A Multiagent Systems Perspective on Industry 4.0 Supply Networks

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Abstract. Industry 4.0 scenarios involve Cyber-Physical-Systems to achieve a higher degree of individualization. Multiagent systems show the main characteristics to reach the goal of increased individualization possibilities by flexible interactions of agents. However, the organizational complexity of individualized manufacturing processes and thus the complexity of current supply networks require the extension of current multiagent system models. Enabling interaction between various multiagent systems representing autonomous actors of a supply network is necessary to cope with the increased complexity. This paper presents ongoing research and adds to the literature by modelling multiagent systems as fractals of a supply network using logistics modelling approaches. We present three examples for applying the multiagent perspective to such Industry 4.0 supply networks.

Keywords: Multiagent systems · Supply networks · Organizations

1 Introduction

The Industry 4.0 paradigm describes the forth industrial revolution with the vision of "everything connected with everything else". In particular, the focus is set on companies that build up cooperative networks of unique specialists [1]. These networks facilitate the step from single plants to supply networks, but require substantial information exchange between the actors for a seamless inter-organizational process flow. The demand for highly customized products and services is continuously increasing. Hence, processes in supply networks have to be constantly adapted to changing conditions that, due to the high and further increasing complexity, cannot be handled with current planning and control methods [2]. An important new element of these networks are Cyber-Physical-Systems (CPS). Due to their IP-based communication capabilities, they offer new options to bridge the gap between physical manufacturing processes, human employees, and information technology supporting monitoring, coordination, and controlling of the operations, and the local processes themselves [3].

New organizational forms are required to manage Industry 4.0 operations in emerging hybrid organizational settings, where humans and CPS cooperate in well-organized, small teams to produce and deliver their local output to the overall supply network. In such supply networks, the competitiveness of each of its parts is directly related to the competitiveness of the overall supply network. The key factor for

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competitive success of these networks is their ability to react appropriately to changing market demands. These factors include (i) a faster reaction with less costs and of higher quality to individual customer demands, and (ii) the creation of new products and services for customers.

The concept of intelligent, cooperative software agents and multiagent systems (MAS) offers a well-suited approach to model, analyze and design such systems. Research in Distributed Artificial Intelligence (DAI) has identified appropriate organizational concepts for problem solving systems. However, they mainly focus on the flexibility of distributed and cooperative search algorithms, neglecting the stability of the organizational structure such as stable resource and task allocation within enterprises.

Existing approaches in multiagent technology often neglect the fact that autonomous software agents generally cooperate in a loosely coupled MAS, which dissolve after the objectives have been achieved. For industrial applications, however, it is mandatory for MAS to guarantee a certain degree of economically required stability concerning their existence and structure, while preserving their problem solving flexibility. Further, supply networks are built on a set of flexibly cooperating organizational units. They are capable to immediately adapt their network structure to the changing demands of suppliers, customers and their environments.

A number of Industry 4.0 scenarios exhibit the complexity of MAS. For instance, the application of autonomous agents in the automotive manufacturing industry has gained significant attention. However, these manufacturing companies are generally situated in a supply network and thus depend on multiple suppliers. This further increases the complexity of the system and raises the question, whether and how the concept of MAS can be extended to meet these network-related requirements.

The aim of this paper is twofold: First, we survey extant literature from DAI and management science with respect to organization theory. Second, we develop a model for cooperation between different MAS, which is suitable for Industry 4.0 scenarios. The proposed artifact is based on (i) logistics (the right material in the right quantity, at the right time and the right place) and on the (ii) paradigm of fractal companies introduced by Warnecke [4].

The remainder is structured as follows. Section 2 discusses related work on multiagent organizations. Section 3 introduces models used in logistics. Section 4 presents the extension to multi-multiagent systems with corresponding examples in Sect. 5. Section 6 concludes.

2 State of the Art

This section surveys the state of the art on DAI, management science and their interrelations. First, literature on multiagent organization from the perspective of DAI is presented. Then, we compare the findings to approaches in management science, followed by reviewing the paradigm of fractal enterprises.

2.1 Multiagent-Organization Models Revisited

Organization as a Social Metaphor. Researchers in the field of MAS/DAI with backgrounds in management science have noted that "organization" is a metaphor that can be useful to describe, study, and design distributed software systems [5, 6]. As compared to organizational theories in management, however, MAS/DAI still lacks similar fine-grained concepts and instruments for describing, analyzing, understanding and designing organizational phenomena within agent-based systems [7]. It is very difficult to find out how an organization made up of people will change if software agents are joining this organization. This is a significant barrier for collaborative DAI innovations. However, first approaches consider the formation of teams within organizations, which may involve both software and human agents [8].

Organization has often been thought of as a top-down concept: starting from a given task, and, through iterative processes of task/sub-task decomposition, fine-grained task trees (top-down) and sub-solution synthesizing procedures (bottom-up) are designed. This approach leads to a top-down design of distributed problem solving systems. However, there exist many problems, in which large parts of the problem space are unknown. In such cases agent systems need to be configured bottom-up such that the relevant method is self-organization [9–12].

Organization as a Pool of Resources. The concept of cooperative problem solving (CDPS) approaches the integration of existing single problem solving experts (intelligent agents) into an overall framework [13]. The aim is to make synergetic use of their individual abilities. Otherwise, these abilities can only be used locally. This bottom-up perspective of building up a CDP system is accompanied by a top-down perspective on coordinating global processes of problem solving.

This approach can be compared to the perspective of management science, in which organizations are systems that pool individual resources in order to gain additional benefits for all of their members. However, so far in contrast to organizational theory, MAS/DAI research does not adequately address the question why an agent may join and contribute to a system.

Organization as Partitioning of Problem Spaces. From an organizational perspective, distributed problem solving implements the concept of dividing labor among a set of individuals, each possessing a particular capabilities profile. The idea is to assign to each agent the competence to solve a particular task type. For instance, Gasser states that "Organization is a precise way of dividing the problem space without specifying particular problem subtrees. Instead, agents are associated with problem types, and problem instances circulate to the agents which are responsible for instances of that type" [14].

As an immediate consequence, distributed problem solving leads to role concepts such as the role concept of the C-Net system [15]. However, the definition of roles in DAI is quite different to organization theories in management science. The latter refers to a role as to a precise definition of the expected behavior a particular organization member will exhibit. Role definitions are created by formal organizational procedures. Whenever a new individual joins an enterprise it has to formally commit itself to a particular set of organizational roles.

Computational and Mathematical Organization Theory. Besides models for solely human organizations this field of research does also comprise organizational models that involve software agents and consider distributed artificial intelligence. For instance, Kaufer and Carley model IT components as artificial agents that have different levels of information processing capacities. One major part of the model is the communication capabilities of agents: (i) how agents find communication partners, (ii) how information is communicated to the selected communication partner, and (iii) the consequences for the organization resulting from the communication [16]. This approach analyzes the effects of adding or removing agents from the organization by observing additional communication channels between the organizations' participants [17]. Literature on computational and mathematical organization theory mainly focuses on two ways of conceptualizing the design of an organization: (i) as a set of attributes or (ii) as a set of matrices [18]. Both ways can be used to structure parts of the overall design including resource access, authority/communication, or requirements.

OperA. Organizations per Agents (OperA) is a framework that enables the representation of organizational structures [19]. It incorporates an organization modelling language to define organizations and strictly distinguishes between the organizational structure and the instantiated agents populating the organization [20]. The modelling language uses three interrelated models: (i) The Organization Model describes the organizational structure including objectives, norms, roles, interactions, and ontologies, (ii) the Social Model mapping previously defined organizational roles to specific agents including contracts about role enactment, and (iii) the Interaction Model specifies the interaction among agents enacting organizational roles at run-time [20]. The OperettA toolset can be used for graphically supported modelling in OperA [21]. In the context of OperA the term organization describes a "specific solution created by more or less autonomous actors to achieve common objectives" [19]. The restriction to common goals is widespread in literature. However, in social organizations it is not necessary for all participant to share a common goal but they have to be motivated to contribute to the goal of the organization. Of course an incentive system might lead to the adaption of organizational goals for single agents but this cannot be generalized.

2.2 Comparison with Organizational Theory in Management Science

The concept of cooperating intelligent agents incorporates several important advantages with respect to the challenges of more and more human-like robots, of self-contained autonomic systems, of (so-called) autonomous cars and drones, and of Industrial 4.0 systems. However, in all these cases two conceptually different types of actors are involved. Thus, two completely different bodies of organizational theories have emerged.

On one hand, management science mainly considers organizations from a social science perspective. They build on the basic assumption that humans form an enterprise in order to fulfill a concrete market demand (e.g., production of autonomous cars). Organizational rules and definitions (e.g., definition of positions) are required to coordinate the division of labor, the behavior of employees, and all operational processes to produce, sell, and maintain goods and services. It is well understood, that enterprises need stability with respect to their suppliers and customers, to their employees, and to their infrastructural, technical and financial production factors. Indeed, the increased dynamics of their environments (e.g., changing consumer behaviors, changing market demand, changing market structures, changing market coordination, etc.) does also require an increase of organizational flexibility.

On the other hand, DAI has developed organizational theories that build on the assumption that artificial intelligent software agents form a "well-organized" problem solving system. DAI distinguishes so-called distributed problem solvers from cooperative distributed problem solvers and MAS. In any of these cases aims and success factors are given by technical criteria, based on methods and definitions of artificial intelligence. The main tasks include to conceptualize, implement and run an AI system, which is capable to efficiently deal with distributed knowledge and with knowledge requests. "Organization" thus refers to the "organization of symbolic knowledge within one knowledge base", to the division of overall knowledge into a well-"organized" set of sub knowledge bases, or to the "organization of search processes". "Organization" is understood as a tool to facilitate the search for symbolically represented formal knowledge within a set of knowledge bases. It enables agents to achieve their aims even in previously unknown environments and to pursue their goals even in hostile environments or, if necessary, also in collaboration with antagonistic agents. These include either antagonistic technical systems (e.g., several autonomous cars approaching a crossing, where each car has been implemented as a selfish agent with the overall aim to drive as fast as possible) – or humans aiming to stop their robots[1], which exhibit a behavior that is unacceptable for their owners (or human organizations).

2.3 Fractal Enterprises and Fractal Enterprise Processes

In order to meet the challenges of the increasing complexity and the dynamics of world-wide competition, it has been argued that the enterprise of the future will be radically decentralized. Decentralization involves the allocation of autonomy, resources, and responsibilities to deeper levels of the organizational hierarchy (for instance, see work of Tapscott and Caston [23] or Warnecke [4]). This requires enterprises to replace hierarchical planning by more decentralized concepts of coordination. In turn, autonomous organizational subunits need to exhibit a much greater degree of intelligence and self-referencing skills than they do today. This has given rise to the notion of organizational fractals [4]. Organizational fractals are characterized by the following major criteria [4]:

- **Self-similarity.** The criterion of self-similarity describes the structural characteristics of the organization and the modalities of generating added value. The self-similarity between different fractals enables resource sharing especially for informational resources.

[1] In this paper robots are cyber-physical systems controlled by agent-based software (see the concept of mouth-head-body architectures suggested by Steiner, Mahling & Haugeneder [22]).

- **Self-organization and Self-optimization.** Self-organization and self-optimization require autonomy to apply individual solutions to the corresponding tasks, and thus addresses the strategic, the tactical as well as the operational level. This decentralized approach aims at processes that require highly dynamic adaptation.
- **Goal-orientation.** This paradigm assumes that the overall goal system results from the individual goal systems of the fractals and is designed in a way that prevents conflicts between different goal systems. Thus, the performance of each fractal can be measured continuously.
- **Dynamic.** In contrast to traditional manufacturing islands, fractals show a higher degree of autonomy and thus of dynamic behavior. Different fractals are connected by an information and communication system and enable flexible adaptations to dynamic environmental requirements.

Organizational fractals involve a maximum degree of local autonomy, self-control, and self-organization skills. Organizational fractals aim to maximize their local utility (for instance, in terms of profit). They make decisions on their own whether they are willing to cooperate or collaborate with other organizational units. There is no direct means by which fractals can be compelled to behave in a certain manner. The only acceptable way to control the behavior of an organizational fractal or a group of cooperating fractals is the design of a globally consistent system of aims and objectives [4]. However, due to bounded rationality, organizations are generally not able to establish consistent goal hierarchies. Instead, the different goals that exist within an organization are more or less inconsistent, the knowledge about goals and relationships between them remains necessarily incomplete, uncertain, fuzzy, and sometimes even false. Additional goal conflicts may arise between the goals of an organization and the preferences of its customers, between different organizations that wish to cooperate, and between the customers of distinct organizations that wish to pursue their aims in close cooperation.

Organizational fractals form organizationally stable parts of an enterprise. They have well-defined interfaces to their environments. They execute locally well-defined production functions (transformations) and they are supposed to guarantee a maximum

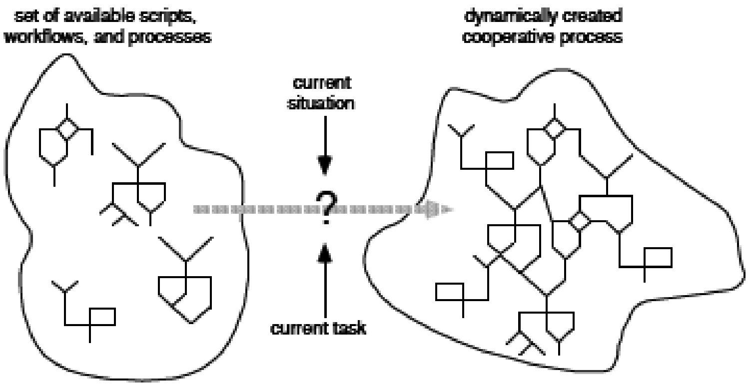

Fig. 1. Integration of business processes

of internal stability in terms of their operations and processes, their requests for resources, their availability, and their responsiveness. Their flexibility results from their capability to cooperate and even merge with other fractals in order to create a more complex fractal. This is depicted in Fig. 1, where four different fractals described by their individual process landscapes (left hand side of the picture) decide to establish a close cooperation (right hand side of the picture) in order to jointly fulfill an external demand.

3 Models for Logistics

The flow of goods and its optimization have always been a major concern in logistics research. The term "organization of logistics" in literature is mainly used in the context of structural enterprise organization. However, a strict focus on structural organization does not sufficiently consider the increasing influence of process organization especially in a logistics context [24]. The following sections introduce some of the existing models for logistics and highlight necessary extensions for the use of multiagent technology.

3.1 Systematic of Logistics Tasks

The task of logistics is that some requesting entity is supplied with the right good (quantity and quality), at the right time and the right place at minimal costs. A general model of logistics processes uses a graph to visualize temporal storage points of objects as vertices and the possibilities of the objects travelling through the logistics network as edges [25]. Figure 2 shows the three different basic structures of logistics systems: (i) single-tier systems with direct flow from source to sink, (ii) multi-tier systems with break-bulk and consolidation points in between, and (iii) combined systems that have direct and indirect flow of goods.

As stated above, the basic functionality of logistics systems is the spatiotemporal transformation goods. The optimization of these transformations are fulfilled by the following processes [25]: (i) Core processes of goods flow (transport, transshipment and storage processes), (ii) supporting processes, e.g. packaging processes and (iii) order transmission and processing processes.

The core processes of logistics together with the production processes can be modularly assembled to form a supply chain and are independent of a certain domain. A generic example from the manufacturing industry would be the storage of a resource (temporal transformation) that has to be prepared for pickup (transshipment), transported to the targeted destination (spatial transformation), prepared for further processing (transshipment), physically adapted (production), again prepared for pickup (transshipment) and so on. This short example shows that the core logistics processes occur continually. Even for information goods that are not physically transformed, the schema can be applied: An information is stored in a database (temporal transformation), made available by some database accessing protocol (transshipment), transported via a network connection to another destination (spatial transformation), handled by the

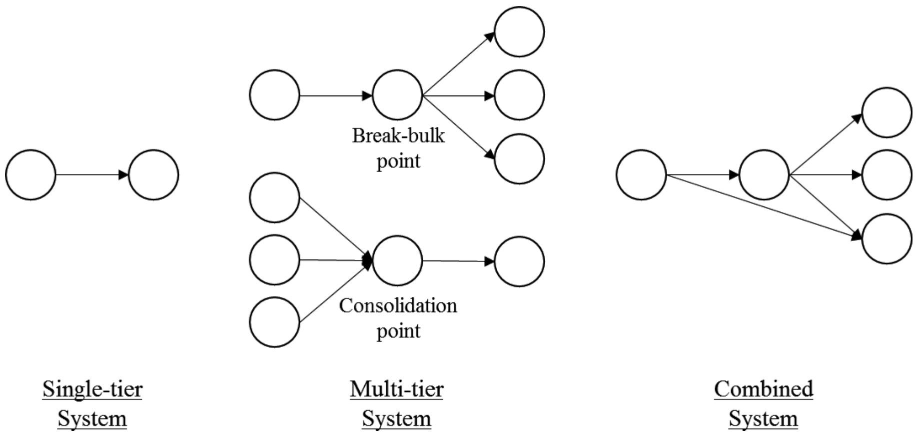

Fig. 2. Basic structures of logistics systems [25]

local network layer (transshipment) and processed by the IT system. The single processes are characterized as independent and modular fractals that individually optimize their processes to obtain an overall process flow.

These processes are independent of a certain domain and also independent whether the processed object is a physical good or an information. The widespread visualization as a graph is also domain-independent and enables also logistics networks as an extension of a logistics supply chain [26].

3.2 Approaches for Formalizing Logistics Tasks

Dependent on the specific modelling goal, there are numerous approaches for formalizing logistics tasks. This section will provide a short excerpt of available methods that are used to model intra- and inter-organizational problems. Besides business driven approaches like the Architecture of Integrated Information Systems (ARIS) that provides general means for business process modelling [27] and the Supply Chain Operation Reference (SCOR) Model that is an industry-independent framework for evaluation and improvement of supply-chains [28] a huge range of quantitative decision models exist in literature.

For models that go beyond sole descriptive analysis and that are used for planning and decision making, at least particular aspects have to be represented in quantitatively parameterized mathematical models [29]. The problem is often modelled as a deterministic single or multi criterial optimization model, either as a linear (mixed integer) or non-linear optimization model. In that way, numerous variants of supply chain optimization problems can be addressed. In general, these models assume some central designer that is able to enforce an optimized production plan to all instances of the supply chain. However, in real-world scenarios this is usually not the case as even in supply chains with one dominant company the other companies remain autonomous and follow their own interests.

Hence, these models are used to describe and optimize single fractals by aiming for an increased stability of the subsystem. The following classes of quantitative decision models are representative for this kind of logistics task formalization [29]:

- *Deterministic single-criteria optimization models* show only one single objective function that has to be maximized or minimized. The correlations between different parameters are known and, thus, the solution is not uniquely defined. Dependent on the structure of the objective or restrictive functions linear and non-linear as well as integer or mixed-integer optimization may be distinguished.
- *Multi-criteria optimization models* have multiple objective functions or criteria that have to be considered simultaneously. This allows even for competitive objective functions, which however hinders unambiguous optima. In this case, optima can only be determined per objective and overall solutions may only be distinguished by the dominance of other solutions.
- *Stochastic optimization models* assume that the available data is not complete and, thus, multiple environmental states are possibly occurring with a certain probability. Like for multi-critera models, there is no unambiguous solution as even the feasibility of the solution cannot be clearly determined, in case of stochastic elements appearing in side conditions.

3.3 Logistics in the Perspective of a Fractal Supply Network

Logistics is about the transportation of goods and the systematics mentioned in Sect. 3.1 are independent of a certain domain and the types of processes presented show similar characteristics: Goods have to be transported, handled and stored. In general, this is even independent of the fact, whether the good in question is physical or informational. For information goods the border between these core processes and the order transmission or processing might diminish as no physical good is present. In this case, the core process is an information flow just like the order processes.

Independent of the physical presence of a good, it can be observed that supply chains are in many cases divided into different fractals. These fractals are autonomous and cannot be fully controlled from a macro perspective. Depending on the context, these fractals might be whole enterprises (e.g. in a manufacturing supply chain) or different departments (e.g. in a hospital) that show a certain amount of autonomy. Hence, the overall process cannot be planned in detail against the motivation of the single fractals.

4 Multi-multiagent Systems

Logistics fractals in a supply network are autonomous and are organized to maximize internal stability as well as efficacy and, thus, show high potential for the representation by MAS. However, the formation of supply network requires the different MAS to communicate and cooperate with each other to fulfil their goals. This section addresses problems arising when different MAS are involved in the formation process including the dynamic reconfiguration as presented by Hannebauer [30].

4.1 Basic Approach

Since the emergence of the multiagent paradigm numerous MAS have been developed for various domains, e.g. manufacturing and logistics, and in most cases the design is focused on specific issues [31]. Although developed independently, the different MAS cannot be viewed as separated autarkic systems as they interrelate with each other in many ways. The coupling of these MAS imply new questions: (i) How should interfaces be designed between different MAS? (ii) How should the information exchange and service delivery between these separated systems be organized? The first question may be addressed by standardization of communication protocols, like the FIPA-standards (Foundation for Intelligent Physical Agents). The standard is widespread, but still not all MAS under development pursue the specification with the corresponding overhead, so communication between different systems is still an issue. The second question, however, cannot be solely solved on a technical level: The organizational structure between two or more independently developed MAS usually involves the relations between the represented real world organizations. The technical as well as the organizational question has been addressed by the platform Agent. Enterprise in a logistic scenario [32]. Agent.Enterprise is not restricted to intra-organizational value chains already represented by MAS, but integrates multiple instances of these into inter-organizational supply chains. This combination of multiple MAS is called a multi-multiagent system (MMAS) and works cross-organizational. Each MAS remains locally controlled, but obtains features of inter-organizational communication and cooperation to further increase flexibility and decrease costs. In Agent.Enterprise each MAS plans and optimizes its logistic and production processes individually, but informs other systems of unforeseen and potentially disturbing events. On the basis of this information exchange, plans of other MAS may be adapted or inter-organizational contracts may be renegotiated [32]. Figure 3 shows the Gateway-Agent concept used to structure the communication between two FIPA-compliant MAS [31].

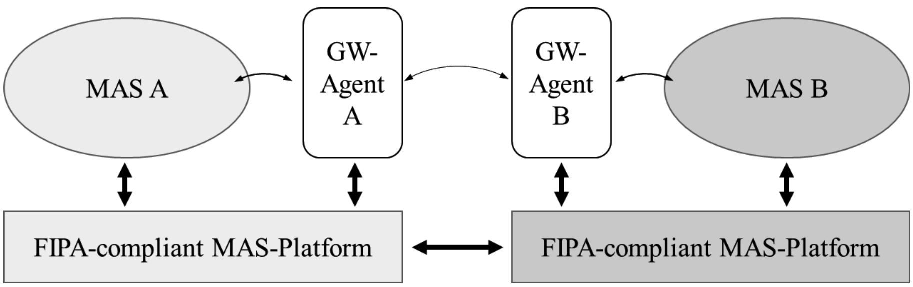

Fig. 3. The gateway-agent concept [31]

4.2 Abstractions

Already in 1966, Grochla raised the question in organizational theory, whether machines are getting intelligent enough that the task they are carrying out can be placed on the same level like those of humans [33]. One main argument is the increasing autonomy of technical systems and this thesis has been controversially discussed in organizational theory literature. Since then, the technical development has made substantial progress and also multiagent literature states autonomy as the key feature of actors in MAS enabling the consideration of unpredictable environmental effects. The agents gain autonomy by learning from experience and thus are able to compensate incorrect or incomplete built-in knowledge making the agents themselves independent from the developer [34].

Hence, different MAS show differing characteristics. Each MAS exhibits its own identity by defining interfaces to its environment and by developing an individual internal organization. This organization might be structured top-down or bottom-up depending on the learning capabilities and includes appropriate coordination mechanisms and responsibility rules. In logistics supply chains, one can find different levels of organizational structure, e.g. in a manufacturing supply chain, there are usually different companies that work together for one final good. Thus, we can distinguish between intra- and inter-organizational structures, e.g. the intra-organization structure of a company is embedded into the inter-organizational structure of the supply chain that involves various other companies whose behavior is not controllable, but has to be motivated. However, this structure is also present in other domains: Processes in hospitals are characterized by highly autonomous departments that can only be limitedly controlled by the central hospital process management. This leads to fractal processes within the hospital where each department again can be represented by a single MAS.

Table 1. Meta-model of fractal modelling

Label	Symbol	Description
Process Fractal		A self-contained and self-organized series of activities with a permanent nature that involves a certain number of actors and is available via interfaces
Actor		Smallest organizational entity in a process fractal that has the competency to make decisions with a given scope
Interface		Coupling point of a process fractal that allows for incoming or outgoing products, services or humans from or to another process fractal
Interaction Path		Bidirectional communication link between two actors of a process fractal
Transshipment		Transition of a product, service or human from one process fractal to another one

Independent of a certain domain, network-wide processes consist of flexibly coordinated process fractals being under local control of complex agents, e.g. a single MAS. Table 1 presents the meta-model for modelling fractal supply chains that is used in Fig. 4 to show an abstract example of a supply chain consisting of multiple MAS that represent autonomous fractals. The figure shows that two dependent organizational problems evolve: (i) the intra-organizational structure of each MAS that may differ significantly and (ii) the overall inter-organizational structure that aims at a final product and that is not able to fully control the single process fractals.

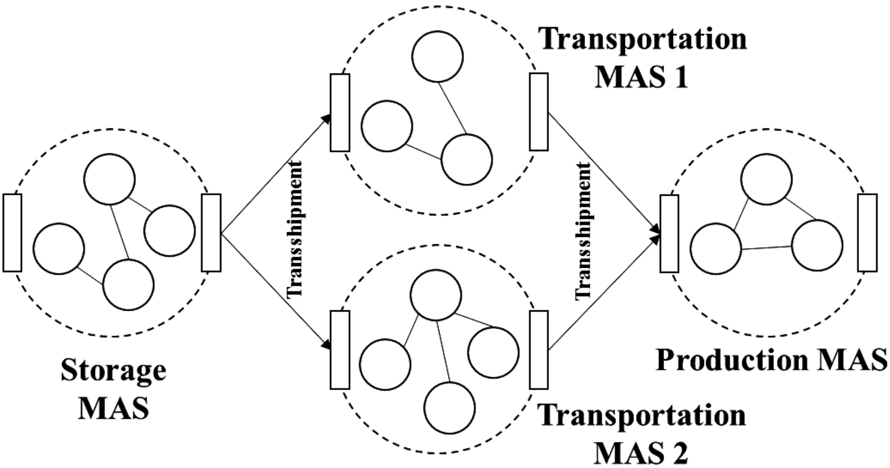

Fig. 4. Multiagent systems in a fractal supply chain

Each fractal has a logistics task based on domain independent types: (i) spatial transformation in form of a transportation process, (ii) temporal transformation in form of storage as well as (iii) physical transformation in form of a production process. The single fractals are each represented by a MAS that has input and output interface to form a supply chain and to follow the objective of the MMAS. The interfaces are connected by a transshipment function that allows the output of one MAS to be used as an input for another one.

5 Examples

This section presents three examples of research projects that used the flexibility of MAS for the supply chain networks. The examples are further analyzed in Sect. 5.4 with respect to principle of fractal enterprises.

5.1 Example 1: Agent.Hospital

Agent.Hospital is a virtual clinic that consists of various sections representing the different parts of the healthcare domain in Germany [35]. With unpredictable courses of

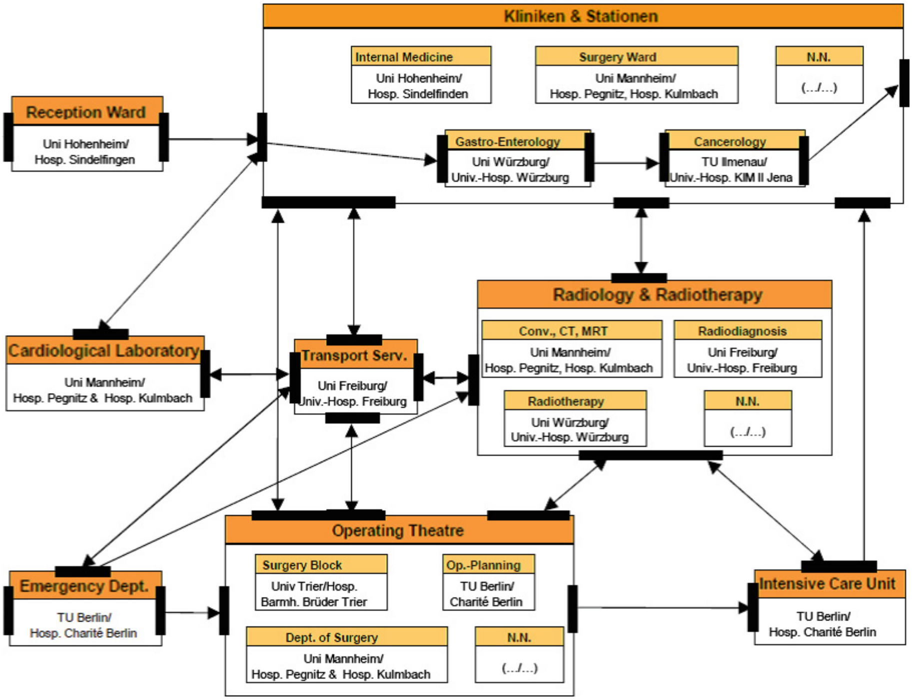

Fig. 5. Organizational structure of agent.hospital with selected supply chains [36]

treatment, highly situational dynamic and the consideration of emergency cases, planning in the healthcare domain requires high flexibility considering numerous priorities, preferences and goals. The variety of available resources and significant time consumption of each case further contribute to the complexity of the decision problem. The research project ADAPT as part of Agent.Hospital addressed this problem with an agent-based approach in which the goal system of each participant has been implemented as a BDI-agent [37]. Figure 5 shows the organizational structure of Agent. Hospital with the supply chain of a selected scenario.

5.2 Example 2: BREIN

The research project BREIN funded by the European Commission had the goal to open grid technologies for the appliance in companies. BREIN considered the supply chain optimization with the involvement of multiple companies at an airport. The considered ground handling scenario of airline service providers shown in Fig. 6 is highly dynamic and short-term orientated: Local disturbances at the airport apron and the aircraft ground handling require rapid adaption to increase the number of slots and therewith revenue. Here, only the customer of the supply chain, the airline, is fixed and resources, e.g. busses, baggage, staff, have to be assigned to the ground handling. An agent-based approach ensures that the individual interests of all participants are considered and that

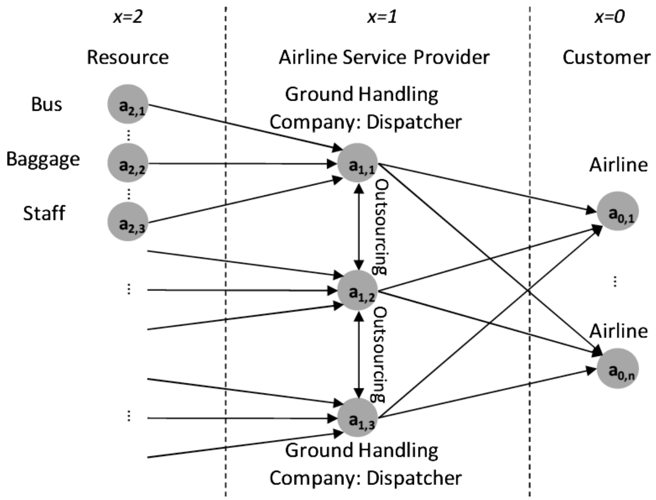

Fig. 6. Service networks for airport ground handling in BREIN [39]

the service network can be adapted in a flexible manner. This intra-organizational n:m market is characterized by n resources and m ground handling companies. The resource allocation is performed by a reverse auction and is specified in an allocation protocol, which prevents overcommitments and guarantees socially optimal allocations [38].

5.3 Example 3: EwoMacs

The research project EwoMacs addressed the coordination complexity and the ability to supply in customizable supply chains. The supply chain is viewed as a problem solving network that has been analyzed in a shoe manufacturing scenario. Shoes are produced according to individual requirements and, thus, the customer has been modelled as the first software agent. The contributions of each participant of the supply chain are coordinated using the principal agent theory. The organizational roles of customer and supplier have been specified according to the individual situation. The coordination was optimized by identifying, analyzing and designing transaction costs of the whole supply chain (see Fig. 7).

5.4 Lessons Learned

The examples presented in the previous sections show only a short excerpt of the variety for domain specific instantiations of MAS for supply networks. The overall MMAS, however, reveal significant correlation concerning their structure. Table 2 gives an overview on the presented research projects and their individual challenges by showing the organizational structure on the macro level as well as the appearance of

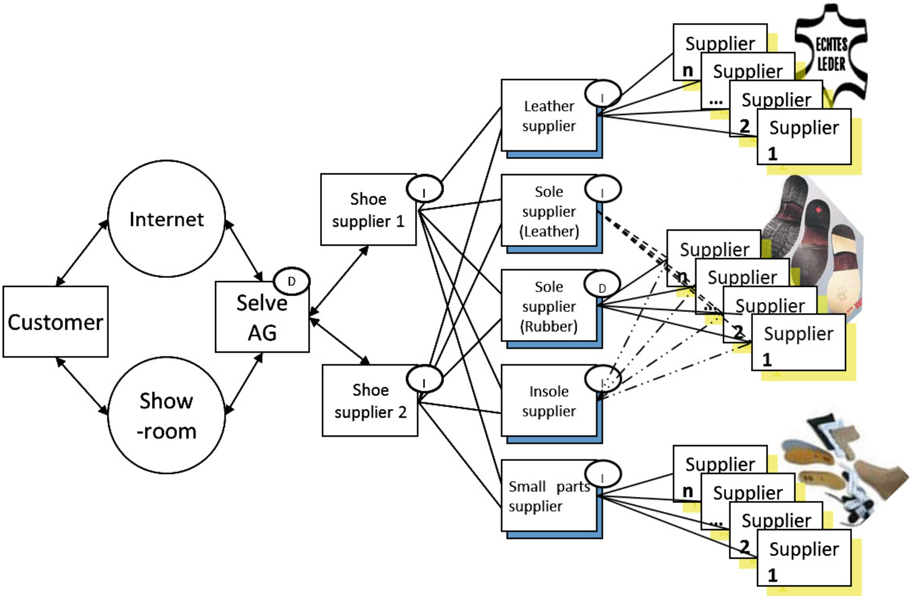

Fig. 7. Supply chain of shoe production in EwoMacs [40]

Table 2. Overview on research projects

	Agent.Hospital	BREIN	EwoMacs
Problem/ Challenge	Unpredictability of demand and resource capacities	Coordination of adaptive business grids	Complexity of co-ordination and ability to supply
Organizational Structure	Hierarchical Structure of an hospital with autonomous departments	Supply chain with different autonomous companies that have individual organizational structures	
Fractals/MAS	Different departments of a hospital	Ground handling companies at airports	Supplying companies for individual shoe producer

fractals that are represented by single MAS. The examples exhibit that the presented formalization of MAS as fractals of a supply network has potential to provide a structure that addresses the balance between organizational stability for reliability issues and flexibility to achieve an efficient inter-MAS process on the macro level.

6 Summary

Logistics is an abstraction of processes across departments and corporate boundaries. Current development of information technology and its implementation in industry 4.0 scenarios shifts the customer order decoupling point, where individualized instead of standardized parts are required, further towards the customer. The customer receives a product with a higher individualization, but the delivering supply network has to cope with the resulting complex requirements.

MAS have a high potential to meet the demands as the paradigm is conceived for flexible interactions under conditions with distributed knowledge and interests. However, the autonomous actors in a supply network using MAS for the coordination of their internal processes, require interaction of multiple MAS on the supply network level. As a first step towards this goal, we presented a formalization of MAS as fractals of supply networks that allows MAS to communicate and cooperate by providing basic functionalities independent of the participating agents like identity or organizational knowledge. The paper presents ongoing research. For applicability in real-world scenarios, the model presented needs further formalization of the meta-model and a comprehensive evaluation in industry context.

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References

1. Brettel, M., Friederichsen, N., Keller, M., Rosenberg, M.: How virtualization, decentralization and network building change the manufacturing landscape: an industry 4.0 perspective. Int. J. Mech. Aerosp. Indus. Mechatron. Eng. **8**(1), 37–44 (2014)
2. Scholz-Reiter, B., Görges, M., Keller, M., Philipp, T.: Autonomously controlled production systems – Influence of autonomous control level on logistic performance. CIRP Ann. – Manufact. Technol. **58**, 395–398 (2009)
3. Rajkumar, R., Lee, I., Sha, L., Stankovic, J.: Cyber-physical systems: the next computing revolution. In: Proceeding of the Design Automation Conference, Anaheim, USA (2010)
4. Warnecke, H.J.: Revolution der Unternehmenskultur – Das Fraktale Unternehmen. Springer, Heidelberg (1993)
5. Malone, T.: Modeling coordination in organizations and markets. Manage. Sci. **33**(10), 1317–1332 (1987)
6. Fox, M.: An organizational view of distributed systems. IEEE Trans. Syst. Man Cybern. **11** (1), 70–80 (1981)
7. Hübner, J.F., Boissier, O., Kitio, R., Ricci, A.: Instrumenting multi-agent organisations with organisational artifacts and agents. Auton. Agents Multi-Agent Syst. **20**, 369–400 (2010)
8. Dunin-Keplicz, B., Verbrugge, R.: Teamwork in Multi-Agent Systems – A Formal Approach. John Wiley & Sons, Chichester (2010)
9. Conte, R., Castelfranchi, C.: Cognitive and Social Action. UCL Press, London (1995)
10. Ishida, T., Gasser, L., Yokoo, M.: Organization self-design of distributed production systems. IEEE Trans. Knowl. Data Eng. **4**(2), 123–134 (1992)

11. Jennings, N.R.: Joint Intentions as a Model of Multi-Agent Co-operation. Ph.D. thesis, University of London, United Kingdom (1992)
12. Bond, A., Gasser, L.: An analysis of problems and research in DAI. In: Bond, A., Gasser, L. (eds.) Readings in Distributed Artificial Intelligence, pp. 3–35. Morgan Kaufman Publishers, San Mateo (1988)
13. Durfee, E., Lesser, V., Corkill, D.: Trends in co-operative distributed problem solving. IEEE Trans. Knowl. Data Eng. **1**(1), 63–83 (1989)
14. Gasser, L.: DAI approaches to coordination. In: Avouris, N.M., Gasser, L. (eds.) Distributed artificial intelligence: theory and practice. Comput. Inf. Sci., vol. 5, pp. 31–51. Kluwer Academic Publishers, Boston (1992)
15. Davis, R., Smith, R.G.: Negotiation as a metaphor for distributed problem solving. Artif. Intell. **20**, 63–109 (1983)
16. Kaufer, D., Carley, K.M.: Communication at a Distance: The Effect of Print on Socio-Cultural Organization and Change. Lawrence Erlbaum, Hillsdale (1993)
17. Carley, K.M.: Computational and mathematical organization theory: perspective and directions. Comput. Math. Organ. Theor. **1**(1), 39–56 (1995)
18. Carley, K.M., Gasser, L.: Computational organization theory. In: Weiss, G. (ed.) Multiagent Systems – A Modern Approach to Distributed Artificial Intelligence, 1st edn. MIT Press, Cambridge (2001)
19. Dignum, V.: A Model for Organizational Interaction: Based on Agents, Founded in Logic. Dissertation, Utrecht University (2004)
20. Dignum, V., Padget, J.: Multiagent Organizations. In: Weiss, G. (ed.) Multiagent Systems, 2nd edn. MIT Press, Cambridge (2013)
21. Aldewereld, H., Dignum, V.: OperettA: organization-oriented development environment. In: Dastani, M., El Fallah Seghrouchni, A., Hübner, J., Leite, J. (eds.) LADS 2010. LNCS, vol. 6822, pp. 1–19. Springer, Heidelberg (2011)
22. Steiner, D.D., Mahling, D.E., Haugeneder, H.: Human computer cooperative work. In: Proceedings of the 10th DAI Workshop, Bandera, Texas (1990)
23. Tapscott, D., Caston, A.: Paradigm Shift: The New Promise of Information Technology. McGraw-Hill, New York (1993)
24. Klaas-Wissing, T.: Logistikorganisation. In: Arnold, D., Isermann, H., Kuhn, A., Tempelmeier, H., Furmans, K. (eds.) Handbuch Logistik, 3rd edn. Springer, Heidelberg (2008)
25. Pfohl, H.-C.: Logistiksysteme – Betriebswirtschaftliche Grundlagen, 7th edn. Springer, Heidelberg (2004)
26. Domschke, W., Scholl, A.: Grundlagen der Betriebswirtschaftslehre – Eine Einführung aus entscheidungsorientierter Sicht, 4th edn. Springer, Heidelberg (2008)
27. Scheer, A.-W., Nüttgens, M.: ARIS architecture and reference models for business process management. In: van der Aalst, W.M., Desel, J., Oberweis, A. (eds.) Business Process Management. Models, Techniques, and Empirical Studies. LNCS, vol. 1806, pp. 376–389. Springer, Heidelberg (2000)
28. Stewart, G.: Supply-chain operations reference model (SCOR): the first cross-industry framework for integrated supply-chain management. Logist. Inf. Manage. **10**(2), 62–67 (1997)
29. Scholl, A.: Grundlagen der modellgestützten Planung. In: Arnold, D., Isermann, H., Kuhn, A., Tempelmeier, H., Furmans, K. (eds.) Handbuch Logistik, 3rd edn. Springer, Heidelberg (2008)
30. Hannebauer, M.: Autonomous Dynamic Reconfiguration in Collaborative Problem Solving. Ph.D. thesis, Technische Universität Berlin (2001)

31. Stockheim, T., Nimis, J., Scholz, T., Stehli, M.: How to build a multi-multi-agent system – The Agent.Enterprise Approach. In: Proceedings of the 6th International Conference on Enterprise Information Systems, Porto, Portugal (2004)
32. Woelk, P.-O., Rudzio, H., Zimmermann, R., Nimis, J.: Agent. enterprise in a nutshell. In: Kirn, S., Herzog, O., Lockemann, P., Spaniol, O. (eds.) Multiagent Engineering – Theory and Applications in Enterprises. Springer, Heidelberg (2006)
33. Grochla, E.: Automation und Organisation – Die technische Entwicklung und ihre betriebswirtschaftlich-organisatorischen Konsequenzen. Gabler, Wiesbaden (1966)
34. Russel, S., Norvig, P.: Artificial Intelligence – A Modern Approach, 3rd edn. Pearson, London (2009)
35. Kirn, S., Anhalt, C., Krcmar, H., Schweiger, A.: Agent. hospital – health care applications of intelligent agents. In: Kirn, S., Herzog, O., Lockemann, P., Spaniol, O. (eds.) Multiagent Engineering – Theory and Applications in Enterprises. Springer, Heidelberg (2006)
36. Heine, C., Herrler, R., Petsch, M., Anhalt, C.: ADAPT – adaptive multi agent process planning & coordination of clinical trials. In: Proceedings of 9th Americas Conference on Information Systems, Tampa, USA (2003)
37. Heine, C., Herrler, R., Kirn, S.: ADAPT@ agent.hospital: agent-based optimization & management of clinical processes. Int. J. Intell. Inf. Technol. (IJIIT) **1**(1), 30–48 (2005)
38. Karaenke, P.: Multiagent resource allocation in service networks. Ph.D. thesis, University of Hohenheim (2014)
39. Karaenke, P., Schuele, M., Micsik, A., Kipp, A.: Inter-organizational interoperability through integration of multiagent, web service, and semantic web technologies. In: Fischer, K., Müller, J.P., Levy, R. (eds.) ATOP 2009 and ATOP 2010. LNBIP, vol. 98, pp. 55–75. Springer, Heidelberg (2012)
40. Dietrich, A.J., Kirn, S., Sugumaran, V.: A service-oriented architecture for mass customization – a shoe industry case study. IEEE Trans. Eng. Manage. **54**(1), 190–204 (2007)