A Complexity Based Approach to Collaborations in the Tool and Die Industry

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Abstract. Nowadays the tool and die industry has to meet various new challenges. An increasing number of production sites distributed world-wide requires a high flexibility in the procurement and maintenance of tools and dies. This flexibility is strongly connected to an increasing complexity and increasing costs. However, enterprises are more and more exposed to competitive pressure by new entrants from Eastern European Countries and the Far East branching out into the tool and die market with simple commodity moulds. To keep their business profitable, tool and die manufacturers need to strategically re-align their organisational management. A promising approach is the collaboration in at least regional tool and die making networks. Cost effects in terms of lower tooling costs and a decrease in maintenance efforts can be achieved as well as technological progress by joining the individual competencies of the collaborating tool and die makers. However, collaborations in production industry yield to new challenges for the participating enterprises. The lack of problem-oriented understanding of the required systems set-up and underlying control mechanisms currently leads to a high failure rate of collaborations. Academic research in management science has expanded on models accounting for the individual company as an entity. Complementary approaches to address the characteristics of enterprise-networks are therefore required. The application of principles of complex systems from natural sciences to collaborative enterprise networks considered as socio-technical systems might yield these complementary approaches.

Today's Challenges for the Tool and Die Industry

Tool and die making has become an important but critical function within a demanding field of tension [1]. Established between product development on the one hand and manufacturing and assembly on the other hand, tool and die making contributes both sides up- and downstream the value chain. Concerning the product development, it provides know-how for the specification of parts and the development of efficient production processes. For manufacturing and assembly, the tool and die making process provides productivity and operational availability. Therefore, the tool and die making process is a key process for realising shortened time-to-market goals and competitive cost structures [Fig. 1].

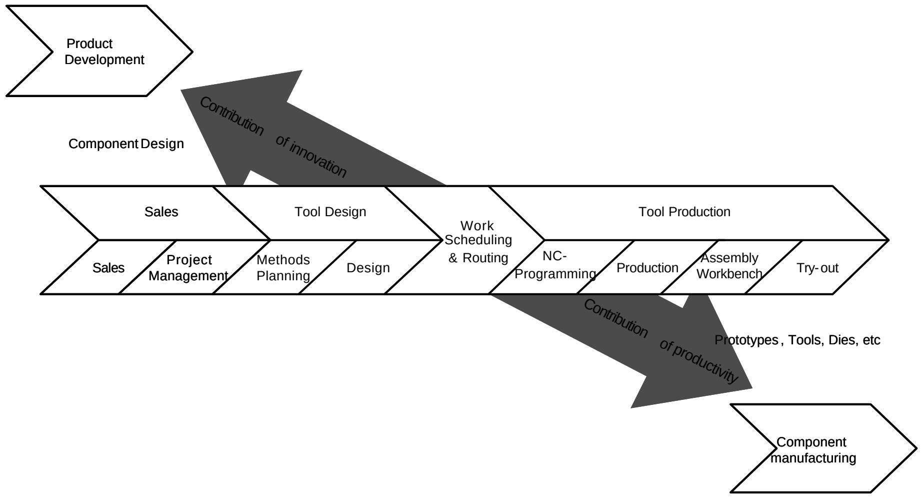

Fig. 1. Contributions of a tool and die shop to the adjacent value chain processes

As a consequence of this key position within the value chain, the tool and die shops make various contributions to the value and economic success. The first type of earnings are those gained by tool construction and manufacturing. In addition, productivity is provided by maintenance and repair of tools and dies. Thus, from individual repair and maintenance orders of flat-rates, the second type of earnings emerges. While maintenance usually requires a medium- or long-term planning and consequently can be considered quite foreseeable, repairs mostly fall due unexpectedly. To decrease wear and improve stability, tools and dies could be produced at a higher level of quality. This would minimise the likeliness of a breakdown on the one hand, but at the same time increase the expenses for manufacturing, decrease the flexibility and extend the time-to-market on the other hand. As a consequence of the higher manufacturing expenses, the competitive pressure, which is mainly caused by new entrants from Eastern European Countries and the Far East, increases. If a tool and die shop decides to produce at a lower level of quality, more spare capacity has to be kept in the shop in order to guarantee productivity by reacting swiftly to tool or die breakdowns. This inevitably leads to underutilisation and therefore to additional personnel costs [2].

The Network Approach

Changed Requirements

A promising approach for tool and die shops to cope with this dilemma is to collaborate in regional networks. Sharing their capacities enables the collaborating companies to highly reduce their spare capacity and consequently decrease the rate of underutilisation. By joining their individual competencies an optimal tool supply can be achieved at a higher level of quality. Besides, the Intellectual Capital of all participating partners in industrial collaborations can be significantly increased by application of the optimal partners and balance of power within the collaboration [3].

In addition, the flexibility to react to changes in customer needs can be increased and the time-to-market can be shortened. However, collaborations with other tool and die makers – even with competitors – require adaptations by companies in order to fit the characteristics of industrial networks. Although the conditions for collaborations have been improved during the last years – especially in terms of information technology and data-communication – the management of tool and die shops needs to tackle the increasing complexity of networked structures [4].

The world of management has been overfed with theories that might have been adequate to at least some enterprises dealing with contemporary challenges of industry, however, not to others [5] – for example Business Process Reengineering, Core Competencies and Lean Production. All these theories have in common that their foundations stem from a variety of presuppositions pertaining to different factors that might directly influence the rate of success of an organisation at one place and time. Direct transferences of these approaches to networked enterprises regularly fail as they lack problem-oriented interdisciplinary inferences. A new perspective to advance research in industrial collaborations – and therefore in tool and die making networks – can be achieved by incorporating findings from sciences of complex systems.

Increasing Complexity

The static perspective, which is characteristic for many areas in management science, is especially found in approaches and methods for outsourcing, partnerships, alliances as a make-or-buy decision [6] or a strategic decision related to competencies [7]. This perspective oftentimes leads to one-time decision-making and ignorance concerning the continuously acting dynamics of the tool and die sector's environment. The reduction of transaction costs, enabled via technological improvements in communications and logistics during the last years, entails an increasing outsourcing tendency in the tool and die industry while simultaneously increasing inter-firm complexity for coordinating the value chain.

Outsourcing may lead to a reduction of complexity within the single enterprise. Scientific Management, inspired by Taylor at the beginning of the 20th century, pinpoints the underlying effect: the complexity of a task decreases by dividing it into several sub-tasks while increasing coordination efforts. Assuming that these sub-tasks need specific competencies, they are allocated to different partners within an enterprise-network. At the same time, a significant increase is needed in allocated resources for coordination and control of product development and manufacturing. Consequently, studies reveal that at least 50% of all collaborative projects in manufacturing industry fail [8]. The reasons for this are manifold:

- The often postulated heterogeneity in networks has lead to a lack of guidance and control
- rendering these networks participative, but dissipative. Hierarchical structures could be helpful, but are not part of the postulated network paradigm;
- The ignorance concerning what type of network architecture and type of control should be installed when a certain type of task has to be solved;
- The unforeseen, emergent network effects in elasticity, controllability and overall network and production system behaviour.

Even with these detrimental effects, the benefits of the pending boom of division of functions among network members still promises to be greater than the stress it causes and will especially increase the rate of innovation and improve the performance by speed and flexibility.

Adapting tool and die shops and their networks to the dynamics of the environment requires more than one-time interventions that are seeking for stability. They will have to increase their Complexity Handling Capability, which means the ability to cope with the changes in their environment and the associated complexity pouring in [9].

Reducing and managing (internally oriented) complexity aims mostly at structuring organisations, and implementing organisational changes. An example for such an approach can be found in modular product configurations (e.g. Dekkers & Sopers; Schuh et al., [10, 11]). Regardless of how companies build on existing capabilities that are present in available resources and current structures, alternatives for coping with external changes remain limited. Finally, tool and die shops will have to adapt to the external changes by means of increasing the Complexity Handling Capability. This means to build on existing capabilities for new situations or incorporating new knowledge in order to create new capabilities.

Research Challenges

The aforementioned problems constitute a lack of knowledge concerning flexibility, adaptation and instability management of networked enterprises. Up-to-date, network sciences have not yet resolved the contemporary problems of the tool and die industry sufficiently, especially because they have not been considering the characteristics of tool and die making networks. Consequently, the theories of complex systems, accounting for these characteristics and found in biology, physics or chemistry - in short: natural sciences, can be considered the upcoming paradigm for the phenomena of networks. Whereas, with regard to management science, the complexity paradigm vice versa constitutes a new theory for understanding enterprise networks and promises major progress for the handling of socio-technical systems.

The application of the function-oriented concept virtual factory [12] is the first operational concept for networked SMEs, focusing on the way cooperation is configured as a socio-technical system. The establishment of trust-based relationships is the precondition for modelling cooperation. The concept provides guidelines for structuring the cooperation process in such a way that ad-hoc cooperation can be built up quickly and flexibly. Recent studies at the Laboratory for Machine Tools and Production Engineering at RWTH Aachen University show that yet not all effects and interrelations have been integrated into the concept. A lack of both management functions and trust has been identified as major pitfall in four analysed systems [13].

The development of models and methodologies for a holistic complexity management of tool and die making networks remains the challenge for management science. The crucial question is: What constitutes complexity in a network that is considered to be socio-technical system? The constructivist school according to Watzlawick [14] and Foerster [15] states that the human mind “constructs” a model of the environment to cope with the complexity of measurable parameters. This constructivist approach is a valuable step towards the reduction of complexity and is therefore considered in “reality management”; an approach which is similar to Soft

Systems Methodology [16] and the Viable Systems Model [17]. According to Riedl [18] the human senses and mind are archaic instruments that are construed for coping with reality in less challenging and complex times. He postulates that now, with a continuously increasing complexity of our environment, the mere capacity of the apparatus for stimulus processing is no longer sufficient to fully resolve the complex problem of a situation. Consequently any reduction of complexity, i.e. simplification, aims at producing a manageable level for humans assigned to controlling complex socio-technical systems. The degree of simplification largely depends on the amount, interdependence and behaviour of inherent core complexity drivers. The latter represent the underlying structure (static dimension of complexity) and behaviour of the overall system (dynamic dimension of complexity). Alternatively, the research might aim at increasing the Complexity Handling Capability of the individual tool and die enterprises and the networks they participate in; much of the complexity, i.e. the new challenges, are imposed by the environment of the networks and their elements, which are the individual organisations. Hence, the challenge for complexity research in tool and die making networks is the identification of adequate forms of system representation. Also demanding is the analysis of interdependence among core elements such as tool design and tool production, and the specification of complexity drivers, accounting for the complexity imposed by the environment, e.g. increasing requirements for the tool and die quality in combination with lower costs will help to survive in the competition with tool and die makers from Eastern Europe or Far East.

The Socio-Technical Approach

General Systems Theory deals with the representation of systems and characterizes organisations as open, dynamic, purposeful and productive socio-technical systems [19]. Several approaches of General Systems Theory exist, such as Maturana & Varela [20] or Beer [21] and others, specifying generic organisational concepts; Ropohl [22] for example focuses on the integration of social systems and technical systems within three dimensions. He distinguishes three subsystems: The action system, the execution system and the goal setting system as the dimensions of the inner structure for any socio-technical system. The methodology known as the Delft School Approach, practiced by the Section Strategy, Technology and Entrepreneurship (Delft University of Technology), designs organisational structures for socio-technical systems. The approach limits itself to equifinality [23] by means of the exploitation of the steady-state model, for the modelling of recurrent processes, the related organelle structure model and the breakthrough model for processes of change [24]. The most important aspects of the methodology are the design approach and the application of a systems theory that were already exemplified during the 1970's. None of these systems theories have been adequately implemented in the domain of networks yet.

These methodologies apply systems theories in order to model organisations from a cybernetic point of view, which matches the third system level according to Boulding [25] (Fig. 2), and they combine these theories with a socio-technical approach for the design of new organisational structures. Since organisations represent the eighth system level according to Boulding, the systems theories might require some further elaboration by means of the adoption of theories for complex systems, networks and biological models. Concerning this level, the validity of the design approach should be scrutinised. The design approach has the characteristics of static, one-time interventions, which tool and die shops have to avoid due to their severe effects on organisations. The review of other theories, such as those of complex systems, networks, and biological models, can facilitate the identification of the structures of tool and die shops and their arrangement in networks, which is required for adapting to environmental changes and continuous change.

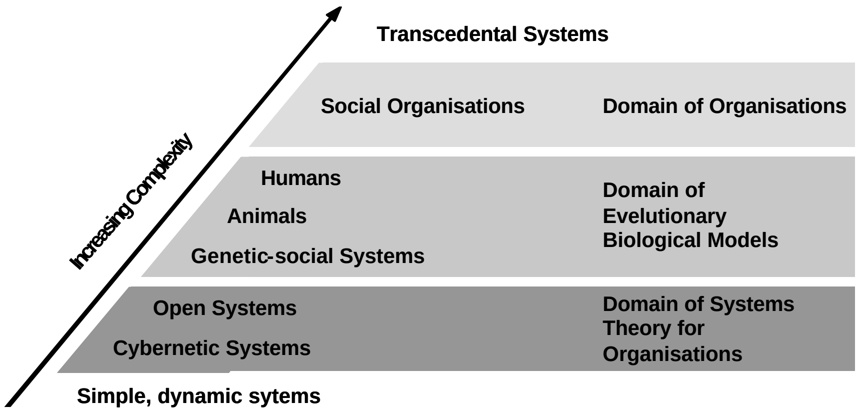

Fig. 2. The nine levels according to Boulding [25]

Human-influenced complex networks as in tool and die shops have common properties, which are hardly in line with existing cybernetic approaches. As a consequence thereof the lack of network-orientation within such systems theories becomes obvious when one considers the fact that most companies nowadays act in such networks - Here one must draw the conclusion that existing approaches remain hypothetically and are not capable of representing the reality of networking companies. One of these properties, the so-called small-world property which is the most common of the specific properties, states that the average path length in the network is relatively small when compared to the system size [26]. Another property of complex networks is clustering, i.e. the increased probability that pairs of nodes with a common neighbour are also connected. Therefore, increased efforts were made to identify other measures of complex (enterprise) networks [27]. Perhaps, the most important one is the distribution of degrees, i.e. the distribution of the number of links between the nodes. It has been pointed out that several real world networks have scale-free distributions, often in the form of a power law. In these networks, a huge number of nodes have only one or two neighbours, while a couple of them are multiple-connected. The three specific properties mentioned hardly appear in the original systems theories such as the Applied Systems Theory [28].

While a number of models have been proposed to generate networks with different combinations of the three properties, each of these models describes a process that ends up in a network having the desired properties. Less effort has been devoted to the design of a dynamic system that would not only generate but maintain such a network. While there exist only few model approaches [29, 30], most of them are based on the assumption that the system size or the number of links increases.

Therefore, advances in theories for tool and die making networks should focus on the dynamics of socio-technical systems accounting for the typical properties of complex networks.

Implications from Network Science

Latest empirical surveys on successful networks [e.g. 31, 32, 33] corroborate the hypothesis that in networks only two different paradigms of control exist (Fig. 3):

The first is the paradigm of guided networks which comprises features of hierarchical control in terms of first order cybernetics with the controller being a constituent element of the system, e.g. a producing enterprise with a tool and die supplier network. This type's fundamental specifications are hierarchical networks and focal networks. Guidance is realized in guided networks by means of explicit planning of interaction in advance to execution.

The second paradigm is the self-organized, organic network which is implicitly managed by the invisible hand of an external context according to Adam Smith, not being explicitly a control element of the system (second order cybernetics); at this point one might differentiate between dyadic and triadic networks. Inherent to its character of local intrinsic-triggered interaction, self-organised networks can only be managed in an implicit way. This means a non-deterministic coordination of activities. An active preparation of the network's context by means of establishing an effective rule setting channels network-activities towards a specific aim. Synergistic effects emerge by making the network's entities acting congruently, maintaining a necessary level of efficiency. In doing so, the network's entities adapt their own complexity (i.e. activities, structure, behaviour) to the external requirements as parameters for their context. In the process a global order emerges as a result of congruent local interactions [34].

	Guided Networks (↙ Hierarchical Networks, ↘ Focal Networks)	***Self-organised, organic, emergent Networks*** (↙ Dyadic, ↘ Triadic)
Characteristics:	▪ Two levels: Network and Collaboration ▪ Explicitly managed [focal entity] ▪ Configuration and Planning of interaction in advance to execution/enactment ▪ high span of control >1	▪ One level: Collaboration as Network ▪ Implicitly managed [context] ▪ Instantaneous, local dyadic interaction [self-organization] ▪ Span of control =1
Field of Application:	▪ Tool Development and Design ▪ Tool Production (Manufacturing, Assembly)	▪ Tool Innovation ▪ Procurement ▪ Sales & Marketing ▪ Service

Fig. 3. Control paradigms for tool and die making networks

Depending on the type of problem considered, one of these two paradigms is effective. All intermediary forms do either fail or evolve to either of the two forms over time. The rather constructivist approach of guided networks matches especially tool development and production; the implicit capability of the management is the alignment of ideation activities, procurement and service. For innovation processes, which constitute a paradigm for traditional technomorphous milestone-concepts, creativity and effectiveness are more important than efficiency. Hence, stability and instability issues in tool and die making networks can be driven by factors related to appropriate network control, although these driving factors have not been established, yet [35].

The guidance paradigm is well established in cybernetic approaches for system control, systems engineering or management cybernetics.

Taking into consideration the different dimensions of complexity in socio-technical systems, the two network and control paradigms entail different types and patterns of complexity for tackling different types of collaborative problems. Ashby's *Law of Requisite Variety* postulates that only complexity can absorb complexity [36]. Giving consideration to this requires a matching of the collaborative system's variety (behaviour) with the complexity of the problem, henceforth increasing the Complexity Handling Capability.

Implications from Complexity Science

With the proliferation of the network paradigm the hierarchical approach towards control has lost its charm and attention in science. Inspired by the Zeitgeist of the late 1980's, the trend of decentralisation and the postulation of non-hierarchical, participative and distributed control in society and organisations also penetrated complexity science [37]. With the activities of the Santa Fe Institute in the early 1980's, the paradigm of self-organisation emerged and opened a new branch for the description and control of complexity [38]. With the increasing number of elements in artificial systems - that are turned into net-like entities – their control became increasingly complex [39]. This made the deterministic, top down approach to systems control inefficient, if not impossible, especially for highly dynamic environments.

It is assumed that even in the study of complexity simple and therefore comprehensible laws exist. The field of study for complex systems holds that the dynamics of complex systems are founded on universal principles that may be used to describe disparate problems ranging from particle physics to the economics of societies [40]. The development of complexity science offers a shift in scientific approach with the potential to profoundly affect business, organisations and government. Complexity science strives to uncover the underlying principles and emergent behaviour of complex systems. Complex systems are composed of numerous, varied, simultaneously interacting agents. The goal of complexity science is to understand these complex systems - what "rules" govern their behaviour, how they adapt to change, how they learn efficiently, and how they optimise their own behaviour.

The term complexity can be understood in two ways that are relevant to this research:

a) As an expression of structure, mostly internally oriented either part of networks or an individual system;
b) As an expression of emergence, more rooted in new behaviour and complexity imposed by the environment.

Internal complexity can be seen as a design parameter, even though not sufficiently defined in cybernetic approaches. To cope with emergence, different entities might develop different types of Complexity Handling Capability; under these conditions, balance will hardly be achieved, only paradigms that address the dynamics of industrial networks and the environment will be chosen for an elaboration within the scope of this research. In an organisational context, complexity provides an explanatory framework of how organisations behave, how individuals and organisations interact, relate and evolve within a larger social ecosystem. Complexity also explains why interventions may have unanticipated consequences [41]. The intricate interrelationships between elements within a complex system give rise to multiple chains of dependencies.

The theory of complex adaptive systems as the state-of-the-art of research in the field of self-organisation cannot be assigned to one particular field of science [42]. However, it has found its way into many adjacent disciplines, e.g. evolutionary computation, evolutionary biology and technology management. Self-organisation, as a general theory for complex systems, is considered a new paradigm and a fundamental challenge for the traditional, linear and deterministic programme in science as a whole and its ideas of certainty and randomness. In adaptive systems that involve large numbers of entities, emergent, global behaviours that emanate from localised interactions are a critical concept. Understanding and shaping emergence may be essential for the success of such systems; from this perspective, explanations have been found that yielded more appropriate insights for phenomena that are difficult to comprehend. Agent-Based Modelling is a new and special branch of computer simulation that emerged as a methodology for studying complex systems [41]. Agent-Based Models consist of agents, which have states and behavioural rules, and an environment. In the environment, which is either spatial (e.g., a rectangular grid) or non-spatial (e.g., an abstract trading community), interactions among agents take place. The interactions can either be direct where the action immediately changes the state of the partner, or indirect when the action changes the environment which, in turn, causes the partner's state to change. Similarly, theoretical evolutionary biology has recently used game theories to explain and describe phenomena related to speciation. Especially, Adaptive Dynamics considers new approaches for the description of stability in populations [43, 44], thereby relating the development of species to state spaces. Traditional social sciences, especially classical economics, have very strong assumptions concerning the rationality of agents. Most Agent-Based Modelling uses bounded rational agents that have only local, limited information, and limited ability and time to process that information, similar to the real-life situation in industrial networks.

Both complexity sciences and network sciences are two sides of the same coin for future research in different disciplines. Only if a profound and interdisciplinary understanding of complex adaptive systems can be gained, quantum leap improvements in handling and purposefully using these systems can be attained. A close interaction between both approaches and a notion of one another's experiences and problems, i.e. approved solutions, is required. In doing so, the potential progress in both disciplines, complexity science and network sciences, may not only be additive but multiplicative.

Implications from Evolutionary Science

The progress in the science of complexity has also affected models in evolutionary biology. 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 closely relate 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. The main models for describing the interaction between organism and environment are:

- The NK-model based on fitness landscapes [40];
- The Evolutionary Stable Strategies, application of game theories to the domain of biology [44].

A preliminary study in these evolutionary mechanisms and their meaning for organisational development reveals the importance of the criteria of sustained fitness, optimisation and mutation to reach a local optimum, and evolvability, which means the capability to penetrate the new product-market combinations and disperse in combination with bifurcation processes [24].

Several approaches exist in literature to describe the evolution of cooperation and collaboration. Doz [45] stresses that evolution of cooperation might be constrained by the conditions of the inception of the alliance and influenced by the collaboration process that consequently takes place. Larsson et al. [46] propose two different inter-organisational learning dynamics by using game theories. Both describe the dynamics of the transparency and receptivity as a result of conditions. The first kind of interorganisational learning dynamics deals with possible barriers while the second kind concentrates on empowerment. Meeusen [47] has added a base for a more profound model by connecting the approach of Larsson et al. to Kauffman's NKmodel for fitness landscapes according to Kauffman [40]. 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. 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 [24], yielding more appropriate models to describe collaboration; in turn this might lead to a higher effectiveness of collaborations and a more purposeful development of cooperation. Additionally, a more effective collaboration will result in adaptations by agents in networks to the dynamic environment.

Conclusions

Which correlation exists between the type and complexity of the collaborative problem and the most suitable underlying network structure for solving in tool and die industry?

9.1 Implication for Research

With the field of complexity research still being a scattered patchwork of insights, a pragmatic and interdisciplinary approach holds the potential of yielding valuable insights into complexity modelling in today's networked production industry. The most common approaches focus on the complexity of structures (mostly internal complexity) with a static character; this links to the most common system theories. In our opinion, the dynamic dimension of complexity, found in recent progress in natural sciences, will fit the characteristics of tool and die making networks.

9.2 Industrial Implications

The implementation of this framework enables tool and die shops to react more flexible to arising market opportunities, thus to increase their competitive position, and allows to manage the networks they participate in more adequately. The adaptation to changing environmental conditions and the drive for innovation and fast tool and die development will benefit from the results in this field of research. New paradigms for tool and die making networks will stretch beyond the traditional issues of trust, power, and supply chain management.

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