox of control and self-organization, the CAS approach provides a bottom-up perspective on logistics activities which could provide novel insights and increased understanding. The bottom-up perspective could act as a complement to the dominant focus on global phenomena and the associated top-down approach related to this. There are several reasons in favor of a CAS approach with emphasis on a bottom-up perspective on logistics.

Firstly, since "*the complex whole may exhibit properties that are not readily explained by understanding the parts"* [14 p.VII], the result is that emergent phenomena formed from the bottom-up i.e. everyday activities, by local interactions of autonomous individuals and parts, are not being captured in traditional global phenomena models and theories. Bonabeau [19] paricularly addresses the fact that emergent phenomena may in several cases be counter-intuitive, which makes these emergent phenomena impossible for managers to either plan or control, especially with the aid of over-simplified models and tools.

Secondly, real-life logistics practice is to a great extent characterized by last-minute changes and rearrangements due to accidents, changes in customer demands, machine and computer breakdowns, mistakes etc., while logistics theories and modeling approaches are often based on certainty and determinism, especially on the microlevel i.e. where actions and activities actually are performed. In other words, unpredictable and dynamic relationships of a self-organizing character sometimes create novelty and innovations and sometimes chaos and frustration for the people involved.

Thirdly, the individual level is of major importance for logistics management since it is on this level that actions are performed and affected by autonomous individuals. As a result of their actions and their perpetual interpretations of the outcome of other individuals' actions, global phenomena emerge. Bonabeau [19] points out that it is the individuals within firms (and not processes) who make mistakes and cause errors and he goes as far to point to a paradigm shift from spreadsheet and process-oriented approaches to focus on the

[1] www.clm1.org, 20040830.

individuals. Furthermore, the individuals are the ones who are often involved in customer processes and consequently, their interpretation, 'sense-making', and following actions along the value-adding flow affect the performance of the logistics processes. Allen points out that as a process of interpretation and 'sense-making': *"there is a complex and changing relationship between latent and revealed preferences, as individuals experience the system and question their own assumptions and goals"* [20 p.83]. In other words, there exists a great deal of heterogeneity in logistics systems. Furthermore, since it is impossible for individuals to obtain accurate and perfect information, diversity will exist even if individuals interpreted information the same way. Nonetheless, common models and most logistics frameworks are based on an objective reality and homogeneity of the constituent parts.

Consequently, what is required for logistics management in order to move towards adaptive logistics management is a shift in mind-set. Park addresses this clearly by stating that *"executives must realize that the old top-down, command-and-control structure is ineffective, and in many cases counterproductive"[21 p.61]*. Therefore, a paradigmatic change from a planning and control approach (top-down) to an emergent and self-organizing approach (bottom-up) would result in changes in the way logistics activities are being managed. However, such a change in mind-set needs motivation and an understanding of the implications a CAS approach may have on logistics activities and business performance. One applicable method and tool in this regard is agent-based modeling (ABM).

4. Agent-based modeling

ABM is based on bottom-up assumptions and provides an applicable and helpful method for facilitating and realizing the CAS approach to logistics phenomena. In ABM the focus is on agents and their relationships with other agents or entities [12]. The agents represent real-life components identified in the context of interest, and have some degree of autonomy. Van Dyke Parunak [22] describes an agent as being a software entity with its own thread of control and with the ability to execute operations without being externally invoked.

In the logistics context an agent might represent a machine, a production process, an order-handling process, inventory handling, trucks etc., i.e. reasonable tangible parts of logistics operations which are influenced or affected by individuals and thus have some degree of autonomy and decision making. As described earlier, the individuals who are involved in logistics operations lack perfect information, have their own goals, and sometimes their own policies i.e. they are heterogeneous and are characterized by bounded rationality. ABM provides a useful method to enclose such behavior and the diversity which exists in real-life operations among different activities, individuals or groups of such.

In the logistics context ABM enables another characteristic of importance, namely the dynamical distribution of activities in both time and space [23;24]. This means that with agent-based models and simulations, global as well as local behavior can be analyzed and evaluated. Consequently, validation and verification of any system being modeled can be made for each agent i.e. on micro-level, and for the logistics system as a whole i.e. on macro-level. Consequently, as introduced earlier (see figure 1), both structure and dynamics can be handled in ABM. Structure involves the distribution of activities in space since it involves physical distances of machines, people, processes etc. which are connected to some extent, directly or indirectly. Dynamics, on the other hand, suits the change of logistics activities i.e. the flow of products, packages, and information from point of origin to point of consumption. Furthermore, ABM also enables the modeler to include the property of adaptation to some extent, since what is happening within the model is a result of different agents' actions and reactions to stimuli from agents and other entities they are connected with.

There are a growing number of published articles, especially in an operations management context, where ABM is used to describe and improve different types of phenomena. For example, Ma and Nakamori [25] use ABM to model technological innovation as an evolutionary process based on constructional selection and environmental selection. They model a set of producers, producing different types of products, and consumers which evaluate and purchase those products based on different requirements. One of the conclusions is that *"ABM and simulation can be used to aid intuition about technological innovation"* (p.14). Another example is Emerson's & Piramuthu's article [26], which describes an agent-based framework for dynamic supply chain configuration. Their framework is tested on an example of two types of supply chains, a two-stage and a three-stage type.

Both these articles illustrate some interesting results concerning dynamical patterns in and among organizations, however, the examples are very simplified and no real data is used in the models, nor are the models verified with empirical cases. For most ABM cases found in literature, general results based on axiomatic modeling and simulation examples are provided. Any empirically driven simulations are much more difficult to find in literature, especially where the models have been verified with actual outcomes. Furthermore, the majority of cases in literature simulate issues and phenomena of an economic character i.e. showing patterns, from a company perspective on a strategic, long-term level. Consequently, the implications and recommendations are not applicable to companies when it comes to issues on a tactical and/or operational level.

The cases described in this paper are empirically driven since they both are based on ABM simulations which aim to mimic actual company behavior on an operational level. The focus is set on the micro-level behavior found on "the floor" and the models produce macro-level behavior for the case companies, primarily influencing their tactical management but also having strategic implications.

5. Case one: fast-moving consumer goods company in Sweden

The purpose of the study at the FMCG company was to create, from the company's perspective, an applicable and usable tool for the management to evaluate different scenarios with. In the initial discussions with staff at the company several opinions and arguments were provided by people responsible for different functions of the company i.e. inventory, production, production planning, marketing, sales, logistics and supply chain management. There was a debate among the functions concerning how to keep total costs low while at the same time increase the level of customer service. The debate focused particularly on costs in inventory versus the costs in production. Furthermore, questions where raised how the company forecast reports influenced the actual results concerning service levels and production efficiency i.e. set-up times, batch sizes etc.

In order to gain insights concerning the different problems which the managers in the company provided arguments for, a CAS approach was used and an agent-based model was developed. There were several reasons for this combination i.e. the CAS approach together with ABM:

- The situation was characterized by several different entities which had access to limited information and with more or less influence on the company operations i.e. heterogeneousness and bounded rationality existed.
- Parallel activities were taking place and decisions were made by several people in different parts of the company i.e. discrete activities and decentralized decision making.
- The situation was resource-constrained i.e. there were limited resources in terms of money as well as time.
- Different performance measurements were used in different parts of the company, which on a company level were in conflict since some of these restrained each other.

Furthermore, in this specific case the FMCG company had specific requirements for the modeling process, based on earlier modeling efforts within the company:

- The company wanted a customized model, similar to their operations which they understood i.e. not a general model derived from common computer programs. In this regard, it was easier to build a model which fitted into the company's operations than to tailor the company's operations to an existing model.
- The company wanted a flexible model which could be extended with other functionalities and entities at a later time.

5.1 The agent-based model

Within the company several agents were identified and designed to represent the FMCG supply chain operations. These were found in production, in production planning, in inventory, and in the market.

Concurrent to the agent mapping process, data for the simulation model was collected in three different ways; interviews, observations, and document studies. Several interviews were conducted with managers responsible for logistics (in-bound, out-bound), supply chain management, operations planning, production, and inventory. In addition, observation was carried out in order to examine the daily behavior of the people involved in the actual activities performed within the company. Three investigators were on site at least once or twice a week during four months, and carried out follow-up interviews, participant observations and ordinary observations on several occasions. At the same time quantitative data was gathered from all functions and put into the database for the model. Data from January 1st - March 21st 2004 was put into the model. The reason why this period was chosen was primarily that it had been quite a stable period and there was sufficient data available to verify the results.

The model aimed to mirror the actual operations as accurately as possible, including enough details to provide valuable insights, however, without being too resource- and time-consuming i.e. the question of decomposability became central. The issue of decomposability was solved particularly by the type and amount of data available. Within the organization there was a general belief that adequate data was quite easy to obtain. However, when it came to data collection for the model the situation was rather different. There were different types of data for certain processes and no data for others. This led to quite considerable efforts needed to structure data, and necessitated several meetings with staff from different functions of the company. The model was built in Microsoft Visual J++ 6.0.

The agents represented the different activities and processes which were observed in the company. The reason for the chosen set of agents was derived from the data available and the abstraction level needed to enclose the real operations in a resource- and time- efficient way. It was later shown that the chosen decomposition of the system was enough to mirror the operations at the company and produce valuable scenarios which had great impact on both costs and service levels.

Each agent was specific and designed according to its state, constraints, policies, and rules in the following way:

FMCGAgent = {state, constraints, policies, rules}

5.1.1 The production agents. Ten production lines was designed as specific agents, Production Line Agents (PLA),

$P = \{PLA_1,\ldots,PLA_{10}\}$

with specific characteristics:

$PLA_i = \{S_1,\ldots,S_i; C_1,\ldots,C_j; P_1,\ldots,P_m; R_1,\ldots,R_n\}$

The reason why ten PLAs were needed was that every production line had unique properties, such as speed, products produced, and changeover time. In addition, there existed unique properties for each product when produced on a specific production line. All ten production lines in the factory were included.

The rules of each PLA are:

R1: when production list is received from the PPA (Production Planning Agent), the production sequence is updated.

R2: When a full pallet is produced it sends the pallet to the SA (Stock Agent).

R3: If a PLA is not producing and a production list exists the following steps are carried out:

a. The next item in the production list is removed.

b. The line is set to produce next item and calculates the change over time.

c. The time to produce a pallet is calculated.

d. The state is set to "*Producing item*".

e. The agent goes inactive until the changeover has been effected and the first pallet is produced

Else (if no production list exists), the PLA goes inactive until a new production list has been received

PLAs are connected to the PPA and the SA. A PLA could theoretically decide to change the order in which it wants to produce products, but in reality the policy is that it always produces in a way which is predetermined by the production planning. However, the produced quantity of a product, although set by the PA, is finally a result of the PLA's operation due to its state and constraints.

5.1.2 The stock. The Stock Agent (SA) represents the collective activities which take place in the storage facility, and if not there is not enough available room, it also covers any extra facilities that are needed to keep stock i.e. capacity is expanded if needed, however, at a higher cost. The SA is connected to fourteen agents; the PA, the three MAs, and the ten PLAs. It is designed in the same way as the other agents however with its own specific characteristics.

P1: accept the items delivered by the PLAs.

P2: accept and deliver the orders received from the MAs.

P3: update orders in the database at specific times, which in reality is each Sunday evening.

The SA is governed by the following major rules:

R1: When items are received from the PLAs, it registers them as part of the stock. Arrival time, quantity, position in the storage, specific products maturity time, and expiration dates for products are stored, the dates in order to ensure that no old items are shipped to customers. If the storage is full the items are registered as "overflow stock" i.e. a higher cost facility is enabled since in reality other facilities have to cover such events.

R2: When an/the order received from the MA (market agents) the following is done:

a. The quantity of correct items in stock is checked i.e. excluding items not matured (the products need to be matured before dispatched to customers) and out-of-date items.

b. If the stock contains the necessary items, the items are delivered (deleted from the stock) and a variable, "items-delivered" is increased. If the SA cannot fill the order, a variable, "not-delivered items", is increased.

R3: When it is time to update the database the SA sends a simplified version of the stock to the database. This simplified version does not contain any information concerning out-of-date items nor items that are not matured, only the total quantity of each product. This is the way the communication between stock and planning is done in reality.

5.1.3 Production planning. The policies of the PPA (Production Planning Agent) can be described as follows:

P_1: Once each Tuesday the PPA takes the stock balance from the planning system database.

P_2: Once each Sunday a production list is sent to the PLAs.

The rule for making the production list is the following:

R_1: For each PLA in the system, the PPA finds out which items to produce according to the following sequence:

a. *Start hour* of production for item is estimated. This is based on a predetermined sequence for each PLA.

b. The quantity to produce the following week is calculated according to the following steps:

1. Calculating the safety stock cover to set via the start time by formula: *cover = (cover setting *7 + start hour / 24) / 7*
2. The quantity of the item in stock is set to the start value.
3. The quantity produced or planned to be produced this week is added.
4. The forecast quantity of the current week, the subsequent week (the week of production) and for *cover* weeks is added.
5. If the result is equal or greater than zero, there is no need to produce anything the following week.

6. Otherwise, the quantity to be produced is the same as the negative value of the result.
7. If the quantity is less than the smallest batch quantity permitted, the quantity to be produced is set to the minimum batch quantity.

c. The PPA controls if the same item is planned on another production line.
d. If that is the case, this quantity is subtracted from the calculated quantity.
e. If the quantity to be produces is greater than zero, and the line has available planned utility, the item with its calculated quantity is added to the production plan.
f. If the estimated utility exceeds maximum utility allowed, the quantity is reduced to match the maximum level of planned utility.

The batch setting is checked for each of the items in production plan. If the batch setting is set to "split", the quantity is divided into two production occasions in the production plan. This happens only if a quantity is two times greater than the minimum batch quantity.

5.1.4 The market. The Market Agents (MA) are designed identically, however they use different data sets i.e. state, and constraints are different. The policies and rules the MAs follow can be described as follows:
P1: Once each Monday the MA gathers information about the weekly orders. There are two rules for doing this (depending on the parameter settings):
R1: actual sales of the same week from sales history or
R2: estimated sales from forecast data with item- and country-specific forecast error calculated by means of a Gaussian distribution.
The weekly orders are divided into daily orders using a uniform distribution algorithm.
P2: Once each weekday (Monday to Friday) at 12 a.m. each MA sends a message to the SA, with the orders of that particular day, containing the quantity of each item ordered.

5.2 Model verification

Before any simulations began the model had to be verified. The verification process was divided into two parts: microverification and macroverification. The purpose of the microverification was to ensure the individual agent's behavior while the purpose of the macroverification was to confirm that the model created a reasonable result compared to real data. The microverification involved meetings with each and everyone who was represented in some way in the model as an agent. For example, the behavior of the production planning agent, who in reality is one person, and the computer system the company have for production planning, were verified during two meetings. During the first meeting the set of state, constraints, policies, and rules was agreed on and during the second meeting the computer simulation was run and the PPA was verified by the person himself. The same procedure was done for the other agents as well.

The microverification process helped to guarantee that company employees involved felt confident that the model actually worked. At the same time, the CAS approach was communicated and considered to the behaviors in the microverification and the results from the macroverification.

The macroverification was conducted with a reference scenario which would mimic operations during the period from January 1st - March 21st 2004. It was a requirement from staff at the company that the reliability of the model should be very high in order for them to the place their trust in the outcomes of the scenarios created later on. In discussions with the different managers involved a set of output parameters was decided on to be used as verification of the model. These were: 1) number of products in stock, 2) service level (on-time-in-full deliveries), 3) production utility, 4) total cost and 5) storage balance on Sunday evenings. These output parameters were also used to evaluate forthcoming scenarios. The reference scenario was run several times (> 30) and the distribution of the runs was evaluated and an average was used to compare the reference scenario with real data (see table 1 for comparison at the end of the simulation). This was done together with staff from the company, the supply manager, the production manager, the production planner, and the stock manager.

5.3 Scenarios

The output of the model resulted in several scenarios which were evaluated and discussed by the management team involved. Two of these will be described next. Table 1 (se below) provides the result of these two simulation runs compared to the reference scenario created in the verification process.

Table 1. Results from two scenarios.

	Reference scenario	Scenario 1	Scenario 2
No. of products in stock	4000	3900	4300
Service levels	-	+ 0,8 %	+ 1.6 %
Production utility	68%	+ 5 %	- 0.5 %
Total cost	-	+ $650000	+ $30000

Scenario 1. In this scenario, the batch size in production was split in half; since management argued that this would make the company more responsive to customer orders. The result of simulation shows that, while the service level increases costs increase

considerably at the same time. The increase in cost derives from more cleaning of machines, increased people involvement, and as a consequence of more changes increased waste of products.
Scenario 2. In scenario 2 another issue discussed by management is tested; namely, the change in production planning from Wednesdays to Fridays and with an addition in safety stock policy from 1.2 weeks per item to 1.3 weeks per item. What this would provide is more updated production lists which would be closer to actual orders. The increase in costs is minimal at the same time as the increase in service levels is significant.

5.4 Case conclusion

Even though the model is quite simple i.e. no advanced algorithms or optimization efforts, results such as the ones described in table 1, provided the managers involved with new insights into how to approach changes in different parts of the company. These results have had an impact on actual operations and indications show that service levels are increasing in accordance with the results from the second scenario since the managers agreed on changing their planning policy accordance to this scenario. However, even more importantly, during the process of development of the model, the CAS approach gave the managers a new reference frame for discussing and improving business performance. They had to understand each other's perspectives and real-life operations i.e. how production set-up times were set, how planning was done, what the costs were for full inventory levels etc. In a follow-up interview recently, the Nordic supply chain manager expressed that the scenarios created have had impact on the way system-wide effects are discussed in the company i.e. how intuitively correct changes needs to be evaluated with a system perspective since it might bring other, unwanted, effects on the operations. The research project is still going on and further work needs to be done in order to verify the actual 2004 outcome. Furthermore, the CAS approach will also be further developed and evaluated in this particular context.

6. Case two: packaging company

The second case is based on a study and simulation of a packaging company in the UK where a complexity perspective was used at a plant and its customer relations. For reasons of brevity and confidentiality, some details have been left out and focus is instead placed on a discussion of the CAS approach and the result of the ABM simulation model which has been developed for the company.

The company was facing increased turbulence since customer demands were changing rapidly at the same as the costs of keeping high service levels were increasing. What the managers in the plant were looking for was a "virtual factory" to test the impacts different policy changes would have on their customer service levels, on their internal logistics, and on production. In order to facilitate this they contacted a consultancy firm named Eurobios[2], which uses agent-based modeling and insights from the science of complexity to solve its clients' problems. The approach Eurobios used was the development of an agent-based model that would represent a virtual factory, covering machines, inventory levels, batches, lead-times, products, orders etc. The programming language used was JAVA.

6.1 The agent-based model

Based on several interviews with staff, process maps of flows and interactions, and the available data for each and every possible part which had significant impact on the operations in the plant, an agent-based model was developed. The agents identified ranged from orders, machinery and shift plans to decision-making rules. In order to identify appropriate agents, process maps were made of the flow thorough the factory, both the physical flow and the order/information flow. Agents were identified in the plant based on their impact on the value-adding process. The agents were constructed on the behaviors, the policies and the constraints which could be recognized for each identified agent. Quantitative data for each agent during one year (2001) of production was collected and transferred to a database. The total amount of orders was approximately 20000 and the number of products was close to 2500. In total the plant had more than 100 different customers. There was no need to average or simplify any of these orders, products or customers since each entity was modeled.

6.2 Model verification

The output of the model was designed to mirror the service levels of the company. More explicitly, output parameters were missed dispatches, warehouse levels in terms of pallets (stock and non-stock items), machine utilization, process man orders, and renegotiated process man orders. The verification of the model was conducted on several occasions during the development process. This was done by means of workshops with staff from the packaging company where the previous year was modeled and compared to the real outcome through several parameters. The plant manager stated that *"based on the fact that there are several experienced managers operating, and that their business is quite stable, they have found it quite easy to check the reliability of the model compared to the experience and the figures they have concerning the operations."*

[2] www.eurobios.com

6.3 Scenarios

Based on the model several scenarios were created and evaluated by the management. One of the scenarios tested concerned the renegotiation of customer contracts. The second largest customer needed more products but the plant was close to its maximum capacity. At the same time the contract with the largest customer was going to be renegotiated and past experience of working with this customer was that the costs of high service levels were very high, however packaging company did not know to what extent. With the model as decision support the company decided to drop its largest customer since both intuition and results from the model indicated that the service level provided for this customer was too high in cost. Consequently, a contract with the packaging company's second largest customer with its planned increase of products could be agreed on without any major investments in new capacity. This what-if scenario was simulated at the beginning of the third quarter and the results from the simulation model for the fourth quarter indicated that such a decision would have great impact on profitability. The model estimated a reduction in warehouse levels of 35 percent and a decline in missed dispatches of 15 percent which would result in a total decrease of costs of £120 000. These figures were almost identical to the actual result produced three months later.

6.4 Case conclusion

While it is a fact that some of these decisions concerning the customer and production changes would have been made without the input from the model, several of the decision makers expressed their opinion that *"the model provided us with understanding and indicators of what could happen which made the decisions much easier to make."* All in all, the great advantage of the model, as expressed by the managers at the plant, was that it was directly comparable to the actual activities carried out in the factory. They quickly understood what was happening in the model and could easily contribute with more suggestions for fine-tuning at the same time as they were given some insights into the emergent behaviors the model provided in several different what-if scenarios.

7. Conclusions and discussion

In this paper it has been argued that the current, common logistics theories and methods cannot mirror the real-life phenomena logistics managers confront. It has been proposed that by considering more complexity in models constructed, insights can be gained concerning the system-wide effects of logistics systems and the sometimes major effects minor occurrences or changes in behaviors can have on costs as well as on performance.

In order to move towards adaptive logistics management it is the conclusion that two major steps need to be taken. First of all, a theoretical framework is needed, one which is in line with assumptions similar to real-life experience by managers i.e. of a less mechanical character, with emphasis on adaptation and change. In this article, the CAS approach has been successfully proposed and applied in the logistics context. The aim of the CAS approach has been to increase the understanding of logistics complexity and especially the property of adaptation. Furthermore, the aim of the CAS approach is to provide insights concerning how to handle complexity and uncertainty. It may even eventually serve as a catalyst for logistics managers in their actions i.e. provide assistance for a change in mind-set. Based on several interviews with both logistics managers as well as logistics researchers it was agreed that the CAS approach is useful and even more importantly, that he concepts and features of the CAS approach well suit the experiences both managers and researchers have experienced when dealing with logistics issues.

Secondly, in order to implement the CAS approach and provide tangible results in a period of reasonable time it has been concluded that ABM provides a good applicable method and tool. Both the cases reported in this paper, based on extensive simulations of the logistics operations, show tangible results and provide beneficial insights for the people involved i.e. not only logistics managers but other managers in different functions of the case companies.

All in all, in the logistics context ABM provides a method which can handle real-life logistics operations to a high degree, due to the fact that logistics is concerned with flows of goods being realized through dispersed activities as well as decision making, in time and space. Furthermore, it also provides a method that can quite easily be designed to mimic real-life activities since features such as bounded rationality and limited information for each agent, as well as non-linearity, self-organization, and emergence as a result of the interactions among agents, can be considered and included in the development and use of ABM simulations.

In both the cases presented in this paper, these features have had significant impact on the understanding and interpretation of the result by the people involved from the companies. The results so far have shown that ABM facilitates the managers understanding of assumptions of a more complex character, and provides a useful method in the CAS approach towards adaptive logistics management.

It is also concluded that the CAS approach, with ABM as the application, provides a useful and beneficial approach for the understanding of system-wide effects. This means that managers using the CAS approach will increase their understanding of how decisions can sometimes escalate into both positive and negative outcomes of high magnitude, and sometimes diminish and consequently have no effect at all on business performance.

Further research will focus on research concerning interorganizational activities, i.e. extending the cases to include suppliers and customers to a greater extent. By this, increased understanding may be gained concerning how changes at one supplier might affect the downstream operations at the customers'

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References

[1] Robertson, D. A., "Agent-Based Models of a Banking Network as an Example of a Turbulent Environment: The Deliberate vs. Emergent Strategy Debate Revisited," *Emergence*, vol. 5, no. 2, pp. 56-71, 2003.
[2] McElroy, M. W., "Integrating complexity theory, knowledge management and organizational learning," *Journal of Knowledge Management*, vol. 4, no. 3, pp. 195-203, 2000.
[3] Stacey, R. D., *Complex Responsive Processes in Organizations - Learning and knowledge creation* London: Routledege, 2001.
[4] Anderson, P., "Complexity Theory and Organization Science," *Organization Science*, vol. 10, no. 3, pp. 216-232, 1999.
[5] Lewin, A. Y., "Application of Complexity Theory to Organizational Science," *Organization Science*, vol. 10, no. 3, pp. 215, 1999.
[6] Lewin, R. and Regine, B., "An Organic Approach to Management," *Perspectives on Business Innovation*, no. 4, pp. 19-26, 2000.
[7] Beinhocker, E. D., "Robust Adaptive Strategies," *Sloan Management Review*, vol. 40, no. 3, pp. 95-107, 1999.
[8] Pascale, R. T., "Surfing the Edge of Chaos," *Sloan Management Review*, vol. 40, no. Spring, pp. 83-95, 1999.
[9] Tasaka, H., "Twenty-first-century Management and the Complexity Paradigm," *Emergence*, vol. 1, no. 4, pp. 115-123, 1999.
[10] McCarthy, I. P., "Manufacturing strategy: understanding the fitness landscape," *International Journal of Operations & Production Management*, vol. 24, no. 2, pp. 124-150, 2004.
[11] Sutherland, J. and van den, H. W., "Enterprise application integration encounters complex adaptive systems: a business object perspective," *Proceedings of the 35th Annual Hawaii International Conference on System Sciences, 2002*, pp. 3756-3765.
[12] Jennings, N. R., Sycara, K., and Wooldridge, M., "A Roadmap of Agent Research and Development," *Autonomous Agents and Multi-Agent Systems*, vol. 1, no. 1, pp. 7-38, 1998.
[13] Axelrod, R., *The Complexity of Cooperation - Agent-Based Models of Competition and Collaboration*, First ed. Princeton, New Jersey: Princeton University Press, 1997.
[14] Kauffman, S., *At Home in the Universe: The Search for Laws of Self-Organization and Complexity* New York: Oxford University Press, 1995.
[15] Holland, J. H., *Emergence from Chaos to Order*, First ed. Cambridge, Massachusetts: Perseus Books, 1998.
[16] Waidringer, Jonas, "Complexity in transportation and logistics systems: An integrated approach to modelling and analysis." Doctoral thesis Department of Transportation and Logistics, Chalmers University, Göteborg., 2001.
[17] Christopher, M., *Logistics and Supply Chain Management*, 2nd ed. London: Financial Times, Prentice Hall, 1998.
[18] Axelrod, R. and Cohen, M. D., *Harnessing Complexity - Organizational Implications of a Scientific Frontier*, First ed. New York: Basic Books, Perseus Books Group, 2000.
[19] Bonabeau, E., "Predicting the Unpredictable," *Harvard Business Review*, vol. 80, no. 3, pp. 109-116, 2002.
[20] Allen, P. M., "Knowledge, Ignorance and Learning," *Emergence*, vol. 2, no. 4, pp. 78-103, 2000.
[21] Park, J., "Evolving Adaptive Organizations," *Perspectives on Business Innovation*, vol. 4 pp. 59-64, 2000.
[22] Parunak, H. V. D., Savit, R., and Riolo, R. L. Agent-Based Modeling vs. Equation-Based Modeling: A Case Study and Users Guide. Procedings of Multi-agent systems and Agent-based Simulation, 10-25. 1998. Paris. Workshop on Modeling Agent Based Systems.
[23] Lim, M. K. and Zhang, Z., "A multi-agent based manufacturing control strategy for responsive manufacturing," *Journal of Materials Processing Technology*, vol. 139, no. 1-3, pp. 379-384, 2003.
[24] Wakeland, W. W., Gallaher, E. J., Macovsky, L. M., and Aktipis, C. A., "A comparison of system dynamics and agent-based simulation applied to the study of cellular receptor dynamics," *Proceedings of the 37th Annual Hawaii International Conference on System Sciences*, 2004, pp. 86-95.
[25] Ma, T. and Nakamori, Y., "Agent-based modeling on technological innovation as an evolutionary process," *European Journal of Operational Research*, vol. Article in press 2004.
[26] Emerson, D. and Piramuthu, S., "Agent-based framework for dynamic supply chain configuration," *Proceedings of the 37th Annual Hawaii International Conference on System Sciences,* 2004, pp. 168-176.