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REQUIREMENTS MANAGEMENT WHEN INTRODUCING NEW MECHATRONIC SUB-SYSTEMS – MANAGING THE KNOWLEDGE GAPS

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1. Introduction

The "mechatronization" of drivelines with the aim to reduce fuel consumption and emissions is occurring across the commercial vehicle industry as a response to rising environmental awareness and fuel prices. This has given rise to new challenges in the commercial vehicle business processes. Commercial vehicles are business-to-business products. The requirements governing their designs have been heavily focused on performance in terms of power, carrying capacity and low maintenance cost which are the main factors affecting the lifecycle cost for the customer. These circumstances have resulted in the design efforts and resources traditionally being focused on mechanical systems and properties. The new challenges lie in the needs to manage a rapidly increasing number of functions along with different processes and a different culture that accompanies development of electronics and embedded software.

The research about development of mechatronic products is ranging from methods and processes to specific IT support and IT architectures. Many of the issues found are general product development issues for which there are recommendations and guidelines proposed in product development literature such as [Ullman 1997] or [Ulrich and Eppinger 2008]. Focusing on the specifics of mechatronic product development, a key issue is to ensure the most effective integration of the three involved domains of mechanics, electronics and software. Many research efforts are directed towards developing new methods and adapting existing methods to address the issues which arise in the integration of the three domains e.g. focusing on cross-domain interface and requirements management, roles and responsibilities, process and information management and verification and validation management.

[Almefelt et al. 2006] have studied an industrial case and from this empirically derived a set of recommendations for requirements management which, among other things, address the need to early define and focus a certain set of over-arching cross-system requirements. They also address the need to clarify each requirement with the underlying context and intent and define interfaces and verification methods for each requirement. Other contributions such as e.g. [Jansen and Welp 2007] suggest models to primarily overcome the interface related issues by identifying and classifying different kinds of interfaces.

[Adamsson 2007] addresses managerial implications of mechatronic product development and presents a set of proposals regarding increased awareness of the importance of the embedded software as well as the need to organize for cross-domain collaboration together with a reconsideration of the recruitment strategy in order to make sure the competencies of the project participants reflect the three domains present in the product. Other recommendations from [Adamsson 2007] address the need to communicate a clear cross-domain integration strategy and the need to communicate that the product launch is not only about manufacturability but also validation of embedded software.

[Bergsjö 2009] considers process and information management issues and identifies from empirical studies that the different domains have different processes with different information needs and IT tools and presents different ways of integrating the process and IT environments.

As a response to the need for specific methods and processes a VDI guideline called VDI2206 [VDI2206 2004] has been developed which is based on the systems engineering methodology and addresses requirements and interface management issues along with verification and validation pointing towards useable IT tools for modelling, and simulation. The guideline also gives a rough overview of how a mechatronic product is matured from an initial idea to production readiness. The research community has tested the method in several cases [Bathelt et al. 2005], [Rahmnan et al. 2007], [Ziemniak et al. 2009].

The literature in the field of development of mechatronic products thus covers many different areas and aspects as described above. However, the earlier contributions have been focusing on managing embedded software in different ways [Adamsson 2007][Bergsjö 2009] or on applying methods for developing mechatronic products [Bathelt et al. 2005] [Rahmnan et al. 2007] [Ziemniak et al. 2009]. The gap identified in the current research regards the management of the new situation where OEMs have to integrate systems, rather than components, and assure overall functions, manage interfaces and harmonize supplied systems with each other.

The aim of this paper is to focus on interface related issues in development of products containing new, and largely supplied, mechatronic sub-systems. The purpose is to, based on an empirical study, produce a set of recommendations which focus on managing knowledge gaps as a way to manage the new situation and complement other recommendations and guidelines present in the literature. The research question driving this effort has been:

Which issues arise when a new and supplied mechatronic sub-system is integrated into an electronically controlled mechanical product? How can these issues be managed?

2. Empirical setting and research method

The research study was initiated with a wish to study how knowledge gaps were identified and knowledge reused in a project whose main goal was to develop a new driveline containing a new mechatronic sub-system which adds a substantial amount of new functions, interfaces and suppliers.

The study was initiated with two workshops where the line manager of the new department, responsible for the new sub-system, and the chief project manager for the development project were consulted for issues which they wanted to investigate closer. The result from these workshops was a list of issues which were frequent during the development project and needed to be focused and clarified. The focused issues were requirements management, system interfaces, the limitations of the present component oriented line organization, and supplier management.

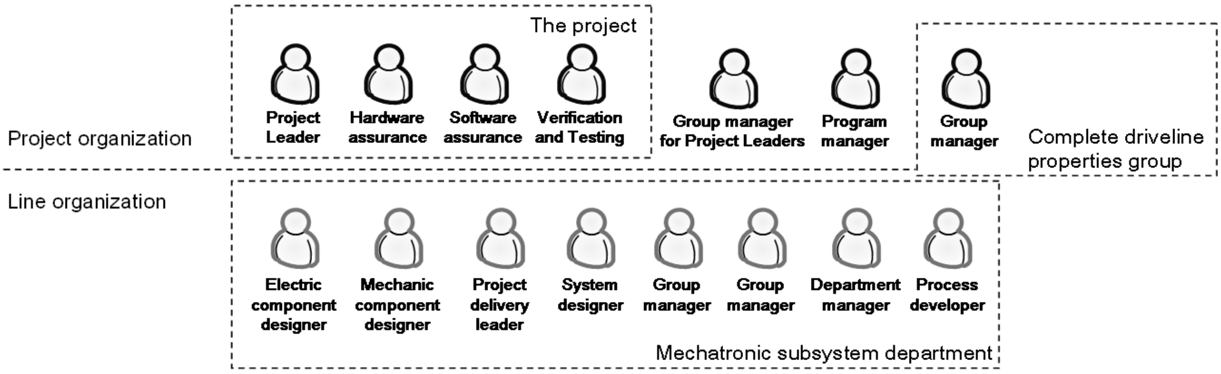

Figure 1. The interviewees placed according to their relations in the matrix organization

A total of 15 interviewees were chosen from both the new line department and the project team, see Figure 1. These were interviewed in semi-structured interviews and were asked to reflect around the focused issues. The interviews were followed by a literature review within the focused issues and a set of prescriptive elements such as recommendations were found. These were later discussed in a set of workshops with chosen interviewees. The elements found were related to supplier management and integration in new product development by [Johnsen 2009] and [Ragatz et al. 1997], requirements management [Hull et al. 2005] and [Almefelt et al., 2006] and knowledge management methods from the lean product development movement [Kennedy et al. 2008]. Findings regarding interfaces have been related to modularization and platform design with methods on how to define and describe interfaces [Ulrich and Eppinger 2008] but not so much on how to document and manage them.

3. Presentation of findings

In this section, the empirical findings regarding requirements management and verification, interface management, supplier management and the limitations of the present component oriented line organization from the interviews are described in more detail.

3.1 Requirements management process

The first high level requirements originate between product planning and the customer with the purpose to frame the scope for the project and are quite general. These are then handed over to the project that makes additions necessary to be able to forward these to the line departments. An issue of critical importance from the line department's point of view is the definition and allocation of requirements to each sub-system of the driveline (e.g. transmission, base engine etc.) because this affects the ability to define and allocate requirements to each component within the sub-system. In the case of the new line department there was a problem to derive detailed requirements needed at the component level due to lack of a legacy and previous knowledge of the mechatronic sub-system both among project and line members, see quotes in Figure 2. This was solved by an iterative approach where the component designer made a qualified guess and went back with a solution onto which the project members could react and refine the requirements. At best this approach was time consuming and at worst it was both time consuming and frustrating. The flow of requirements is top-down driven and there is little preparedness for managing requirements which go the other way e.g. that a certain choice of material on one component restricts the temperature emitted by another component. What usually happens is that these issues are discovered during testing of prototypes and lead to late and expensive changes. During the interviews several of the interviewees mentioned similar problems from an earlier project with a new, but significantly smaller, mechatronical sub-system. For the other (predominantly mechanical) sub-systems the component interfaces are known and such issues considered early on.

3.2 Requirements management methods and tools

Every forum that carries a responsibility of requirements definition and allocation keeps their requirements lists in their own Microsoft Excel files, as illustrated in Figure 2. At the component level this means that there is a specification per component stored locally in each component designer's computer.

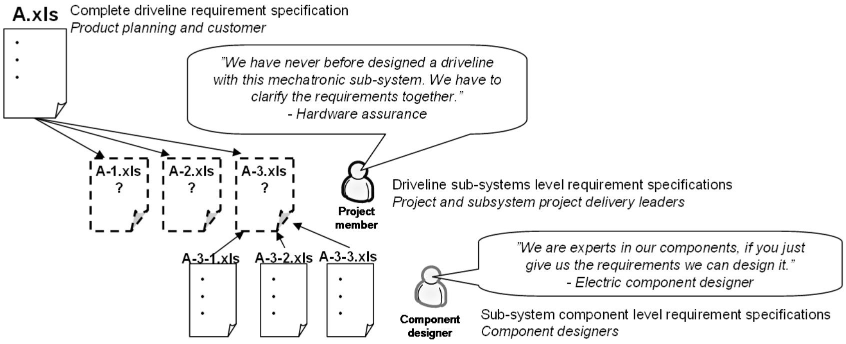

Figure 2. Lack of sub-system level requirement specifications and interviewee quotes

Updates across specification documents are time consuming and error prone, negatively affecting management of cross-component and cross-sub-system requirements. The top-down driven flow of requirements is also reflected in the methods and IT tools which provide no support for a backflow of requirements. Interviewees claimed that this impairs both the creativity of the designer and the efficiency of the project. If a component designer is able to propose different solutions and say that depending on which one is chosen different requirements are posed back on other solutions in the system, system related issues could have been detected earlier. The assumption in the top-down oriented requirements management process is that requirements can be clearly allocated to each component and that the system of components will function optimally. Since this is not the case the complete approach was based on testing and prototypes to detect system related issues and discover unknown interfaces.

3.3 Requirements formulation and prioritization

Much focus regarding the requirements themselves was directed to their formulation. Issues like fuzziness in the way the requirements are formulated have been stated by the interviewees. Some of the members of the line department suggested that quantitative requirements should be formulated in intervals because this would enhance the possibility to consider several solutions and be more creative. Another issue related to the formulation of the requirements is the lack of background and context for each requirement. Many of the respondents, both from the project and the line department, were positive to providing more context in the form of background, change history (with reasons for change) and rationale for specific requirements, which is hard to do in Microsoft Excel. Relations between requirements were also unclear both in terms of how requirements relate to each other in the top-down flow but also how different requirements at the same level relate to each other e.g. across components or sub-systems, which is once again due to the file based requirements management in different Excel sheets, see Figure 2. Two of the respondents argued that an increased context for the requirements would also increase the ability to innovate because a context would provide the possibility to understand the general idea and consider new combinations of solutions.

Regarding mechanical, electrical and software requirements some of the respondents have stated that the designer's background has affected which requirements were prioritized, exemplifying with a mechanical engineer who tended to focus on mechanical requirements.

3.4 Lack of requirements legacy and knowledge

During the interviews several of the respondents referred to the issue of "missing requirements", which represented different phenomena depending on the background of the respondent. When respondents from the line department talked about missing requirements they referred to lacking technical knowledge among the project members in how to define and allocate requirements, resulting in "missing requirements". An example is that the component designer for an electric motor expected specified torques and boundary conditions from the project members who simply could not derive such detailed information from the high level requirements coming from product planning such as "reduce fuel consumption by X percent". When the project members referred to "missing requirements" they see it as a natural consequence of the fact that there is no legacy from which to carry over requirements. Their perception, on the other hand, is that there is a lacking individual responsibility among the component designers to drive and, starting from the fuzzy high level requirements, gain knowledge and define requirements for their components. This misunderstanding of whose responsibility it is to define sub-system level requirements is illustrated in Figure 2.

3.5 Verification management

In the process of defining and performing the verification of requirements the interviewees answered that the verification methods are defined very late in the process and it is common practice that this was done by the component designers alone which was perceived as strange by the interviewees because they did not ensure that the chosen verification methods were congruent with existing methods and equipment in the test department. They were sometimes not even informed that certain equipment was needed.

The interviewees requested more methods and tools for early verification in order to guide the project to a quicker convergence on the final requirements and on conceptual solutions that are to be used.

Suggestions on what this early verification might be included more simulation and more physical test benches for sub-systems.

Finally the issue of verification of supplier components as opposed to in-house components was stated as needing more attention. Several of the respondents argued that verification planning should consider the fact that if a failure is discovered on a supplied component there is a much longer loop of reporting and redesign before the component can be tested again than if an in-house component fails.

3.6 Supplier management and management of concealed requirements

In the particular case of the observed mechatronic sub-system an apparent issue that the component designers had to deal with was the suppliers' knowledge gaps regarding technical automotive standards like sealing, vibrations, temperatures and so on. This was claimed to be the most concerning issue that affected the work.

Several respondents requested that a supplier management process be set up which would be in harmony with the stage-gate process that governs the development project in order to be able to harmonize the work and deliveries from the supplier with the rest of the project deliveries.

Another specific issue for this particular project is that certain critical components only had one supplier. This made it critical to manage the relationship with that supplier in a good way in order not to jeopardize the complete project. For one particular component the requirement specification was perceived by the supplier as too tough. Even the component designer realized this in retrospect and the reflection was that the uncertainty in the complete project caused him to set requirements with a large safety margin out of precaution. The requirements however almost caused the supplier to terminate the partnership and the result was that the requirements specification was revised and a set of follow-up requirements were communicated back from the supplier which was hard to manage in the top-down driven flow of requirements described earlier.

"Management of concealed requirements" was mentioned by one of the respondents and is considered mainly as a consequence of the suppliers' lack of experience of the automotive industry. These requirements are sometimes not even explicitly stated because they are considered as "industry standard". Initially this designer's attitude towards the supplier was that even those requirements which are obvious from an automotive point of view should be stated. However it turned out that due to the fact that these requirements were explicitly stated the price tag from the suppliers was significantly increased. What he noticed was that the component fulfilled these requirements even when they were not explicitly stated which meant that they could be taken out of the contract but they would still have to be verified in the internal verification processes. This was referred to as "management of concealed requirements".

3.7 Interface management in the component oriented line organization

The component oriented line organization is set up with the top-down driven flow of requirements in mind. It is also set up with the assumption that all interfaces are known and well-defined in order to facilitate the allocation of requirements. As the project has had a high level of new components with unknown interfaces a top-down driven flow of requirements was not possible and it resulted in certain requirements falling between component designers only to create a chaos later in the project. The organization has tried to compensate for this as much as possible by arranging "interface meetings" as soon as critical interface issues were discovered. These meetings generated a slowness and a frustration in the project. If two component designers from completely different sub-system departments found an issue that neither of them felt responsible for the project leader was the only higher instance with the mandate to decide, which created frustration.

Several interviewees proposed a function oriented organization, with function owners, to balance the component focus, in order to manage the increased complexity. Two of the interviewees had been working in another automotive company where a functional organization complements the component organization. One of them was very positive and had several successful examples while the other had a negative experience of this organization mainly related to requirements management. His perception was that the two different dimensions led to a behaviour of "over-specification". Function and component specifications overlapped and even conflicted but it was impossible for a single person to be able to detect this due to the extensiveness of the specification documents (> 2000 pages).

Among the other interviewees the notion of function owners was perceived as positive. Some even considered this as a prerequisite for being able to deliver drivelines on time and quality and with an ever increasing content of mechatronic subsystems. Two questions were however raised:

1. Organization (will existing component or systems designers have a partial role as function owners or will function owners be completely new people?)
2. Mandate (which responsibilities should function owners have in relation to the project leader and the line managers?).

One respondent claimed that introducing function owners risks to create a bigger mess. Instead a clarification and accentuation of personal responsibility for driving undefined issues such as detailing of requirements and exploration and management of interfaces.

4. Analysis of findings

This section summarizes and discusses the findings from Section 3 using the notion of “knowledge gaps”, as defined by [Kennedy et al. 2008] and summarized in Section 4.1, in two different categories, requirements management practice and supplier management. The reason why most of the findings and the analysis are about requirements management is that requirements are the main driver of the product development project and it is through issues found in the requirements management process that issues related to interface management and suppliers management are revealed.

4.1 Knowledge gap – the definition

In the Lean Product development paradigm, as described by [Kennedy et al., 2008], one of the key terms is labelled the knowledge gap. In order to understand the knowledge gap product development is divided into two value streams, as illustrated in Figure 3. The product value stream is what is traditionally labelled as the “Product Development Process” in most companies. The product development process is usually gated with stages and deliverables and is believed to cover all aspects of what is needed to be managed. In these processes knowledge is more or less systematically transferred between projects but is not explicitly viewed as a deliverable, the product design is the major deliverable. Even in the academic models of product development processes by e.g. [Ullman 1997] or [Ulrich and Eppinger 2008] the product design is the major deliverable. The major difference between traditional and lean product development is thus that knowledge is defined as an explicit deliverable in the latter and is given a value stream of its' own. The knowledge value stream (KVS) flows across projects and there are methods for managing it in and between projects. This is the major reason why this is considered as “lean”, since having a strategy and methods for capturing and reusing knowledge lowers the risk of repeating mistakes, thus making the product value stream (PVS) more efficient and more effective.

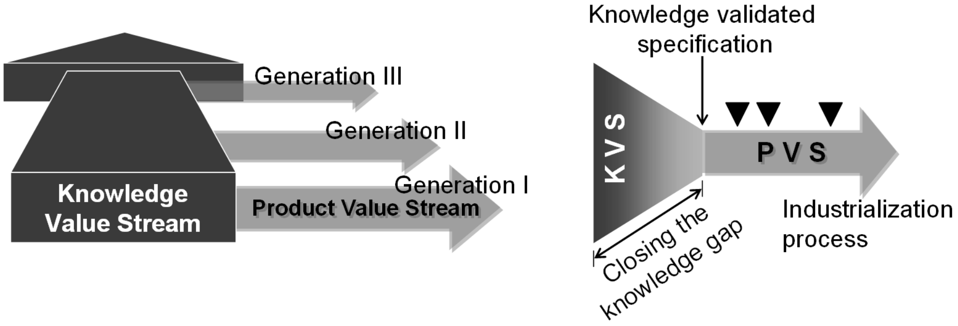

Figure 3. Knowledge Value Stream and Product Value Stream [Kennedy et al. 2008]

According to [Kennedy et al. 2008] knowledge gaps may arise in the interface between the KVS and PVS. The question that is posed is simply “what is known” and “what is needed to be known in order to reduce the risks prior to initiating the PVS for a certain product”. The answers to these questions assume that the company is aware of which parts of the product solution have the highest uncertainty. This uncertainty needs to be eliminated before the PVS starts. The closing of the knowledge gap is characterized by analytical activities to see in which intervals of requirements different principal solutions work and by doing so see which are viable for the current projects requirements.

4.2 Requirements management practice

The requirements management process in the studied case is adapted to the company's standard scenario: a project which develops a driveline with the same architecture in terms of included sub-systems and components as previous drivelines. This standard scenario presumes that:

1. Most components are mechanical, a few electrical and there is a central control system containing almost all the software elements in the driveline.
2. There is a well-known legacy for each sub-system and for most components in the form of previous requirements, solutions, test results and suppliers which can be used as a base line.

The effects of the first presumption are that a system is divided into components for which component designers can be assigned. For each component, its' boundaries will give a clear enough view of which interfaces that need to be taken care of. For the owners this translates into which people they need to keep in touch with. The relatively low number of electrical components, all of which have quite limited number of functions, makes it possible for a few designers to keep track of them. The concentration of all the software to one group of designers responsible for “control systems”, makes it a concentrated function which can be isolated in the development process and integrated only at major releases. The fact that all of the software is developed in-house does not necessitate any detailed processes in how revisions are done since most of the issues discovered during testing can be fixed more or less simultaneously. This set up is depicted in the left part of Figure 4.

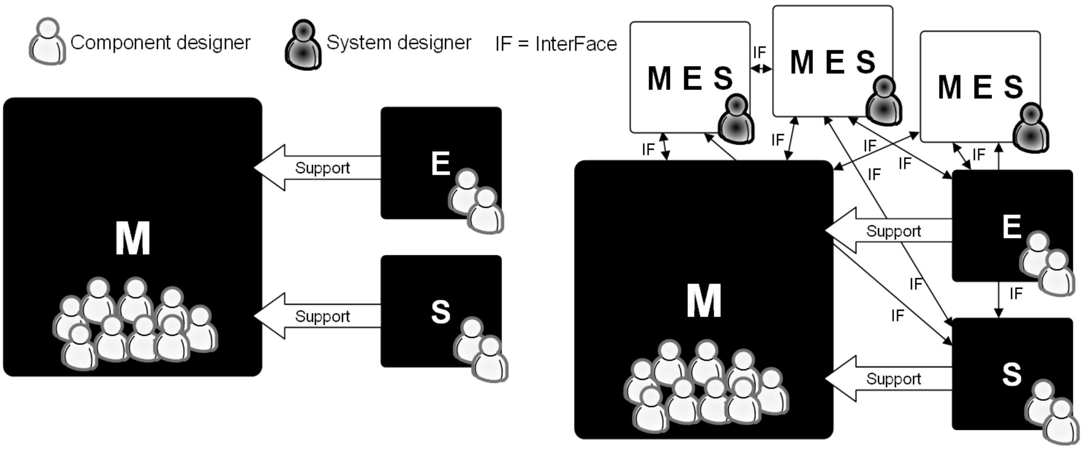

Figure 4. Left: electronically controlled mechanical system. Right: Addition of the mechatronical (MES) sub-system

The second presumption is that knowledge gaps between two projects are small enough to be managed by the individual component designers themselves and do not pose any big risks. The set up depicted in the right part of Figure 4 resembles the scenario in the studied project. The characteristics of this set up are:

1. Most components are still mechanical but a substantial amount of the drivelines functions relies on components which contain both mechanical, electrical and software parts. Software functions are thus scattered around in different parts of the system making the interactions in the structure of the driveline much more complex.
2. Due to the novelty of the new mechatronical sub-system there is no legacy for the new components.

Since the company processes and organization are set up according to the situation in the left part of Figure 4 each of the new MES sub-systems had only one component designer and this person's background affected which of the three domains that were focused in the requirement specification towards the supplier. In addition, this one person had to deal with many unknown interfaces in the three domains. The lack of legacy caused a large knowledge gap in both the interfaces and the requirements which caused schedule slips and late changes. The interviewee who had the role of system designer was the one responsible of figuring out which interfaces there are in the three domains and could witness of a piling amount of testing failures which all were results of missed requirements due to unknown interfaces.

In addition to these knowledge gaps, the group manager for complete driveline properties said that the requirements breakdown process was terminated as they were “in the middle of the left part of the systems engineering V” when detailed design started. A void was thus formed between what kind of requirements the component designers needed and what kind of requirements that were coming from the project. This void was further maintained by the fact that the component designers were expecting the project to concretize the requirements onto a level they could use and the project expected the component designers to take an initiative and do the concretization (as depicted in the quotes in Figure 2). According to literature on requirements management [Almefelt et al. 2006] and [Hull 2005] such a void is bound to give rise to gaps and overlaps between sub-systems and components due to the loss of traceability between system requirements and component requirements. This is also what happened in some interface meetings when requirements “fell between chairs”, as some of the designers put it.

The issues of requirements formulation with lacking context and lacking verification criteria are a consequence of the large knowledge gap initially in the project. These issues are in no way unique for this project and are quite general for any project in the studied company. However, when the component designers were asked about how they dealt with those requirements which belonged to the group “official or unofficial automotive standards” regarding e.g. vibration and sealing, they said that they could get some background and context by talking to experienced designers. This implies that when legacy requirements lack background and context these still exist implicitly in some experienced designer's head (meaning that the knowledge gap for those requirements is not as big as it seems). When context and background are lacking for requirements related to the new sub-system this knowledge can not be found anywhere in the organization, thus the knowledge gap is large. Therefore it is doubtful that, even if the project got more time as requested by the complete driveline properties group manager, they would be able to derive a complete set of sub-system and component requirements simply because nobody had the knowledge enough to do that. A way to strategically address the issue of a knowledge gap according to [Kennedy et al. 2008] is to first make all of the involved parties aware of the existence of such a knowledge gap and actively work on reducing it by modelling and simulating or even testing specific characteristics to generate as much knowledge about the behaviour of chosen parts of the system as possible. The key, according to [Kennedy et al. 2008], is to build small and simple rather than detailed and all-embracing models and tests but big enough to gain the specific knowledge and close the gap. This need for early testing and simulation was expressed also by the interviewees in the discussions around verification management in Section 3.6. This would have given valuable input to the component designers both on how to specify requirements and verifications and manage interfaces.

4.3 Supplier management

In a study by [Johnsen 2009] three decades of research regarding supplier involvement in new product development and innovation is summarized. The findings from this extensive research review are summarized by [Johnsen 2009] in Figure 5.

In the first category, supplier selection, the first factor is early supplier involvement which means involvement during the concept stage or during early feasibility studies. The question is whether this factor has been considered or not in the studied case. The development of the system architecture, that was set by the internal R&D division already in early phases, seems not to have involved any suppliers. This would mean that the suppliers were involved later during embodiment design and detailed design. There are no answers that indicate that the factors of supplier roles and involvement and innovative capability of the suppliers have been given any focus. An issue regarding supplier selection that is not discussed by [Johnsen 2009] is that new product development involves new technology and that the amount of suppliers may be very limited which has been the case for most components in the mechatronic sub-system.

The second category states several factors which have been identified also by [Ragatz et al. 1997] who in their study statistically evaluated different management practices and environment factors which distinguished successful and unsuccessful supplier integration in new product development. They point out that factors related to social, legal and organizational aspects were far more important than aspects related to technological difficulty and complexity. They emphasize that managing the relationship with the supplier through common trust, common goals and visions and involvement has a greater impact than managing them through formal processes and documents. It can be said that many of these factors, such as common trust and goals are missing in the studied project. The interviewees even considered that a higher grade of formality towards suppliers would have been beneficial to the project. Regarding the factor of agreed performance targets and measures in the second category it has been highlighted by the interviewees that they would like to see a higher involvement of the suppliers in the validation of requirements and in verification and testing in order to shorten subsequent redesign loops.

Many saw the low involvement as a result of the lacking structure in validation and verification processes at the OEM. In the third category of internal customer capabilities the second factor is described as the ability to manage cross-functional relationships in order to manage supplier relationships. This correlates well with the found interface issues in the component organization that also affected the integration of suppliers negatively. The recommendation by [Kennedy et al. 2008] to map out the knowledge gaps of the involved parties early on in the project is also valid for the suppliers since it was indicated by the interviewees that there were substantial knowledge gaps regarding automotive standards and OEMs processes. These gaps were not mapped out as potential risks and dealt with openly with the suppliers which would be in harmony with the recommendation by [Johnsen 2009] to manage this relationship based on common trust, goals, visions and involvement rather than formalized contracts. Considering for example the problems with the long software redesign loops for supplied components, compared to short redesign loops for internally developed software, a higher degree of formality in the relationship to the supplier would tend to slow down the redesign process.

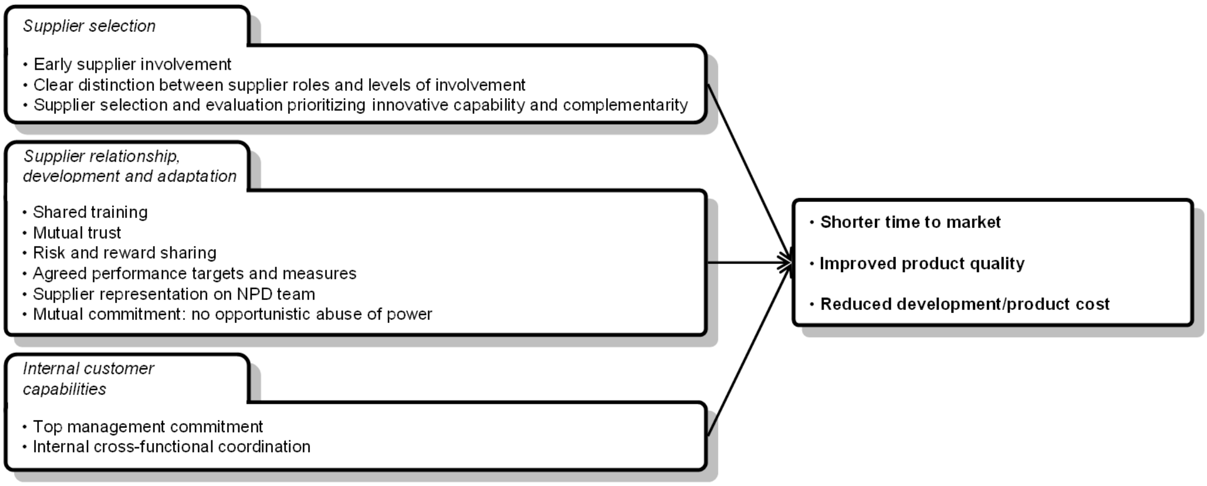

Figure 5. Factors affecting supplier integration in new product development [Johnsen, 2009]

4.4 Knowledge gap in the studied case

The studied project was started in the same way as a project with mostly mechanical parts and no new sub-systems. One of the group managers put this very concretely in the following statement:

"All sub-systems got equal attention and resource allocation which is strange given the fact that issues in the transmission are more explored and well known than those in the our sub-system."

Project planning assured the effectiveness of the project and provided a set of high level requirements. The knowledge gap was implicitly assumed to have been closed by means of experienced designers in the roles of component designers in the mechatronic sub-system. As the sub-system architecture was delivered by the R&D division this was considered as equal to regular carry-over for existing sub-systems. The legacy implications described earlier however show that the amount of carry-over in terms of legacy in requirements, supplier abilities and interfaces had a larger knowledge gap than expected. What was especially lacking were:

1. Functional as well as safety requirements regarding the embedded control software
2. Software interfaces which result from the embedded ECUs in the new components
3. Physical interfaces towards other sub-system components which become apparent only when the solution is tightly packed in the vehicle
4. Interfaces towards equipment in manufacturing and after market
5. Knowledge about supplier abilities and supplier processes for e.g. redesign tasks

Another knowledge gap was found regarding the process needs for the design of the new mechatronic sub-system in relation to characteristics of the existing processes. This relates back to what was mentioned in how system related issues are detected. The existing process fits very well the needs of a development project in which no new sub-systems are added to the driveline. The basic set up of the process is that the designers already know which interfaces their components have and most system effects are known. The complete driveline tests are there only to ensure that any unexpected system behaviour is resolved before production. This approach is however not suitable when a new sub-system with above stated knowledge gaps is introduced since there are too many unexpected system effects. This was not realized by those involved in the project and thus was a knowledge gap in itself.

5. Conclusions and recommendations

This empirical study has found a set of different problem areas related to the introduction of a new mechatronical sub-system to an existing and mature product, a commercial vehicle driveline. Based on the findings and the sub-sequent analysis it is clear that the root cause of the problems encountered in the product development project is the lack of legacy for the new sub-system. The development processes, methods and IT tools at the studied company presuppose that each sub-system already has a base of knowledge which can be carried over regarding sub-system and component interfaces, requirements, verification methods and suppliers. From the presented findings it is clear that substantial knowledge gaps existed for each of these categories for the new mechatronical sub-system. This constitutes an answer to the “which issues” part of the research question stated in the beginning.

The second part of the question addresses the issues of integration of new mechatronical sub-system. This part of the question was stated due to the trends which are going on across the complete automotive industry and the fact that automotive companies are increasingly becoming system integrators rather than component integrators, as illustrated in Figure 5. The component designers are however mainly knowledgeable in only one domain which, combined with the lack of legacy, means that there are substantial knowledge gaps which may be hard for the component designer to realize.

The fact that a new sub-system may be completely supplied by suppliers with no automotive experience makes the consequences of the above stated issues much deeper. As stated in the findings it is hard enough to use the existing processes, methods and IT tools to manage requirements and coordinate the component designers for the new sub-system. Adding the fact that these also have to interplay with the processes of the suppliers creates a situation out of control.

Based on these conclusions the recommendations in Table 1 are proposed and constitute the prescriptive part of this study. A comment on the recommendations is that due to the fact that the delivery from the R&D division was assumed to constitute a regular carry-over the recommendations are geared towards the R&D process, the transfer process and the product development project initiation process. The references in the table are those with similar or same recommendations.

Table 1. Recommendations when transferring and introducing a new mechatronical sub-system into an electronically controlled mechanical system

Issues found	Recommendations
Unknown interfaces in the three domains.	Knowledge about interfaces of the new sub-system components towards other sub-systems and components and how these are dealt with in all the domains needs to be built up or knowledge gaps visualized prior to implementation [Nobelius 2002], [Almefelt et al. 2006]. Functional and geometrical interfaces should be explored and carefully documented but also other interfaces, e.g. electromagnetic, thermal or vibrational interactions between components which result when the solution is packed into a vehicle.
Lack of processes for software development and verification.	There should be a "software developing culture" and acceptance of such roles in the implementing organization and an awareness of the increased functional content in the completely new system [Adamsson 2007].
Unknown interfaces in the software domain.	The responsibility for functions which rely on software should be clear and agreed upon between the internal roles of software developers in the central control system and the component designers who are responsible for a component or small sub-system that carries an embedded ECU and software.
Lack of processes, methods and IT tools for requirements management and verification.	Processes, methods and IT tools needed for the detailed design and adapted to the new issues found in the new sub-system which the existing sub-systems have not encountered. The existing processes, methods and IT tools will reflect and support issues found in existing sub-systems only. The new processes, methods and IT tools should therefore be part of the delivery and put in place before the project starts.
Unknown interfaces between the new components and the product lifecycle.	Knowledge about the interfaces of the new sub-system and the product lifecycle, e.g. testing equipment, manufacturing and assembly equipment, diagnostic equipment, servicing equipment, disassembly equipment needs to be built up [Ullman 1997]. This can only be done by making a prototype vehicle with the solution fully packed and testing, installation, servicing and disassembly discussed with representatives from the respective domain.
Suppliers' lack of knowledge of OEM's processes and automotive standards.	The delivered processes and methods should either be harmonized with the suppliers' processes or the suppliers should harmonize their processes with those proposed by R&D or advanced engineering [Nobelius 2002]. This means that the knowledge gaps regarding suppliers' processes and the suppliers' knowledge gaps regarding OEM's processes and industry standards are closed.
Long redesign loops in the verification process.	The relation with the suppliers of critical components should be managed less formally with increased focus on common visions and goals for the technology. Co-location with the supplier representatives in the development team is preferable [Johnsen 2009].

It is important that the status of each recommendation is either resolved and/or agreed upon among the project leader and members, line department manager and members that own the new sub-system and the R&D or advanced engineering members. A clear status on each of the recommendations will reveal each knowledge gap and clarify the risks and thus also resources and time needed to be allocated in the project plan. Each explicit closing of a knowledge gap, appropriately documented, will also reduce the risk in the product development or industrialization process.

6. Future work

A method and tool for capturing and reusing knowledge about interfaces has been developed and is currently under evaluation by designers in the studied company.

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