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Collaborative Complexity Management by Improving the Virtual Factory

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Abstract
Triggered by a rising international competition and an increasing cost pressure, avoiding risks has become a major concern for industrial companies. Particularly for small companies, collaboration in virtual enterprises is a promising approach to reduce risks and to ensure their competitiveness. The concept of the Virtual Factory aims to support the setup of such collaborations. Experiences in applying this concept show that there is still some potential left in adapting it regarding the ability to handle the increasing complexity in collaborations. This paper shows an approach to extend the concept of the Virtual Factory to cope with this increasing complexity.

Keywords:
Virtual Manufacturing, Cooperative Model, Complexity Handling

1 INTRODUCTION

During the last years, Industrial companies are increasingly challenged by market changes and competitors' behavior. This highly dynamic environment on the one hand requires an advanced flexibility and adaptability [1]. On the other hand, companies have to create unique selling propositions at an acceptable level of investment. Due to their size, in particular small companies have the chance to meet the requirements of flexibility and adaptability. However, they oftentimes lack the resources needed to create innovations and therefore to occupy unique selling propositions. Regarding their costs, they have to tradeoff between the availability and efficiency of their resources.

The seriousness of the small companies' problems is underpinned by a recent survey that exposes the reasons for crises that oftentimes lead to a company's insolvency [2]. Although these reasons are various, some important aspects are that enterprises too much specialize on one market or product, that their creation of value is too extended and that there is a lack in the control of the internal complexity.

For smaller companies, one way out of the dilemma between specialization and efficient resource utilization is to collaborate in virtual organizations. This may lead to major advantages in both capacity and competence management (Figure 1). Enterprises can improve their efficiency by sharing their resources and managing capacity variation inter-organizationally. High peak demands can be compensated by passing demands to other companies of the collaboration. The other way around, additional business can be attained from partners who have a lack of capacities. In addition, every enterprise can focus on its core competencies and therefore attain unique selling propositions, whilst the partners in the virtual organization provide the opportunity to offer system solutions and to enter new markets. Oftentimes, collaborations start with sharing capacities in order to create additional business. This is as the risk of revealing a company's know-how and intellectual capital is less by sharing capacities than by sharing competencies [3]. However, the trust developed from an intensive capacity management enables collaborations to realize a competence management and – as a consequence – to enter new markets and to acquire new business.

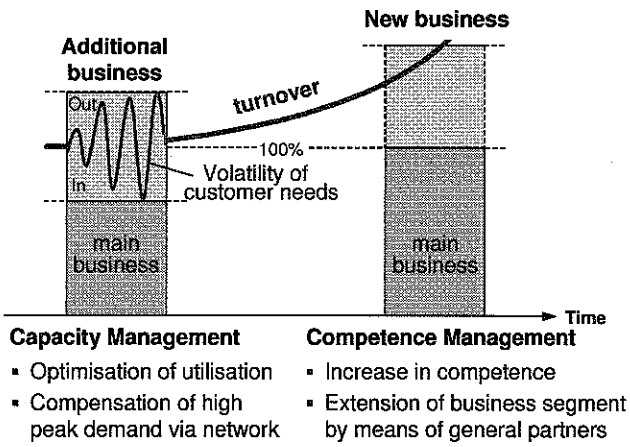

Figure 1: Courses of action to collaborate

Referring to the reasons for crises abovementioned, one can say that engaging in collaborations enables each company to specialize on its core competencies and to reduce the creation of value by allocating secondary activities to its partners. This dividing of a task into several subtasks the same time leads to a reduction of the internal complexity, regarding one single task. However, a new kind of complexity – the complexity of coordination – emerges and increases with the number of partners involved (Figure 2). It is proceeded on the assumption that there exists an optimal point of lowest overall complexity with a corresponding number of partners involved. However, this interrelation largely depends on the kind of task to be solved collaboratively.

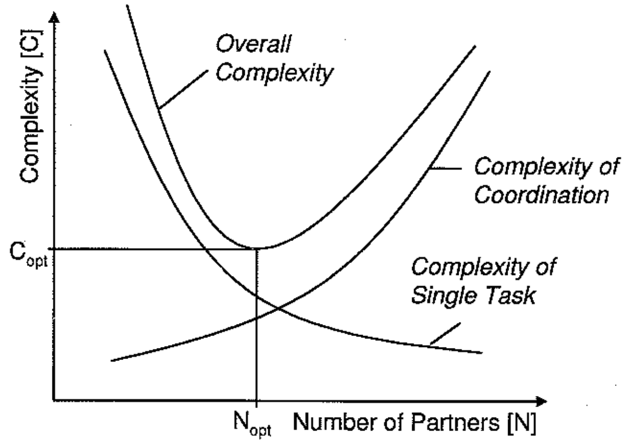

Figure 2: Interrelations in collaborative complexity

Although collaborations can be comprehensively supported by modern information and communication technologies, this only leads to a lower gradient of the complexity curve and does not change the mentioned interrelation basically. Therefore, additional resources for the inter-organizational coordination are required in collaborative order processing. In practice, the complexity of coordination oftentimes is underestimated. That might be one reason for the high failure rate of collaborations that is near 50%. It seems that managers often ignore to match the type of a network's system setup with the type of task to be solved. And even if they do take this into consideration, there is a lack of knowledge about network complexity that may lead to insufficient results. Reliable instruments and models that support a network manager to handle and to match both the complexity of a task and the coordination complexity are not available, yet. Moreover, there are multiple unforeseen, emergent network effects that increase the overall system complexity. These might be effects in elasticity and controllability as well as the overall network and production system behavior.

2 MODIFYING THE VIRTUAL FACTORY

2.1 Research Challenges

The research in the field of collaborative complexity is motivated by the high potential and prospects promised by collaborations. To this day, most approaches aimed at structuring organizations and implementing organizational changes – such as used in modular product configurations [4,5] or Release Engineering [6]. Considering complexity as a key challenge in collaborations is a basically new approach to the understanding of a collaborative system's nature.

The starting point of research was the identification of existing concepts for virtual enterprise that may provide contributions to the reduction of the coordination complexity [cp. 7,8,9]. Most of the existing concepts are explicit generic and do not consider differences in industrial sectors or in the position within the value chain.

2.2 The Virtual Factory

With the concept of the Virtual Factory [10], a function-oriented concept for the production industry has been developed. The main objective of this concept is to link stability and flexibility by creating an organizational system that gains its operating efficiency by differentiating between a static base network and dynamic, order specific collaborations out of this network. The static base network joins independent enterprises loosely. The intercompany coordination runs by market mechanisms without any central control. In case of any market demand, collaborations shall establish by combining according to the requested competencies and the required flexibility. To harmonize the collaboration and to fix basic principles, there exist rules, roles and instruments. For the marketing the virtual factory acts as one company and therefore has the chance to compete with larger companies.

This approach implies a reduction of the coordination complexity by setting fix organizational duties and responsibilities to some key persons acting in the collaboration. However, the system setup of an order-related production system not only has to reduce complexity but to match the complexity of the task the best way. Therefore, an entity is required to configure the system setup regarding that the system's complexity matches the complexity of the task that shall be handled. But how can this entity be implemented to the concept of the Virtual Factory and how does this entity know how to perform the required problem-to-system match?

A promising approach towards this is to add an additional function that combines several roles and enhances them by complexity management abilities. This so called Business Processor can be considered as an interface between the stable platform and the order-related collaboration (Figure 3).

The second part of the question – how to perform the required task-to-system match – is the more challenging one. The application of principles of complex systems from natural sciences to collaborative enterprise networks – considered as sociotechnical systems – might provide an answer to this generic question. In the following, some promising approaches from different disciplines are outlined.

3 APPROACHES FOR COLLABORATIVE COMPLEXITY MANAGEMENT

3.1 Networks as Socio-technical Systems

General Systems Theory deals with the representation of systems. According to Ulrich [11], it characterises organizations as open, dynamic, purposeful and productive sociotechnical systems. Whereas several approaches of General Systems Theory exist - such as Beer [12,12a] that are describing generic organizational concepts – However, Ropohl [13] focuses on the integration of social systems and technical systems within three dimensions. Therefore, he distinguishes three subsystems: the action system, the execution system and the goal setting system. These typological dimensions are regarded as the inner structure of any sociotechnical system.

The methodology known as the Delft School Approach - practiced by the Section Strategy, Technology and Entrepreneurship (Delft University of Technology) designs organizational structures that meet criteria that were derived from a company strategy. According to Dekkers [14], this methodology limits itself to equifinality: by means of the application of the steady-state model, for the modeling of recurrent processes, via the related organelle structure model and with the breakthrough model, for processes of change [15]. Key aspects of the methodology are the design approach and the application of a systems theory that has been developed during the 1970's. None of the systems theories have been adequately transferred to the domain of networks, yet.

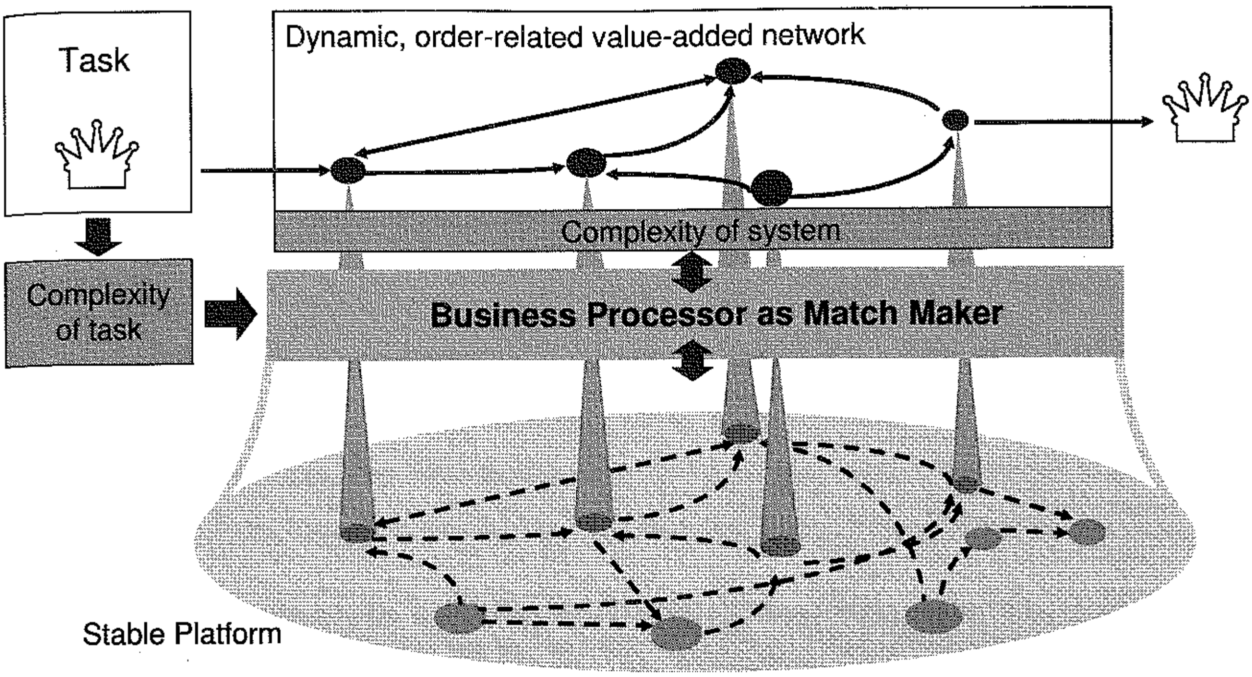

Figure 3 : Business Processor as Task-to-System Match Maker

These methodologies establish systems theories in order to model organizations from a cybernetic point of view according to the third system level of Boulding [16], Figure 4.

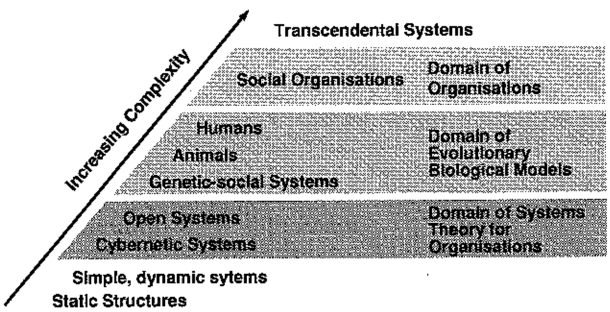

Figure 4: The nine levels of Boulding [16]

In addition they take into consideration a sociotechnical approach for designing new organizational structures. Since organizations represent the eighth system level according to Boulding, the systems theories might require some further elaboration. An accurate solution could be achieved by adopting theories of complex systems, networks and biological models; however, the level of validity for the design approach might be scrutinized. The design approach has the characterristics of static, onetime interventions, which companies might have to avoid because of their severe effects on organizations. A Review of alternative theories, such as complex systems, networks, and biological models, might facilitate the identification of organizational structures and industrial networks that are essential to adapt to changes in the business environment. Human-influenced complex networks such as the World Wide Web or human acquaintance networks have common properties, which are hardly compatible with existing cybernetic approaches.

Considering that most companies nowadays interact via such networks, the lack of networkorientation within systems theories becomes obvious. According to Milgram [17], the socalled small-world property, which is the most renowned specific property, implies that the average path length in the network is relatively small compared to the system size. This phenomenon has already been subject to scientific studies for more than three decades. According to Fricker [18], another property of complex networks is clustering, which deals with the probability that pairs of nodes having a neighbor are also connected. Increased efforts have been dedicated to the identification of other measures of complex (enterprise) networks. Probably the most important measure is the distribution of degrees, which means the distribution of the number of links that connect individual nodes. It has been proved that several real world networks possess scalefree distributions, oftentimes in terms of a power law. In these networks, a large number of nodes only have one or at least two neighbors, whereas some are multiple-connected. According to Dekkers [19], the specific properties mentioned before hardly appear in the original systems theories, such as the Applied Systems Theory.

While several models have been proposed to generate networks by means of combinations of the three properties, virtually each of these models describes a process that results in a network having the desired properties. Less effort has been devoted to the design of a dynamic system to not only generate but maintain a network. While there are only few of these models existing, most of them are applied on the assumption that the system size respectively the number of links increases. Therefore, advances in theories for industrial networks should focus on the dynamics of socio-technical systems that account for typical properties of complex networks.

As a consequence of these dynamics for the concept of the Virtual Factory, an ongoing maintenance is required additionally to the first-time setup of a value-added network carried out by the Business Processor. Beyond the value-added network, also the assumed 'stable' platform develops in the long term. Thus, the Business Processor has to carry out network activities to maintain an adequate system complexity for future tasks.

3.2 Approaches from Complexity Science

In the early 1980's, the paradigm of selforganisation emerged. Thus, according to Jost [20], a new branch for the description and control of complexity developed. Their control became more an more complex with the increasing number of elements in artificial systems [21]. However, it is assumed that in the field of complexity simple and comprehensible laws exist. Academics studying complex systems hold the assumption that the dynamics of complex systems base on universal principles. According to Kauffmann [22], these may hold the key to describe disparate problems ranging from particle physics to the economics of societies. A further promotion of complexity science means a shift in scientific approach. This shift will have the potential to profoundly affect business, organisations and government. The objective of researchers is to comprehend complex systems considering the following questions: Which principles govern the system behavior? How do systems adapt to change? How can system 'learn' efficiently? How can systems optimise their behaviour/ performance?

The term complexity connotes two meanings relevant to this research:

- Complexity stands for a structure that is chiefly internally oriented; either being part of networks or of an individual system.
- Complexity stands for emergence that is associated with both new behaviour and complexity emerging from environment.

Different entities can develop different types of complexity handling capability. Because of that a balance will hardly be achieved. Therefore, within the scope of this research only paradigms that address dynamics of industrial networks and environment will be chosen for an elaboration.

Complexity sciences and network sciences are two sides of the same coin for future research. A profound and interdisciplinary understanding of complex adaptive systems is key to enable quantum leap improvements concerning the handling and purposefully usage of these systems. Working closely together, both fields can mutually benefit from each other's experience, knowledge and practical solutions. By means of this multidisciplinary approach, the potential progress in both disciplines, complexity science and network sciences, may not only be additive, but multiplicative.

According to Schuh, the potential results provide a basis to enable the Business Processor (see Figure 3) for the concept of the Virtual Factory. Thus, by matching the complexity of a task with the complexity of a collaborative value-added system, the collaborative system setup which regards both internal and environmental complexity can be designed. That means that for example the number of partners or the number of linkages between the partners in the valueadded network can be adjusted to the complexity of a task. Handling a simple production task with definite interfaces, there can be more partners being involved at a lower degree of linkage than it would be required for the development of a complex product. A complex product would rather require less partners but a higher degree of linkage and more overlapping of the partners' competencies.

4 EVOLUTIONARY APPROACHES

The progress in the science of complexity has also affected models in evolutionary biology (see Figure 5). Especially, the models of developmental pathways and co-evolution deserve attention with respect to industrial networks. The responsiveness dictates that companies and industrial networks have to anticipate on changes happening in the market domain and the domain of technology. These changes relate closely to evolutionary biological models that describe and explain the evolution of species. Evolutionary biology makes a sharp distinction between mutation and selection, the two factors that determine the evolution of organisms and species [23]. The main models that are applied to describe the interaction between organism and environment are:

- the NK-model based on fitness landscapes [24], originating from early ideas by Wright [25];
- the Evolutionary Stable Strategies, application of game theories to the domain of biology [26,27].

A preliminary study in these evolutionary mechanisms and their meaning for organizational development reveals the importance of the criteria of sustained fitness, optimization and mutation o reach a local optimum, and evolvability, the capability to penetrate into new product-market combinations and disperse combined with bifurcation processes [6]. Collaborations can be seen as learning processes hence they evolve over time. According to Doz [28], studies of strategic alliance as evolutionary processes are scarce. Most research has been focusing on the determinants of cooperation and the contractual or relational form of the cooperation. Gulati [29] asserts that studying the development of a network over time can provide unique insights into the evolution of networks; Dierkes et al. [30] make a similar statement. Given the fact that this assumption proves to be true, how might collaboration evolve? Several approaches exist in literature to describe the evolution of cooperation and collaboration.

Doz [28] stresses that evolution of cooperation might be constrained by the conditions of the inception of the alliance and influenced by the collaboration process that takes place consequently. Larsson et al. [31] propose two different interorganizational learning dynamics, by using game theories. Both describe the dynamics of the transparency and receptivity as result of conditions. The first kind of inter-organizational learning dynamics deals with possible barriers while the second one concentrates on empowerment. Meeusen [32] has added a base for a more profound model by connecting the approach of Larsson et al. to the NK-model for fitness landscapes of Kauffman [22]. The further development of these models might yield more adequate insights into patterns of collaboration within industrial networks. Research in this matter has to link to evolutionary biological models.

Several approaches exist in literature to describe the evolution of collaboration. During the past decade, advances have been made in game theories, the descriptions of co-evolution, altruism, etc. within the domain of evolutionary biology. These advances can be transferred to the domain of organisations and networks, yielding more appropriate models to describe collaborations; in turn this can be applied to the concept of the Virtual Factory and might lead to a higher effectiveness of collaborations and a more purposeful development of cooperations within this concept. For example, by cooperating several times with the same partner, clusters might emerge in the pool of enterprises providing the stable platform. Enterprises within theses clusters might know the way each other partner works and behaves as a consequence from their joint evolution in former collaborations. This leads to the assumption that in some cases it might make sense to arrange enterprises in a value-added network within one cluster, even if they do not fit regarding other aspects such as their competencies best.

4.1 Multi-disciplinary Research

The new paradigm for industrial networks requires the intense collaboration between the mentioned domains of natural science and management science. This forms the base for a project that will move away from existing approaches to collaboration; it targets at the interdisciplinary development of a generic model of complexity as basis for a problem-to-system match framework for collaborative systems in production industry. The core is the application of principles of complex systems theory from natural sciences to collaborative enterprise networks as sociotechnical systems. The project will attempt to understand collaborative enterprise networks as complex systems that can only assure their viability through adaptation in interorganizational networks.

Six themes have been identified: dynamic description, coordination possibilities, radical & integrative innovation, path dependency, information sharing, modeling & representation. To address these themes and to resolve industrial problems of networked organizations, a pre-evaluation of different scientific approaches has been performed.

Starting point are the identified problems of production industry. Mirrored to these, the development and adoption of scientific approaches is continuously reviewed to achieve major scientific progress in the six themes. The contribution of natural sciences will address the challenges of industrial networks and generate new theory. Contemporary literature in management science attributes the functioning and success and failure in collaboration to common pitfalls, such as culture, resistance to change, change management, working methods. By deploying theories from natural sciences to the research challenges of industrial networks, not only new theory will be generated, those common pitfalls might find new explanations.

The recent insights from complexity science, into the field of collaboration in production industry, will allow the full exploitation of the benefits it may yield in comparison with traditional organizational paradigms. Despite the great complexity and variety of systems, universal laws and phenomena are essential to their inquiry and understanding. Scientific endeavor is based, to a greater or lesser degree, on the existence of universality, which manifests itself in diverse ways. In this context, the study of complex systems as a new endeavor strives to increase the ability to understand the universality that arises when systems are highly complex. A study of universal principles does not replace detailed description of particular complex systems. However, universal principles and tools guide and simplify inquiries into the study of specifics. For the study of complex systems, universal simplifications are particularly important. Sometimes universal principles are intuitively appreciated without being explicitly stated. However, a careful articulation of such principles can enable us to approach particular systems with a systematic guidance that the studies of complex systems often lack. The above-mentioned project will contribute to the issues of interdisciplinary complexity definition (to bring different mental frameworks closer together), translate this definition into a model of problem complexity and imposed complexity (the topic of emergence), and a model of production system complexity (internal complexity). The paramount scientific objective aims at merging the two complexity perspectives of complex problems and complex sociotechnical systems into one match-making generic model of complexity. This will help determine the right network paradigm for different types of collaborative problems as described as the task of the Business Processor in the extended Virtual Factory. According to the framework of complexity modeling outlined in Figure 5 the project yields:

- a classification scheme for complex problems and emergence as well as complex systems in production industry;
- a case specific model of problem and system complexity;
- a generic model of complexity for system coordination in collaborative production networks;
- a framework for problem and system complexity matching;
- an outlook towards complexity metrics for measuring and controlling complexity in dynamic networks;
- a pilot site evaluation.

Throughout the project execution, six crucial questions will direct the research:

1. What are the challenges in setting up and managing different types of networks in collaborative reality (production industry)?

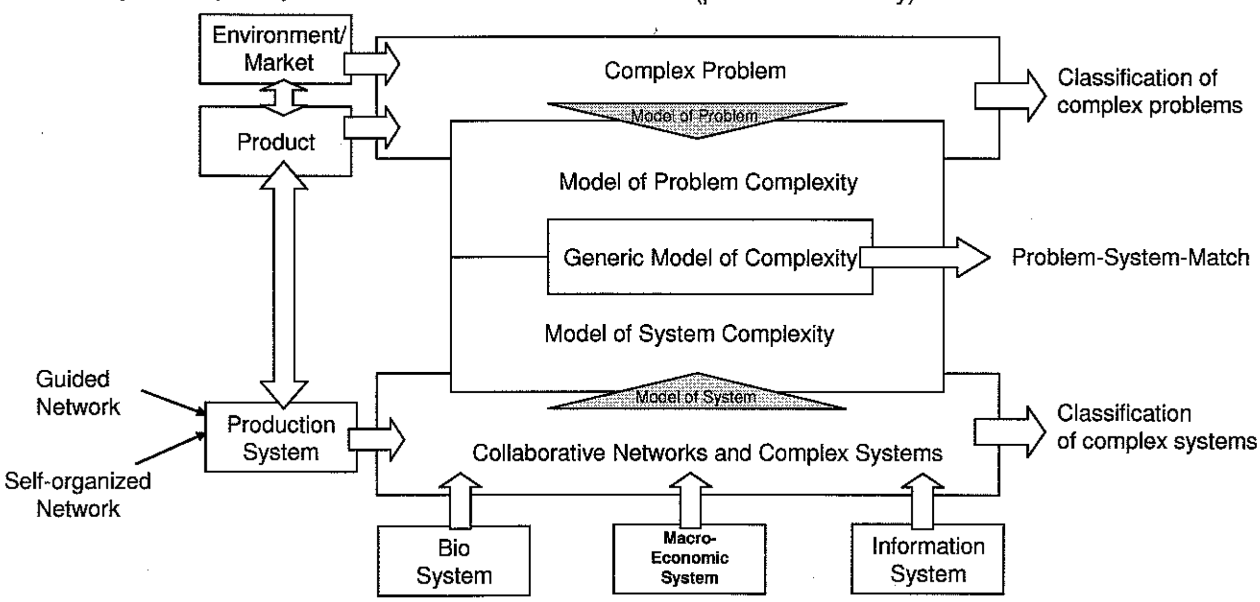

Figure 5 : Approach for complexity matching

2. How can complexity of a socio-technical system be described?

3. What are the characteristics of complexity in different types of natural and artificial systems and networks?

4. How can complexity in such systems be described and measured against the background of holistic complexity management?

5. What explanations guide complexity management in different network architectures?

6. Which correlation exists between the type and complexity of the collaborative problem and the most suitable underlying network structure for solving it?

These questions, as guidance to the project's scientific impetus, contain a high degree of risk of being unanswerable in the project's context. Therefore the project restricts itself to focusing on complexity matching. The specification of quantitative complexity measures as a constituent controlling element to a holistic complexity management can therefore only be subject to subsequent research endeavors; relying on a strong basis of knowledge and understanding of complexity issues in collaborative systems.

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5 CONCLUSION

Complexity has been identified as a major aspect to be regarded in a collaborative production system's setup. Therefore, new organisational systems are required. The modification of the concept of the Virtual Factory by adding an entity – the Business Processor – to manage complexity at the interface between the stable platform and the order-related collaboration can be considered as a promising solution. However, beyond this the core question to enable the Business Processor is: What kind of correlation exists between type and complexity of the collaborative problem and the most suitable underlying network structure for solving it?

In our opinion, the dynamic dimension of complexity, found in recent progress of various sciences, will fit the characteristics of industrial networks. The scientific objective should be to provide a properly designed framework-of-thought for the (technological) implementation of complexity management infrastructures, which rely either on state-of-the-art information technologies or on new insights into architecture and characteristics of complex systems. Consequently, objective of research is to create a framework for complexity controlling systems for future network management tasks that enables the Business Processor in the concept of the Virtual Factory to design and to maintain orderrelated value added collaborations.

The implementation of the Business Processor to the concept of the Virtual Factory enables the participating companies to react more flexible when market opportunities arise, thus increasing their competitive position. The adaptation to changing environmental conditions and the drive for innovation and fast product development will benefit from future research results.

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