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CHARACTERIZING COLLABORATIVE ENGINEERING NETWORKS

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1. Introduction

Engineering is a challenging activity which requires the application and consolidation of multiple knowledge fields from production, mathematical and economic to social and human approaches. In recent years, the challenges have become even higher as both the products and the operational environment have become more complex. The competition and the customers are global. Products are often configurable or one-of-a-kind "systems of systems", including mechatronics, software and services. Sustainable development and concern for environment as well as the whole product lifecycle need to be taken into account. Manufacturing and engineering activities are increasingly distributed worldwide, the transfer of also engineering activities to "low-cost countries" is going on.

At the same time there is pressure to shorten the Time-to-Market and Time-to Deliver which moves the engineering from sequential to more concurrent activities. The shortening lead times and the multi-nature of engineering have increased the need of companies to collaborate across traditional company boundaries. Enterprise networking allows the companies to focus on their core competencies, utilize the knowledge and competencies of other companies, enables the operation at different locations and offers flexibility and concurrency. [Zhang et al. 2008] identify three main driving forces for global engineering networks: globalization of engineering operations, dynamic business circumstances and the use of information technology.

However, the collaboration between different partners is not a simple and automatic solution but the organizational and geographic distribution brings along several challenges. The objective of this paper is to discuss the characteristics and challenges of collaborative engineering networks. The study uses information about industrial cases collected and analysed in a Finnish research project Fudge (Future Models for Digital and Global Extended enterprises), which is focused on configurable variant products. The paper reviews the characteristics of engineering networks using the concepts, frameworks and approaches presented in previous research on collaborative networks, global engineering and collaborative engineering.

2. Background and methodology

In Fudge –project (Future Models for Digital and Global Extended enterprises) information was collected and analyse regarding the engineering and the product information models, structures and processes of Finnish globally acting companies. The focus was on the processes of configurable variant products. The aim was to identify future models and processes for the management of product data in globally operating companies.

One of the methods to collect information was benchmarking [Pulkkinen et al. 2011]. The aim was on one hand to collect information for analysis and on the other hand to share the experiences and solutions among the group of companies involved in the project; thus contributing to common learning. The project was started with initial analysis of the participating companies through interviews about their expectations, objectives and current status of development in different fields relating to product data management. The benchmarking was carried out with workshops on each six sites of the participating companies. Each company presented their main solutions and topical themes, followed by questions and discussion. The events were documented by researchers.

In addition to benchmarking, the research partners analysed some specific themes with part of the companies interested in the topic. One of these topics was distributed engineering in networks. Information about the volume, location, tools, network activities and challenges were collected from five companies. Additionally it was discussed in more detail in workshops of one case company.

While previously engineering and design was mostly performed inside a company, currently it is more and more outsourced to partners and subcontractors. Many of the Fudge project companies are currently in this process; the volume of outsourced engineering is increasing and this causes challenges to the product development.

Thus, this paper uses both the Fudge benchmarking general information and the collected additional information of the current state and challenges of distributed engineering in the case companies. This information is used to analyse the characteristics of the current engineering networks. The analysis is based on consolidating two approaches of previous research:

- the approach of Collaborative networks (CN) research, evolved through several European research projects, but not specifically focused on engineering (for example [Karvonen et al. 2003], [Camarinha-Matos et al. 2005a], [Camarinha-Matos and Afsarmanesh 2005b], [Camarinha-Matos et al. 2008]), and
- a specific approach focused on engineering networks: GEN – Global Engineering Networks [Zhang et al. 2008] which again does not presuppose inter-enterprise operations.

Additionally the concepts are discussed based on the approach of Lu et al. [2007] about collaborative engineering which does not focus on organizational or geographic distribution but takes a human and team-work oriented viewpoint. These approaches are described in chapter 3-4 and consolidated and applied for the characterization in chapter 5.

3. Collaborative networks

There have been several research initiatives in Europe in the field of Collaborative Networks (CN) during the last decade (for example [Camarinha-Matos et al. 2005a]). Most of them have been focused on manufacturing networks and supply chains, only a few engineering cases have been involved.

In the European CN research cluster VOSTER the concepts used in the different projects were analysed and consolidated: Two main concepts for inter-enterprise collaboration were identified according to their objective and duration [Kurumluoglu et al. 2005]:

- On one hand there is a more stable, though not static, form of collaboration where a group of organizations keep on collaboration on a long term to develop and maintain their preparedness to co-operation.
- On the other hand there are short term collaborative organizations which are created for a specific value adding task, for example to deliver a product or a service to a customer, and which are dissolved after the task is finished.

The latter short term organization can be called a Collaborative project, a Virtual organization (VO) or a Virtual Enterprise (VE). Virtual organisation is a temporary consortium of partners from different organisations established to fulfil a value adding task. The organization is “virtual” in the sense that it is not one organization but formed of different organizations and it is expected to work as efficiently as a single organization. Additionally, using IT tools is usually considered as a feature of VOs.

The long term form is often called a Collaboration Network, a Source Network, or a Virtual Organization Breeding Environment (VBE). Thus a VO is created from the network or a VBE for example for a customer order. The concept VBE emphasizes the need for preparing for the collaboration, to be successful and efficient when there is a need to create a VO. The level of preparedness may vary in different networks. Recently a term “ Business ecosystem” has been used for less tight collaboration networks which do not have as high preparedness as VBEs [Ollus et. al. 2011]. Often also customers are considered as part of the Business Ecosystem.

In addition to organizations, also individual professionals can co-operate with other persons or organizations within the so called Professional Virtual Communities. These different organizational forms and their management were studied for example in European ECOLEAD project [Camarinha-Matos et al. 2008].

The collaboration within a network or a VO has several challenges. The objectives of the companies participating in a network are not identical. There are always multiple objectives, part of which may be contradicting. This might be the case already inside one organisation, where the objectives of different sectors or departments may be different [Karvonen et al. 2004]. In a network the partners have greater autonomy than inside one organization [Munkvold 1999] and the decision-making is distributed. Inter-enterprise environment has additional complexity because of more units, functions, and locations, there are more differences in concepts, cultures, processes, practices, skills and management styles between network partners. In information intensive work, like engineering, the exchange and sharing information is important. In inter-enterprise collaboration there may be a need to protect some knowledge and openness is necessarily not accepted. The necessary information exchange is also complicated by a large number of IT tools which do not interoperate. Additionally, companies may collaborate within several networks. They are not willing to take up and use many parallel systems and practices.

The differences in thinking and practices as well as aligning the objectives and tools can be worked by developing collaboration preparedness.

4. Characterizing collaborative networks in engineering

4.1 Situational factors and design parameters – Collaborative networks research approach

Two kinds of descriptive parameters are identified for networks and virtual organizations in Collaborative Networks research [Pedersen et al. 1999]:

- situational factors: these are conditions coming from the environment (lead time requirements, types of needed competencies, ...); that is, factors which cannot be changed or selected.
- design parameters: these are parameters which have multiple alternatives and can be selected (rules for the management, for exposure of competencies, legal aspects…).

In VERAM (Virtual Enterprise Reference Architecture and Methodology) the situational factors and design parameters are called contingency factors [Zwegers et al. 2003]. They are factors to be analysed when designing a network or a VO. In the following chapters some main characteristics are described.

4.1.1 Network topology

One of the characteristics studied in the previous research is the network topology. The topology is in this context defined as a structure describing all the different relationships between the partners (nodes of network), including information, material, monetary and control flows, responsibilities and power relationships [Karvonen et al. 2005]. The main topologies identified are (Figure 1) [Katzy et al., 2005]:

- supply-chain topology; interaction of partners follows mainly a chain, links are in a tiered structure with each partner relating to its upper and lower neighbours.
- star topology, or hub and spoke –topology, with one central partner (main contractor). Links are arranged predominantly star-like between a central partner and the other organisational entities.
- peer-to-peer topology; interaction between all nodes without a hierarchy.

Selection of the topology is of course dependent on the product and the processes and communication needed to develop or engineer it. It should be noted that the operational topology (product or engineering processes) is necessarily not the same as the management topology. For example, for a peer-to-peer operational topology a star (or hub and spoke) –type management topology may be used.

Figure 1. Topologies for networks or virtual enterprises [Katzy et al. 2005]

4.1.2 Preparedness

An important concept in CN research is preparedness**.** Preparedness in general expresses how much effort or actions have been performed to prepare for a certain task before the actual task is carried out. In case of collaborative networks the preparedness is developed in the network or Virtual organization Breeding Environment (VBE). The objective of preparedness is to enable fast set-up of Virtual organizations for customer specific tasks. This is considered as a competitive advantage – to be able to configure fast "world class competencies together into a system of service delivery or production" [Tolle and Vesterager 2003]. The preparedness can be developed on different levels and it can cover many areas, like:

- The network having a common vision and objectives for the future
- Specification of common processes and practices, roles, rules and principles, contracts
- Trust building and maintenance
- Identification of competencies and competence development
- Partner assessment and qualification practices
- Information management and communication, tools
- Understanding the common concepts
- Quality management

The optimal preparedness level is dependent on many factors. For example the situational parameters listed above also have an effect on how well the network should prepare itself for collaboration. The operational environment and the expectations for future collaboration are important: If there are only few collaborative opportunities expected it is not cost-effective to invest in high preparedness.

[Pedersen et al. 1999] present a classification of so called knowledge production forms; that is, systems producing knowledge-intensive products [Christiansen 1996]. Three types of systems are identified and characterized:

- dedicated
- flexible
- creative systems.

The classification is used to identify the optimal preparation level. The degree of preparation is concluded to be highest for the dedicated system and lowest for the creative system.

4.1.3 Trust

There are many definitions for trust and partly they are context-dependent. In [Kürümlüoglu et al. 2005] the following description is given for trust in a Virtual organization (VO):

"…trust in the virtual organization means predictability of behavior and reactions in common issues. This can only be achieved within a win-win situation. This is the foundation for any collaboration".

Cambridge Technology Partners [CTP 2001] present the following definition for trust in the area of networked business:

"Trust is the degree of vulnerability participants to an exchange are willing to assume in pursuit of a mutually positive outcome."

This definition links trust in a given, restricted context (exchange), and it thus seems to suit well for a VO, which is a temporary consortium for a specific task.

Need for trust comes from risks, uncertainty and vulnerability which may cause that the objectives of the VO or a company are not achieved. Trust as such does not make the operations less vulnerable: if the risks are high, trust does not remove them. Justified trust is based on knowing the risk level. The benefit of trust in VOs is mainly linked to efficiency of cooperation. Trust speeds up the inter-enterprise processes and decreases costs of monitoring and coordination. Trusting partners are able to cooperate also in case of incomplete information.

Trust is currently considerably discussed in terms of collaborative networks due to needs of information exchange and collaboration requirements. In this environment the main objects of mistrust are:

- information security (availability, confidentiality, access control, integrity, authentication, traceability)
- uncertainty about the business partners, their intentions, actions and performance.

When performing a specific task or a project (VO) with partners the main issue of trust is how the partners affect the success of the VO. The sources for mistrust are dependent on the risks how the partners may endanger the VO success. The main focus is typically on the following:

- partners' performance of the tasks as agreed (in time and quality), supporting VO objectives also in case of a change or a problem,
- partners keeping up confidential information, avoiding information leaks,
- following rules & laws.

It should be noted that trust violation may be both intentional and unintentional. For example, information leaks may be caused both by purposeful breaking of rules and by human errors. Both forms should be avoided.

4.1.4 Management approaches

Karvonen et al. [2005] analyse the characteristics of Virtual Organizations (VOs) in order to define VO management approaches and their dependence on the characteristics. VOs represent the temporary form of collaboration networks, aiming for a specific outcome, like collaborative projects. Even if the management approach can be seen as a design parameter which in principle is not pre-defined but can be selected, there are some important situational parameters which affect the recommended VO management approaches. These parameters include:

- Type of the VO objective, product or service.
- Importance of different objectives – time, cost, innovation etc
- Risk involved in the VO – what are the consequences of VO failure
- Dependencies between the VO tasks and partners

In [Karvonen et al. 2005] five different VO management approaches are identified, from project management –type, constrained approach to "self-organization" approach.

4.2 Key patterns of global engineering networks – GEN approach

Zhang et al. [2008] discuss the evolution of engineering from a closed system to an open system; towards Global Engineering networks. They study and classify global engineering networks (GEN) through two characteristics: configuration and performance.

Configuration is presented by four key dimensions: network structure, coordination mechanism, governance system and support system. Configuration has two extremes: integrated engineering systems and autonomous engineering federations. For each dimension a characterisation for integrated GEN and autonomous GEN is given.

For performance two fundamental preferences are identified: effectiveness and efficiency. Effectiveness is about reaching the goal: having quick response to business environment changes, effective product development for local markets, customer-driven innovation and flexible resources. Efficiency is about how economically the goal is reached: economies of scale/scope, synergies, sharing and reusing knowledge etc. [Zhang et al. 2008].

By linking the configuration and performance [Zhang et al. 2008] identify two basic patterns: integrated and efficient global engineering networks and autonomous and effective global engineering networks. The combinations of integrated and effective GEN and autonomous and efficient GEN are considered as additional patterns. The authors present three case studies and their evolution on the patterns, however, the cases did not include inter-firm engineering activities.

4.3 Collaborative engineering approach

[Lu et al. 2007] present "A Scientific Foundation for Collaborative Engineering". The aim is to understand "how engineers should collaborate with all stakeholders" and how they would become "more productive collaboration leaders". The focus is more on a team of individual stakeholders than on the collaboration between different organizations. The benefits expected are not only result paybacks but also teamwork paybacks.

A distinction between coordination, cooperation and collaboration is made and considered important, setting more stringent requirements on collaboration. According to [Lu et al. 2007], while cooperation strives for mutual benefits by sharing tasks, collaboration aims at achieving collective results, not only sharing resources (as in coordination) and outcomes (as in cooperation) but most importantly also having a common goal.

[Lu et al. 2007] do not specifically address the challenges of collaboration between different organizations but analyse more the engineering collaboration from the human and teamwork point of view. Using the definition of [Lu et al. 2007], current engineering networks do not always represent collaboration, but often cooperation or coordination.

5. Consolidation and application to case engineering networks

When comparing the CN approach (chapter 4.1) and the GEN-approach (chapter 4.2) it can be identified that both include similar features. Collaborative engineering approach (chapter 4.3) has focus more on the challenges of teamwork and human interaction.

For example the GEN configuration-network structure resembles CN/ VO topology, GEN-coordination mechanism and governance are similar to management approaches etc. GEN - performance (effectiveness / efficiency) is related to the CN/VO objectives which are considered as one important factor behind the preparedness level as well as other design parameters (chapter 4.1).

Table 1 shows the relations between the characteristics in CN research approach and in GEN approach. The features cannot be linked to each other one-to-one but they seem to cover similar topics, within a different structure.

Table 1. Consolidation of CNO research and GEN approaches

Characteristic in CNO research	Characteristic in GEN
Topology	Configuration/ Network structure and Coordination mechanism
Preparedness	Configuration/ coordination mechanism and Governance system and Support system Performance – Effective or efficient
Trust	Configuration/ network structure and coordination mechanism and governance system Performance – Effective or efficient
Management approach	Configuration / Coordination mechanism and Governance system

Table 2 presents the characterization of engineering networks, based on the generalization of Fudge project cases in the CN approach. In some cases the same company may have different engineering networks for different products which is partly affected by the product type (complexity, variety etc.), partly the differencies come from historical reasons. Also not all the relationships between the main contractor and the subcontractor have similar practices within one network. Some may operate with very close connection and integration, some are more loosely integrated.

Generalizing the Fudge cases to the GEN characterization, gives the following result:

- From configuration viewpoint the Fudge engineering cases seem to belong mostly between Integrated GEN and Autonomous GEN but more on the Autonomous side.
- From performance viewpoint the objectives are currently more on efficiency than on effectiveness.

Thus the current state does not seem to follow either of the GEN basic patterns (integrated & efficient and autonomous &effective) but belong more to the additional pattern autonomous and efficient (or semi autonomous-efficient). Additionally some integrated relatioships exist. In the case studies of [Zhang et al. 2008] they identify for example industrial electrics networks to fit to autonomous-efficient. Some of the Fudge cases can be considered to go in this industry type. According to [Zhang et al. 2008] the future evolution might in this section go towards more integration driven by the use of Information Technology. This also seems to be one trend in the Fudge cases.

Table 2. Characterizing engineering networks in CN approach

Characteristic in CN research	Appearance in engineering networks
Topology	Star-like structure seems to be the most common. The subcontractors communicate with and through the main contractor; no direct flows of information between different subcontractors was identified. Typically the subcontractors might not even know other subcontractors.
Preparedness	The preparedness for collaboration seems to be low especially in regard to common vision and objectives, network practices, and competence management. Partner assessment and qualification practices exist. As the outcome of engineering is information, most cases have considered harmonization or definition of engineering and information tools.
Trust	Trust is based on long term experience with the same partners. No systematic approaches to build trust are used. Some kind of partner assessment practices exist but the measurement of performance is not sufficient. Information security issues are considered important and principles for sharing product data have been defined at some level.
Management approach	One of the main objectives is to shorten the product development projects. In addition to time other important objectives are engineering quality and cost management (also cost of project management). For these objectives the project management approach is suited best.

6. Conclusion

This paper analyses the characteristics of engineering networks, based on use cases participating in a Finnish national research project Fudge. The analysis is based on two different approaches: one originating from Collaborative Networks (CN) research and one from a framework focused on global engineering networks (GEN). It was identified that both the approaches are overlapping with similar elements but with a different structure. Because of the background the CN approach goes deeper in the concepts of collaboration preparedness while the GEN approach is able to identify the high level key patterns and their evolution.

Based on the analysis, there are several challenges in the management and operation of engineering networks. Typically distributed engineering has developed along years and there is no systematic collaboration preparedness. The networking is more one-to-one subcontracting than what is typical in manufacturing networks. There is seldom any strategy or a common vision for the collaboration to be shared with the network. There seems to be clear hierarchy and few collaborative development activities.

Among the challenges identified by the Fudge use cases there is a need to shorten the product development times but only unclear understanding how it could be achieved. It is difficult to monitor the performance of engineering. The quality of product data should be improved. There are too many different engineering tools used in the network – often too many already inside one organization. Currently harmonization of tools is on-going in many engineering organizations.

To bridge the gaps, the engineering networks should develop their collaboration preparedness and this should preferably be done in co-creation with the network partners, giving them opportunity to innovate new practices. In some cases, also the customers could be involved. The development of the practices and preparedness could benefit from the Collaborative engineering (CE) approach as proposed by [Lu et al. 2007] and focusing on engineering teamwork and human approach.

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