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SYSTEM ARCHITECTURES FOR MANUFACTURING CO-ORDINATION IN COMPLEX SUPPLY NETWORKS

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As most of today's products are manufactured in complex networks of independent companies, better collaboration and co-ordination across the network are important leavers for improved customer service and efficiency. In this article, we discuss different architectural approaches for information systems supporting complex supply networks. The business requirements are starting point for the evaluation. Three basic types of architectures can be determined: Completely centralised co-ordination, a hybrid architecture of local planning and control modules and central co-ordination, and a completely decentralised architecture with self co-ordinating units. The last architecture seems to be most promising for complex networks of independent companies. The article presents a first approach to this rather new architecture. The 5th-Framework IST-project Co-OPERATE will further advance the discussed concepts.

1. INTRODUCTION

In many industries the product is manufactured in a complex network of companies. As the companies in the network become increasingly dependent on each other in order to successfully compete in the marketplace, co-operation and trust between them have become an important part of their relationships. This co-operative relationship within the supply chain has lead to the idea of the virtual (or extended) enterprise, whose adoption is on the increase and is already yielding benefits (Maloni and Benton, 1997).

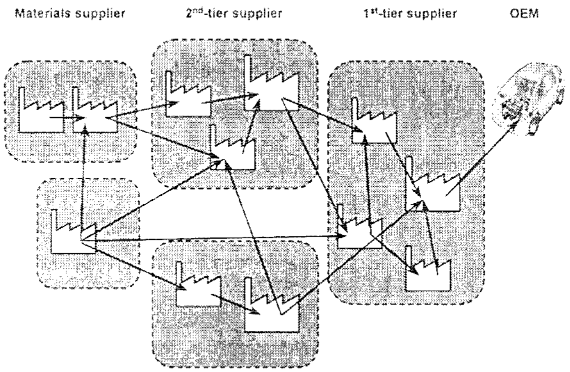

Figure 1 - Schematic set-up and supply flow within the virtual enterprise

However, full benefits of a close co-operation within the virtual enterprise can only be achieved when the business processes of the individual companies can inter-operate. This is particularly important in the complex and highly dynamic environment of the automotive and electronics industries (Figure 1). Here, the information and product flow starts and terminates with the Original Equipment Manufacturer (OEM) and crosses several tiers of component manufacturers to the material suppliers. Companies strive for better customer service and improved efficiency, which can be greatly influenced by the degree of collaboration in the manufacturing network (Tuma, 1998).

2. BUSINESS REQUIREMENTS

The co-ordination and optimisation of complex supply networks consisting of independent companies require a thorough rethinking of traditional purchasing and logistics processes and the definition of new collaboration methodologies (Beamon, 1998). The starting position of independent, heterogeneous, and sometimes competing companies pose additional requirements to the co-ordination system.

2.1. Business processes

An information system for supply networks must be able to link the most important business processes and make them inter-operable (Leach et al, 1997), including:

- Fast communication of demand, demand changes, and forecasts across the whole network with adapted information for each partner
- Co-operative planning based on negotiation methodologies between partners
- Progress visibility and control for early detection of problems and fine tuning manufacturing and logistics processes
- Handling of exceptions which effect other partners and containment actions
- Risk management such as setting right buffer inventory levels
- Performance measurement across the supply network

2.2. Other Business and System Requirements

While the business processes call for close integration across the network, other business requirements prevent too close system integration (Korhonen, Huttunen and Eloranta, 1998).

Independent, sometimes competing companies: Each company remains independent, implying that strict rules for data privacy are maintained and no critical data reaches competitors. The decision autonomy remains with the company, though every company knows that good network co-ordination benefits each partner.

Local information availability and decision competence: Most information and know-how is available only locally and coding and replication of non-standard capabilities to a higher level is extremely difficult. Modern management approaches have therefore moved decisions to the lowest possible level, such as groups or profit centres. This trend should not be reverted by network co-ordination requirements.

Constant changes in network set-up: Companies join networks and leave them again after some time. The systems need to accommodate this with minimal efforts.

Participation in several networks: Companies have many customers and suppliers. They must be able to participate in several networks and balance the priorities.

Heterogeneous environments and interoperability: Each company might have different local systems with which the co-ordination system must be able to interact. Standardised interfaces allow participation in several networks.

3. ARCHITECTURAL APPROACHES

The system architecture is the most important decision for a system. Approaches found in research and commercial systems can be grouped in three categories:

- A centralised co-ordination architecture with local access through thin clients
- A hybrid architecture with distributed modules or agents, which perform local calculations and interactions with users, and a central co-ordination module
- A completely decentralised architecture with self co-ordinating units

Each approach has specific characteristics and strengths and weaknesses, which are discussed in the following sections.

3.1. Centralised Architecture

The completely centralised architecture is presented in Figure 2. The co-ordination algorithms run in a central module for the whole network. The necessary data is stored in a central database or it is at least directly accessible by the co-ordination module. One of the network partners or an independent service provider manages the co-ordination module. The network partners have access to the central module through thin clients. These are simple terminals for data entry and results display and, in terms of co-ordination tasks, completely rely on the central co-ordinator.

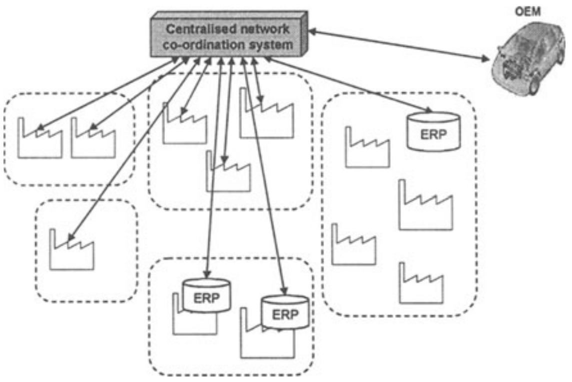

Figure 2 - Completely centralised system architecture

This architecture is typical for Enterprise Resource Planning (ERP) systems such as SAP R/3 or Baan and Supply Chain Management (SCM) systems such as I2 Technologies' Rhythm and Manugistics6. Many researchers have investigated the central planning and problem solving of distributed systems.

3.1.1. Advantages

- **Uncomplicated system architecture and fast algorithms:** Standard algorithms can run with the central database or even completely in memory.
- **Limited network usage**: Since the algorithms run in the central core, data exchange to distributed nodes is only necessary for getting input information and for communicating results.

- **Good product data storage and backup:** The centralised product information can be easily backed up and stored for later usage such as after-sales services.

3.1.2. Disadvantages

- **Undermined independence of companies in network:** Companies need to leave control of essential operations to the central module. This also undermines the freedom to switch back to independent planning and control processes.
- **No provisioning for companies' membership in several networks:** In case of companies belonging to several networks, several co-ordination modules use and plan for the same resources or even the same components leading to conflicts.
- **Data security and secrecy issues:** The companies store crucial data on the central system, leading to many confidentiality issues. This is especially problematic, if the central component is maintained by the lead company in the network.
- **Need for complete and centrally available data:** The product and production data must be complete and centrally available for the algorithms to run properly. The data must be constantly updated in the central system and – as experience has shown with ERP-systems – it will still not comply with the local reality.
- **Remoteness from operative and decision level:** The central component is remote from the operative level of the participating companies leading especially to acceptance and data integrity issues.
- **Difficult set-up and change of network:** For each change in the network, the central system needs to be changed. This usually involves high complexity and fault problems. Any changes involve re-initialisation of the system.
- **Limited flexibility of functionality for different partners:** The centralised algorithms usually use a uniform structure for all entities in the network. This usually will not reflect the different requirements of the partners.
- **Overlap in functionality with existing company systems:** The companies in the network need to maintain their local enterprise system, which usually covers similar functionality as the central co-ordination system. This leads to conflicts regarding planning authority or data integrity

3.1.3. Conclusions

The centralised architecture has been attractive for ERP and SCM systems under the aspects of system development and performance. Up to recently, it was the only feasible approach regarding available information technologies. For applications within a company, the many disadvantages are of limited consequences. For the co-ordination of a distributed network of independent companies, the centralised architecture imposes many limitations in crucial areas. Therefore the completely centralised architecture should be avoided for the new development of an SCM system and will limit the potential for extending existing systems.

3.2. Hybrid Centralised/Decentralised Architecture

Figure 3 shows the mixed centralised/decentralised system architecture. Though similarly looking to the completely centralised system, the central co-ordination module has a much smaller role and functionality, as it is complemented by distrib-

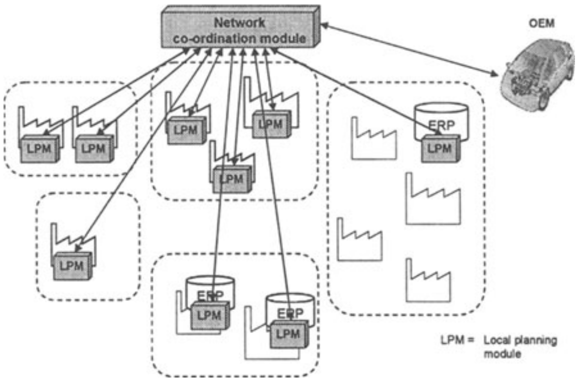

Figure 3 - Hybrid central - decentral system architecture

uted modules on company or even production centre level that provide local planning and control functionality. The central module triggers local planning and scheduling and co-ordinates all local plans to generate a feasible plan for the entire product (Rupp and Ristic, 1999). For this, the central module requires the bills of material and routing information for all deliveries between companies or centres.

The modules use standardised interfaces for communication. The functionality of the local module can be tailored to the specific needs of the company as long as it complies with the communication standards. It can also connect to existing enterprise systems using their functionality and making them accessible for the network co-ordination.

Especially agent-based systems have adopted this approach for co-ordinating distributed systems either within a company or for supply chains [Maturana and Norrie, 1996, Miyashita, 1998, Baumgärtel, Bussmann and Klosterberg, 1997]. Other research projects include X-CITTIC, MASCADA and MUSSELS.

3.2.1. Advantages

- **Network partners can stay independent:** The central module supports only the inter-company co-ordination, leaving the local planning, control, and decision making with the individual company.
- **Critical product or production information can be stored and protected locally:** The central co-ordination module only needs the product's routing information, while all other information is processed and stored locally. This helps overcome confidentiality and trust issues within the network.
- **Network partners can be members of several networks:** Since all planning and controlling is done on a node level, several co-ordination modules can trigger actions and use the results. Data integrity is maintained on the local level and prioritisation is under the control of the unit.
- **Uncomplicated co-ordination algorithms:** The inter-company co-ordination is performed within the central module using results from local planning. The possible algorithms are similar to the completely centralised system, though due to data exchange delays across the network they run slower.
- **Flexible functionality for different network companies:** The local modules can be tailored to the functionality and sophistication needs of each company.
- **Simple interfacing with existing company planning systems:** The local module can interface to and utilise existing company planning systems for the planning and control tasks, thus avoiding overlap.

3.2.2. Disadvantages

- **Limited suitability for varying products with differing network configurations:** Many industries such as the automotive industry feature varying manufacturing networks for different products, which change regularly and only have one or two companies in common. Questions such as how many co-ordination modules are necessary, who is responsible for them and how do they interact are difficult to answer in these complex industries.
- **Need for central information of the entire product:** The central co-ordination system needs only the bill of material and routing information for the product. However, this information needs to be complete and exact at the time, a considerable problem for complex assembly-type products.
- **Difficult handling of areas of the network not covered by the system:** The central component handles all deliveries between companies in the co-ordinated network, but deliveries from companies without computer connection need to be managed by the individual customer. This leads to problems like knowing what parts to handle how and catering for the different processes.
- **Heavy network loading for data exchange:** The reliance on local results imposes considerable loading onto the network. Network latency can become a serious problem for time-critical planning and controlling tasks.

3.2.3. Conclusions

The hybrid system provides a big step towards flexibility and independence of companies while retaining some of the simplicity of the centralised architecture

However, a number of issues still arise from the centralisation of the co-ordination, such as: who is responsible for and has the power of the co-ordination module? How to split complex and overlapping networks between different central modules? How to make the central information reliable and error-tolerant?

The hybrid architecture has its strengths in networks, which have a clear leading partner and limited product and routing complexity. The product itself might change but not its structure and the main suppliers. This makes it well suitable within the semiconductor industry or textile and shoe industry, but not for automotive, machinery or telecommunications equipment industries.

3.3. Completely decentralised architecture

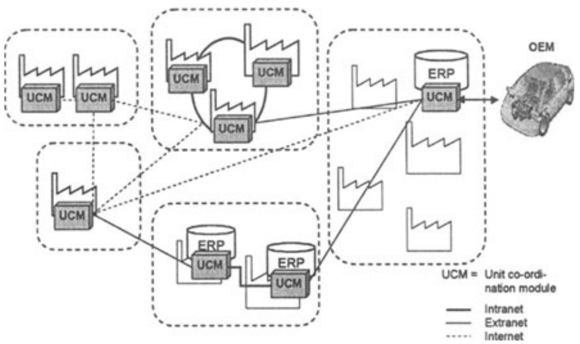

Figure 4 – Completely decentralised architecture

The fully decentralised architecture requires a set of self co-ordinating units (see Figure 4). Either a whole company or the production centres within one company can be the self co-ordinating entities. If a suitable company planning system exists, it can plan for the internal centres while it connects via a co-ordination module to other companies in the network. If there is no company planning system, the network co-ordination can also work on a production centre level, but provide additional consolidation and reporting on a company level. This option supports especially SMEs without sophisticated ERP systems and companies with several locations and separate planning systems.

The local units are connected to one-another using standard network connections such as Intranet, Extranet or Internet without the need for a central co-ordination module [Duffie and Prabhu, 1996]. The co-ordination functionality is integrated into the local modules, each responsible for co-ordinating its direct neighbours – suppliers and customers. The distributed algorithms must provide convergence and optimisation in the network.

European R&D projects such as PRODNET II, SCM+ [Camarinha-Matos, Afsarmanesh, Garita and Lima, 1998], VEGA and VIVE have laid important foundations for the fully decentralised approach. However, the developed solutions either need some sort of central information handling mechanism or do not develop solutions beyond the ICT infrastructures for distributed environments. Current trends of commercial e-business marketplaces (e.g. Ariba, Commerce One, Tradematrix) imply a similar architecture paradigm. However, these approaches do not provide the co-operative planning functionality and co-ordination methodologies for the rich set of business processes as proposed above.

3.3.1. Advantages

- **Best data and process integrity:** All data – supplies, in house manufacturing and deliveries – are under the direct control of the local planners, who best know the requirements and are most affected in the case of problems. This should reduce data errors and their consequences.
- **Highest data protection:** A network partner communicates only requirements to suppliers and delivery promises to customers. All other product and production information can be kept local – leading to the highest data protection.
- **Completely distributed processes:** Each company is responsible for its part of the business process, but the system helps to co-ordinate the individual activities for the whole network.
- **Flexible functionality for different companies:** The local planning functionality can be tailored, while standardised interfaces ensure collaboration.
- **Network partner can be member in several networks:** As all intelligence resides in the local modules, the partner companies can interface to companies in other networks if they comply with the communication standards.
- **Uncomplicated set-up and change of network:** The network is not "hard-wired" but determined by actual customer-supplier relationships and their support by the system. Each module can change or be added to or removed from the system without affecting the rest of the network.
- **Simple provisioning for uncovered areas in network:** The system architecture and co-ordination processes reflect closely the usual processes between companies, but supporting and enhancing them. If a supplier is not connected, the customer company uses the traditional co-ordination routines and enters the results into the system without disturbing the areas covered by the system.

- **Companies stay independent:** Each company has complete control over its part of the system and can withdraw from the network without consequences to their operations. The co-ordination is based on negotiations between the companies, not central orders. The data is stored and controlled by the partner owning it. All these characteristics support the independence of the partners in the network.
- **Good interfacing with existing company systems:** The local planning is a separate module which can consist of a specifically developed solutions or of the existing enterprise planning system avoiding any overlap between systems.

3.3.2. Disadvantages

New and potentially complex/slow co-ordination algorithms necessary: A completely decentralised co-ordination system does not exist yet, so there is no experience with the co-ordination algorithms. Since they are distributed, they rely on network data exchange, which might slow down the system.
Heavy network loading for data exchange in algorithms: Co-ordination algorithms rely on data exchange between the different nodes with a number of iterations, which imposes considerable loading on the network.
Distributed data for reporting, aftersales support, etc.: The advantage of distributed data can be a disadvantage in some cases. The virtual enterprise network needs reports and benchmarking for optimising its performance. Aftersales support relies on information from the different partners. The system must therefore cater for these needs by additional reporting and data warehousing functionality and supporting rules for the data handling.

3.3.3. Conclusions

The architecture of self co-ordinating units has many advantages for co-ordinating virtual enterprise networks. It corresponds directly with the structure of the network and the communication and co-ordination patterns well established and proven in business.
The main disadvantage is that only very few methodologies and algorithms supporting this architectural pattern and the co-ordinating business processes exist. They have to be newly developed or at least considerably adapted from centralised or hybrid systems. The next section shows first approaches for these methodologies.

3.4. Summary Evaluation

All three architectural types have their place in the right setting. The completely centralised architecture has most advantages within a company, where performance and simplicity are more important than flexibility and network suitability. For a virtual enterprise consisting of independent companies, this architecture is not suitable.
The hybrid architecture with central co-ordination and strong local planning modules combines strong algorithms with some local independence. It is best suited for a virtual enterprise either within a large and diverse company or for one consisting of a few, long standing members.
The decentralised architecture seems ideally suitable for the virtual enterprise co-ordination of independent companies. It is the most flexible and versatile architecture mirroring the flexible network. However, this architecture still needs to be de-

veloped and implemented to prove its conceptual strength and capabilities. The further research work is therefore directed to designing a decentralised system.

4. DECENTRALISED CO-ORDINATION

A preliminary design draft of the main architectural modules is shown in Figure 5. The system for one company consists of a communication and co-ordination layer, a local planning layer, an information manager, and a number of distributed graphical user interfaces.

The co-ordination algorithm module is the centre of the whole system. It provides the intelligence for co-ordinating the local activities of the unit with the network requirements and drives convergence to reach a feasible solution. It communicates via the communicator modules with the downstream and upstream companies in the network. The two modules provide very flexible interfaces to partners within or outside the part of the network covered by the system. For connections to modules at other companies, transactional messaging services are envisaged. Standard protocols and interfaces as proposed by RosettaNet (RosettaNet, 2000) and PRODNET II reduce the heterogeneity and ideally allow different systems (complying with the same standards) to participate easily in the network – one of the advantages of a decentralised approach. However, automated (e.g. by EDI or pre-configured rules) or manual data entry (e.g. by web-browser interfaces) might still be needed to provide for companies without a system connection.

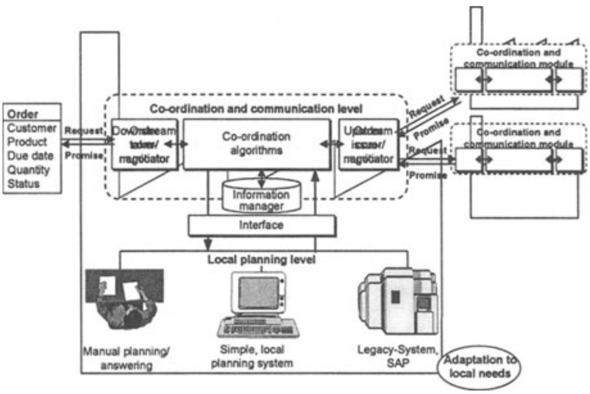

Figure 5 - Preliminary design draft of main architectural modules

The algorithm module uses the local planning layer for decomposing the order into components and planning the local work and requirements from suppliers. The planning layer can be seen as a black box as the local planning is performed either manually, using simple planning systems or a complex ERP or SCM system. An interface module wraps the different local planning methodologies. The interface should also influence the static and dynamic planning properties of the local system. These properties are critical for achieving convergence of the algorithms. Currently, fine tuning issues in such complex systems are not addressed by research, though they have significant influence on planning quality.

The information manager provides general local information. It manages planning results, intermediate data, and routing and connection information to other partners (Zhou and Besant, 1999).

5. ROADMAP TO IMPLEMENTATION

The IST-project 12259, Co-OPERATE (Co-OPERATE, 2000), in the 5th EC-Framework Programme is focused on advancing the presented business and architectural concepts and developing new, distributed co-ordination methodologies for supply networks. The project is targeted at the automotive and electronics industries covering several production stages consisting of large corporations and SMEs. The project partners are: Siemens Automotive (Germany), Alcatel Microelectronics (Belgium), MEMC Electronic Materials (Italy). Imperial College (UK), INESC Porto (Portugal), Druid (UK) and five SMEs across Europe.

A first prototype covers a number of basic co-ordination workflow and information exchange scenarios between companies. The purpose is to develop and refine the building blocks of the solution. In subsequent prototypes, these building blocks are combined to an integrated, dynamic system. A number of real-life business trials will ensure the system's fine-tuning and robustness. This program is spread over the project duration, which lasts two years until the end of 2001.

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