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DRIVERS FOR MODEL BASED DEVELOPMENT OF MECHATRONIC SYSTEMS

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1. Introduction

The vehicle industry is experiencing an increased product complexity based on the development of electronics. New functionality requires micro-controllers, software, and networks. Distributed networked systems and embedded systems are nowadays carrying one third of the development costs of a modern car. The product is inherently integrated; this changes the organizational needs in terms of integrating product, organization, and process. Systems that earlier were stand-alone are now dependent on each other and design changes in one system are therefore reflected and must be considered in other systems.

One trend in the development of embedded and distributed systems is model based development (MBD). There are many definitions of MBD, in this paper it refers to *development based on abstract representations with predefined and documented syntax and semantics, supported by tools*. For mechanical engineering MBD through the use of CAD-tools permeates most organizations nowadays, but MBD of multi-disciplinary systems like distributed control systems is less common.

Complexity is often mentioned as a driver for MBD. Why is that? What is meant by complexity and how is it managed? Several inherent factors of systems make complexity management a challenging task in system development. Some of these factors are discussed in the paper. Another driver discussed is product strategy, specifically in terms of standardization and product maturity.

2. Purpose & Method

The purpose with this paper is to discuss the use of MBD from a knowledge management perspective. The paper is based on results from a case study of MBD performed in the vehicle industry in Sweden. The case study was based on interviews at three different vehicle-producing companies [Adamsson 2003]. An explanation model for the findings is derived from earlier knowledge management theories, and the model is used for an applied theoretical explanation of the results from the study.

3. Theory

The theoretical base of this paper is collected from established knowledge management theories [Nonaka & Takeushi 1995; Hansen, Nohria & Thierney 1999], engineering design theory [Eppinger & Salminen 2001] and theories on the design of Mechatronic systems [Larses & Chen 2003].

3.1 Product complexity

Complexity management is a challenging task in system development. Complexity has been discussed by many authors, for example Eppinger and Salminen [2001]. Three major factors recognized by

Larses & Chen [2003] are *heterogeneity of rationale*, *richness of system content* and *conflicting requirements*.

The *heterogeneity of rationale* behind design decisions adds to the system complexity due to the absence of a common notion of the system. The heterogeneity refers to the difference between engineering domains. A high heterogeneity is often the case in the development of mechatronic systems where domains such as mechanical engineering, electronics and software need to collaborate.

Inside a system, there can be a large number of constituents with different properties and relations. The *richness of system content*, referring to the number of components and relations, increases the system complexity.

Further, most systems need to satisfy multiple requirements such as functionality, performance, and cost. Trading, comparing and modifying requirements may be necessary for a feasible solution. For example, a performance requirement may contradict the requirements of weight and power consumption. With many *conflicting requirements* the trade-off activities become strenuous and more complex.

3.2 Knowledge and the model of knowledge creation

It is possible to distinguish between Tacit and Explicit knowledge. Tacit knowledge is "*knowledge which is non-verbalized or even non-verbalizable, intuitive, unarticulated.*" Explicit knowledge on the other hand is "*specified either verbally or in writing, computer programs, patents, drawings or the like.*" [Hedlund 1994]

		To:	
		Tacit	Explicit
From:	Tacit	Socialization	Externalization
	Explicit	Internalization	Combination

Figure 1. Modes of knowledge conversion [Nonaka & Takeushi 1995; Hedlund 1994]

By separating tacit and explicit knowledge it is possible to distinguish between four types of knowledge conversion as a basis for knowledge creation [Nonaka & Takeushi 1995], see Figure 1. Tacit to tacit knowledge conversion is referred to as *socialization*, explicit to explicit conversion is named *combination*. Conversion from tacit to explicit is labelled *externalization* and consequently explicit to tacit conversion is known as *internalization*. Knowledge conversion can be an internal process within an individual or take place in a transfer between several individuals.

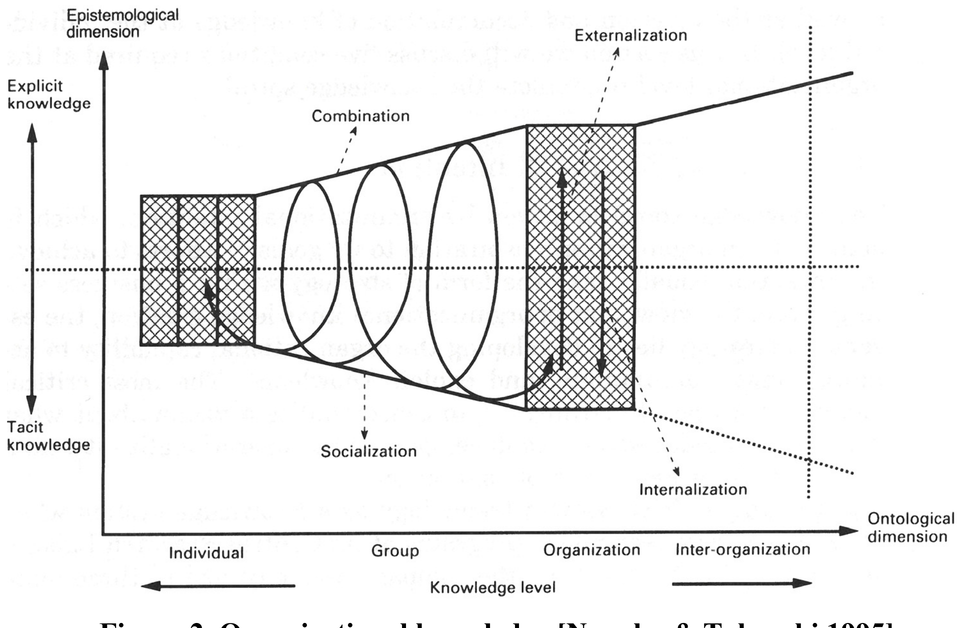

Figure 2. Organizational knowledge [Nonaka & Takeushi 1995]

Knowledge creation is achieved by cyclically alternating between the modes of knowledge conversion, referred to as the knowledge creating spiral. Further, knowledge can be amplified in the organization to become organizational knowledge. All knowledge originates from the individual but it can reach different organizational levels as shared knowledge. The knowledge creating spiral and the organizational levels are illustrated in Figure 2.

3.3 Codification vs. Personalization, a strategy for managing knowledge

Hansen, Nohria and Thierney [1999] recognize two distinct strategies for knowledge management. They distinguish between *personalization* and *codification*, where personalization relies on socialization for knowledge creation and transfer, while codification uses the loop through externalization, combination and internalisation. The codification strategy is based on explicit reuse of solutions and knowledge, while the socialization strategy targets tacit, unique, reinvented solutions. Codification is described as a people-to-documents strategy, while socialization is described as a people-to-people strategy.
Hansen et al indicate three factors that imply a specific strategy. The first factor is if the company pursues a *standardization* or a *customization* strategy. A standardized product increases the value of reuse and indicates that a codification strategy should be pursued, while customization is related to a personalization strategy. The second factor, *mature* or *innovative* product, underlines that a mature product based on well-known technology usually benefits from reuse and standard solutions, thus indicating that mature products should use codification. The third factor is the *use of explicit or tacit knowledge in problem solving*, the problem solving activities in the organization are expected to emphasise one of them.
Hansen et al strongly recommend a distinct choice between personalization and codification, although this choice may differ among business units within a company. Koenig [2001] has seen that a combination of methods has been successfully used at hospitals, also within business units. This suggests that it is possible to slowly evolve from one strategy to another, increasing or decreasing the codification effort as seems fit according to the situation.

4. The derived model of design of mechatronic systems

Based on the theoretical background, a model of competence integration for the design of mechatronic systems is derived. The model describes how integration can be performed; it also supplies a dichotomy of two explicit strategies and a set of drivers for a given strategy.

4.1 A model of knowledge management for integration

The proposed explanation model is based on a combination of the discussed theories mapped to the ideas of Eppinger and Salminen [2001], illustrated in Figure 3. According to Eppinger and Salminen [2001] the three domains product, process, and organization must be considered when studying complex product development. It is expected that industrial firms in which the interaction patterns across the three domains are well aligned will outperform firms for which the patterns are not aligned. The trinity of Eppinger & Salminen is adopted here, further it is assumed that if product complexity (compare product architecture interactions) is increasing, work must be done in both the process domain and in the organization domain to fulfil Eppinger & Salminen's expectations about alignment.
If integration is mainly based on social efforts it can be related to the organization, if it is mainly based on tools and models it is a process-related integration. If Nonaka & Takeushi's theories about a cyclic knowledge creation are transferred onto this model, the focus of management efforts will alternate between the process domain (i.e. formalize tasks and methods) and the organization domain (i.e. re-organize). Further, if the dichotomy of *personalization vs. codification* is used it is possible to make a strategic choice, placing the focus on either aspect. In this discussion the interactions within the product architecture are considered to be given by the results of the development efforts, and the complexity of these interactions is expected to increase with time.

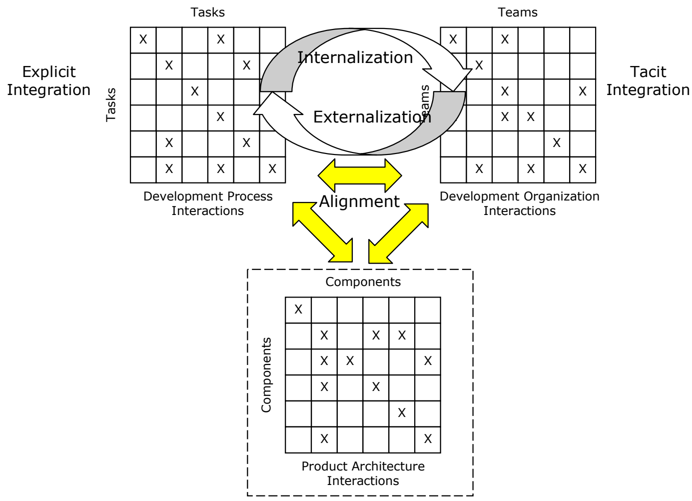

Figure 3. The explanation model based on Eppinger & Salminen [2001] and Nonaka et al [1995]

In an inter-organizational perspective of MBD the Nonaka model can be used, where the knowledge level moves up from an individual level through expanding communities of interaction that cross departmental and organizational boundaries. As an example, one parallel can be drawn to the implementation of CAD in product development. At a certain point the use of CAD became interdepartmental instead of just supporting the individual engineer. Later on, standards were agreed upon that rendered an interchange of models between organizations that were using different CAD software. Considering this background and also the different organizational levels shown in Figure 2 it is possible to recognize that the character of competence integration is different among organizations.

4.2 Integration strategy

The dimension of personalization and codification as a knowledge management strategy can be recognized in practice in the integration of process and organization. Organizational efforts such as matrix and project organization structures are used to improve the socialization aspect. Process efforts as the introduction of development tools and formalized development models are more in line with a codification effort, this implies that MBD is a manifestation of a codification strategy.

Firms that choose a *personalization strategy* are thus expected to work more with the organization issues and less with process issues as integration mechanisms. Consequently a *codification strategy* suggests more MBD, more focus on processes, and less focus on the organization. The product, the process, and the organization dimensions should be aligned.

4.3 Drivers for model based development

To handle organizational diversity in product development, integration mechanisms are proposed by Nihtilä [1999]. Nambisan and Wilemon [2000] discuss how New Product Development research has focused on integration mechanisms related to People and Process (socialization), and research in Software Development has focused on Technology and Process (codification). Naturally, the choice of integration mechanism is related to the context. MBD, however useful for integration in some mechatronic systems, is not necessarily a good integrator for the design of all mechatronic systems. In line with the thoughts of Hansen et al [1999], the *maturity* of a given product technology and a *standardization* strategy increases the possibility to reuse, and also the inclination to adopt a codification strategy embodied by MBD. The maturity is expressed for an entire industry, while standardization is expressed only for a specific market segment. Further, when *complexity* is increasing, more explicit knowledge is utilized in the process of system architecting and component integration, making decisions among alternative solutions. *Heterogeneity of rationale* requires more views of the system, *conflicting requirements* call for more monitored variables and *richness of system contents* increases the amount of analysis necessary for each alternative. Thus, increased complexity would be the third driver for codification in line with Hansen et al [1999]. Complexity is also only applicable for a given market segment, not an entire industry.

5. Empirical findings

A case study was performed in the Swedish vehicle industry in 2003 [Adamsson 2003]. The purpose with the study was to investigate how MBD could affect integration when developing mechatronic systems. Selected results from this study are presented in Table 1.

Table 1. Results from Adamsson (2003) together with a classification of the companies products

	Company ATV All Terrain Vehicles	Company T Trucks	Company A Automotive
Results from interview study by Adamsson (2003)	MBD locally and domain-specific. Low use of CACE/CASE.	MBD locally and domain-specific. Medium use of CACE/CASE.	MBD as an integrator between different departments (domains). High use of CACE/CASE.
Classification of product	Innovative product Customized product Low complexity	Innovative product Modularized product Medium complexity	Innovative product Standardized product High complexity

The table shows a classification of the situation for the three firms. The first row indicates the use of MBD for integration purposes; the second row shows an evaluation of three drivers of MBD. The classification of the products relates to the embedded control systems, and not the entire vehicle as a system. Entire vehicles as products are mature; however the functions implemented by the embedded control systems are still new and innovative. This is the same for the three companies as they operate in closely related industries.

The all terrain vehicle is the most customized product of the three, developed or adapted for each individual order. Company T utilizes modularization to create a high variety and customization with a high standardization of components, allowing each sold unit to be tailored to the customers needs through a set of standard solutions. The automotive product is even more standardized with fewer options for the customer. Thus, the automotive product is the most mass-produced of the three.

The complexity in the products is mainly evaluated in terms of richness in system content. The heterogeneity of rationale in the different organizations is similar as the electronics and software departments are studied and all three companies have mechanical products with some electronics content. All products have conflicting but different requirements, this complexity would be comparable but hard to measure explicitly. Concerning the richness in system content, the automotive company has the most electronics with the most relations, the ATV company has the least electronics content and the truck company is in between.

In Company A socialization efforts were not sufficient to handle the increasing product complexity and MBD was therefore used as an integrator between organizational entities. In Company T, MBD was less used, and instead development relied on informal and tacit integration. Company ATV used MBD only for domain specific needs and not for system level multi-domain needs. The estimated level of MBD is based on the use of modelling tools. If common or linked tools and models are used by groups working in separate engineering domains the tools are regarded an integration mechanism.

Table 2. Strategies and drivers of MBD

	Drivers	Present situation
Company ATV	Customized product Low complexity	MBD used very locally Relies on personalization
Company T	Modularized product Medium complexity	MBD used locally Relies on personalization
Company A	Standardized product High complexity	MBD used semi-globally Both personalization and codification

The degree of tools usage for integration is an indicator of the integration strategy of the firm, as shown in Table 2. Considering the classification of the products, the derived integration strategies are expected. All companies operate in related industries where the maturity is at a given level. For this reason, the maturity is omitted in the table. It is possible to make a comparison with the more mature domain of mechanical engineering where MBD through CAD is used at all three companies. The other drivers for MBD of embedded control systems are strongest in the automotive company and least strong in the ATV company which is reflected in the codification strategy of the automotive firm and the socialization strategy of the ATV firm.

6. Conclusion

Three drivers for MBD are suggested: *maturity*, *standardization* and *complexity* of the product. The maturity level is common for related industries at an inter-organizational level and creates a reference level of MBD. Companies within a given industry may diverge from the reference level determined by the strategy of codification or personalization. The complexity and standardization of the company's product are drivers to adopt a given strategy at the intra-organizational level. It is possible to recognize from this discussion that a strategy for design management can be chosen, and that the focus of competence integration efforts will change in respons to the drivers.

The combined theories give an interesting model of management of engineering design organizations. The developed model shows the dynamics of competence integration and also relates organizational knowledge to efforts in organization or process. Based on the limited case study expected results are achieved, the proposed drivers for model based development cannot be refuted but further work must be performed to build more solid evidence.

Nomenclature

CAD – Computer Aided Design, CASE – Computer Aided Software Engineering, CACE – Computer Aided Control Engineering, MBD – Model Based Development

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