Managing concurrent engineering with early supplier involvement: 
a case study

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Concurrent engineering (CE) works best when designers share information early during 
product development. This information can be incomplete or contradictory. Information 
sharing is even more important when it crosses company borders to include customers 
and suppliers in the development of complex products. This applied research focuses on 
CE with early supplier involvement (ESI). A review of CE and ESI related literature finds 
a lack of efforts that address the two issues of structuring the process of customer-
supplier collaboration, and placing the supplier in the customer’s engineering process. 
This paper reports the findings of a case study addressing these issues conducted within 
two European companies (customer and supplier). This test uncovered difficulties in 
implementing CE across company borders. It also found that document processing, the 
most common coordination method, does not capture the engineers’ view of their work. 
Rather, engineers view their work in terms of assigning values to specifications and 
describing the relationships among specifications. This view is well supported by 
parameters. The resulting parameter approach is useful in allowing information sharing, 
data communication, and in controlling data validity. This paper discusses these findings 
as well as implications relevant to those seeking to incorporate knowledge available from 
suppliers into the engineering design process.

Keywords: Inter-organizational collaboration; Complex product design; Product data 
management; Parameter; Engineering workflow

1. Introduction: concurrent engineering with early supplier 
involvement for complex product development

Information technology allows manufacturing to move 
from mass production to mass customization. To respond 
quickly to customer needs, companies are collaborating to 
develop products. The concurrent engineering (CE) 
concept calls for the involvement of all parties with 
needed expertise within the preliminary phases of design. 
Collaboration between different areas of expertise can 
span company borders and include both customers and 
suppliers during early product development (Eisenhardt 
and Tabrizi 1995, Graaf and Kornelius 1996, Takeishi 
2001). Due to advances in information and communica-
tion technologies (ICT), new more agile forms of 
enterprise organization are emerging. The current trend 
for companies to focus on their core competencies is 
leading to closer cooperation between customers and 
suppliers through the establishment of company networks 
(Jagdev and Thoben 2001). Benefits at the product 
development level include reduction of development costs 
(Bonnacorsi and Lipparini 1994). In this setting, the role

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of supplier is evolving from the provision of components to a role that includes the provision of design information and knowledge (Culley et al. 1999). Designers now must rely heavily upon suppliers for information and expertise throughout the engineering design process. These changes impact the customer–supplier relationship.

Identifying where suppliers are involved in the customer’s manufacturing processes will enable:

- All involved parties to work in a concurrent rather than serial manner.
- A reduction of engineering changes (ECs) by means of early and intensive communication with the suppliers.
- The structuring and control of information shared between work-groups and their members.

Engineering changes often result from the iterative nature of engineering design. To support these iterations, supplier involvement in the customer design processes should be managed carefully. One aspect of this research is to identify where the suppliers are involved in the engineering process of the customer, and how to inform suppliers and concerned parties about an EC’s impact as early as possible.

This paper contributes to the CE and ESI literature by addressing the two above issues via a case study. This is focused on the design specifications that are usually provided early in product development in manufacturing. This is novel research in the area of ESI and product development that shows how the customer–supplier interface works. The remainder of this paper begins in section 2 with a brief literature review. Section 3 lays out the research methodology. Section 4 motivates the case study. The following section describes the case study itself and its major findings. This section also contains a short review of the parameter-based approach to coordination. The paper concludes in section 6 with a discussion of the implications of this study and defines future research directions.

2. Literature review and solutions needed

Our literature review uncovers the three following relevant observations.

First, supplier involvement and ESI is an emerging and important research area both for the research community and practitioners (Graaf and Kornelius 1996, Culley et al. 1999, Huang and Mak 2000, Wijnstra and Pierick 2000, Takeishi 2001, Wijnstra et al. 2001). It appears that the customer–supplier interface now plays a key role in the design and development of complex new products. For example, Culley et al. (1999) have found that 86% of the surveyed companies take account of the ‘information and knowledge’ previously obtained from suppliers. Moreover, significant benefits can be achieved if suppliers are involved in product development phases as early as possible (Bonnacorsi and Lipparrini 1994, Huang and Mak 2000, Takeishi 2001, Wijnstra et al. 2001). Accordingly, customers now require their suppliers to be more involved in product development, thus shifting some design and engineering responsibility to outside specialists (Takeishi 2001). While the benefits of ESI are acknowledged, recent investigations in manufacturing industries have revealed that this approach is not widely practised in industries and its implementation has been a great challenge to researchers and practitioners (Graaf and Kornelius 1996, Huang and Mak 2000).

Second, while organizational aspects of ESI have received much attention, the mechanism by which suppliers are incorporated into the customer’s engineering design process in practice has not. This has been raised by recent studies (Culley et al. 1999, Huang and Mak 2000, Takeishi 2001, Wijnstra et al. 2001). For example, Takeishi (2001) wrote ‘managers have continually struggled with the question of where to set the boundary between what work takes place inside versus outside a company, what kind of relations to build with supplier, and how to manage the division of labour with them’. Culley et al. (1999) found only one-third of the surveyed companies had formal guidelines to aid respondents in decisions such as when to involve suppliers in the engineering design process, and what should their level of involvement be? Even though the importance of ESI is recognized, early involvement is extremely difficult in product development (Kiessling et al., 1997, Fleischer 1998, Huang and Mak 2000). Huang and Mak (2000) reviewed a number of methodologies to support ESI. However, they found them of limited value because they did not ‘model and analyse the interfaces between customers and suppliers’. Among complex issues facing manufacturers in achieving effective and efficient supplier involvement during product development identified by Wijnstra et al. (2001), are the identification of processes and tasks that need to be carried out. The German national research project GIPP (Kiessling et al. 1997) modelled the interface between the customer and its suppliers through establishing links between the Bill of Material and the associated process models at different levels of detail (see figure 1, from Kiessling et al. 1997).

The GIPP study held that the upper level is not useful and therefore not taken into account. The medium level was considered as the reasonable range for the establishment of supplier involvement, whereas the lowest level is too complex to handle. The lowest level is exactly the main scope of this paper. It is the most meaningful level for the identification of the actual need for communication between customers and suppliers. This paper’s findings as to the ability of handling this level of complexity differs from those of GIPP, as will be explained in section 5.
Third, identifying where suppliers are integrated in the customer’s engineering processes also facilitates quick reaction to engineering changes (EC). Whilst it is necessary to identify the impact of change on both the customer and supplier sides, recent literature on EC only addresses changes within a single company (Huang and Mak 1999, Terwiesch and Loch 1999). Efforts are lacking to manage ECs within a customer–supplier relationship.

Siemens SGP (the customer in the case study, further referred to as SGP) was re-organizing its engineering processes taking into account concurrent engineering issues. In such a move, SGP wished to involve Knorr-Bremse GmbH (a major supplier, further referred to as Knorr) early in its future engineering platform. This paper describes this effort, associated problems during analysis, and new findings. The study assumes that the decision to outsource had been made and is beyond the scope of this study. In addition, SGP and Knorr had already defined the product development process, interface, and the strategy. Before describing the case study, the next section lays out the research methodology used.

3. Research methodology

The concepts mentioned above were tested in an application as part of a European research project. This test was focused on a detailed study of a railcar wheel-motor-brake unit (called a bogie) design that is manufactured by two European companies: SGP and Knorr. The two companies have different profiles (table 1).

Table 1. Company profiles.

<table>
<thead>
<tr>
<th></th>
<th>SGP</th>
<th>Knorr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employees involved in product development</td>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>Product development organization</td>
<td>Project</td>
<td>Project</td>
</tr>
<tr>
<td>Development time</td>
<td>1.5—2 years</td>
<td>1–6 months</td>
</tr>
<tr>
<td>Complexity</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Variants</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>Series</td>
<td>100–300</td>
<td>5–100</td>
</tr>
<tr>
<td>Reuse of information</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Computer skill</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>End customer</td>
<td>Siemens TS</td>
<td>Transportation</td>
</tr>
</tbody>
</table>

Both SGP and Knorr operate in an engineer-to-order environment. In this setting, they cooperate to design a complex product. Processes generated are characterized by high uncertainty, frequent changes and disturbances, many iterations due to the interactive nature of design, and multiple levels of data ‘maturity’. We use the term ‘maturity’ to denote the degree of consensus over and stability of data. A mature value is unlikely to be changed or deleted, and will have the required tightness or tolerances.

Engineer-to-order (Wortmann et al. 1997) requires a considerable amount of design input. As each product is new there are often many engineering changes.

Data collection was longitudinal and made by one member of the project staying on site for 12 months on a full-time basis. Activities included: analysis of SGP’s engineering business processes (including information about milestones, design life cycle, supplier involvement, standard product structure); study of existing documents; interviews and observation of how engineers perform their
activities. SGP's engineering processes for the conceptual and embodiment design phases (see later figure 8) were analysed by means of the business process modelling tool, ARIS Toolset\textsuperscript{1}, of IDS Prof. Scheer GmbH.

Interviews and meetings were first internal to SGP. They were held with 13 engineers from SGP, including the head of Product Management of the bogie division. Engineers had different backgrounds including CAD engineers, CAE engineers and design project managers. All were closely involved in the daily technical work. This on-site study enabled first hand observations of, and participation in, department meetings and discussions. Interviews and meetings were then extended to involve five Knorr engineers including the head of their purchasing department. Finally, collected data were analysed and new ideas were tested and refined in collaboration with other members of the project including three engineers from another supplier of SGP, three engineers from an ICT company (the director, a head of unit, and a senior consultant), four engineers from a leading European Product Data Management solution vendor (a project manager and three software developers), and the help of three researchers from two European universities.

Since SGP is responsible for the entire bogie system, as well as planning and control of the engineering processes related to the system, analysis focused on SGP's engineering process and identified which activities required the involvement of Knorr. In future SGP engineering processes, Knorr's business functions and organizational units to be involved will be directly linked to the particular engineering activities and events of SGP. Thus, the SGP engineering becomes a CE process backbone, which directly triggers and controls the involvement of the corresponding suppliers (see figure 2).

The case study focused on the analysis of a bogie design. Figure 3 shows the Bill of Materials for this product. Three components (running gear, drive unit, and brake system) were selected for the case study. SGP manufactures the running gear and the traction drive unit, whilst Knorr designs the brake system at three different sites. The bogie engineering process requires many SGP-Knorr interactions. Approximately one hundred engineers from SGP and Knorr cooperate to design a new bogie.

4. Motivations and difficulties of the case study

4.1. The challenge for ESI and cooperation between SGP and Knorr

In recent years cost-reduction efforts at SGP have increasingly led to discussions on what should be done in order to achieve product development efficiency and effectiveness. Particular emphasis was therefore placed on the following:

1. The integration and selection of the best supplier with the latest machinery; as a consequence an extensive supplier assessment and qualification system has been set up especially for this purpose.
2. The establishment of a tightened customer–supplier relationship with more efficient communication and product data interchange; however, technical cooperation in and between different SGP engineering departments and suppliers was not sufficiently supported as far as communication and information sharing.
3. The move from project-based to product-based design and manufacture.

SGP acquired significant experience and knowledge over the past decade concerning bogie design projects. Currently it is migrating from project approach to the business (i.e. one-of-a-kind bogie engineering and manufacturing) to a product approach (i.e. customer-independent bogie platforms with order-dependent product adaptation and manufacturing). In such a move, SGP’s upper management wished to apply CE principles and to include its suppliers early in its future product design. A head of one
department at SGP stated, ‘successful concurrent engineering does not necessarily result in shortened engineering throughput times, but in a reduced time-to-customer, reduced product costs and improved product quality’. He later added, ‘Shortened engineering throughput times may be achieved through migration from a project to a product business.’ In a project-based business, the company designs and manufactures rail-car bogies to customer order using a one-of-a-kind approach. Basing the business upon products, instead of projects, the company will engineer customer-independent platforms, which will be adapted and manufactured to order. By moving toward a product view of meeting customer demand, SGP is trying to move toward a more economical model. Disadvantages of one-of-a-kind production when compared to mass production include:

- The inability to spread development costs over many units.
- Less opportunity to climb the learning curve.
- Fewer opportunities to reduce logistics costs.

The required number of units to justify the research and development (R&D) costs varies widely. Aircraft manufacture can be profitable with a series run of about 100 units. Automobile manufacturers require many thousand units to cover the R&D expenses. The cost of manufacturing a given product decreases over time. This is referred to as the learning curve. In the manufacture of a complex product, the 10th unit can cost 30% less to produce than the first. When a project delivers only a single item or a small production run, this potential for learning is limited. A project geared toward meeting a specific customer demand can limit the opportunities for reductions in the logistics costs. These can stem from a lack of coordination in ordering inputs, production inefficiencies, and post-manufacturing costs.

The change from a project approach to a product approach also impacts the collection and handling of data and knowledge. In a project business, each delivery would have its own data, such as Bill of Materials (BoM). The BoM for the Brooklyn Bridge would be just that, not one for a ‘Lattice Style Bridge—Brooklyn variant’. Moving toward a product approach would allow the re-use of some or much of this information. New versions of previous products can be based upon previous versions (e.g. the Volkswagen Golf Mark II of 1986 could use much of the data from the VW Golf Mark I of 1978). Specific customer modifications can be handled as variants. For example, the VW Golf IV can have variants, VW Golf IV GL and TDI, both of which need to make only relatively minor changes to the Golf IV data including the BoM.

Taking into consideration the move from project-based to product-based manufacturing, it was therefore decided not to capture the current practice in one-of-a-kind bogie engineering, but to design right from the beginning an engineering process representation, which can be used as a guideline for the re-organization of the engineering domain with respect to CE issues. This decision produced many challenges (see section 4.2).

Another driver that encouraged SGP and Knorr toward early cooperation related to barriers to the provision of information to both companies. From Knorr’s view, early collaboration will reduce interface problems. For instance, communication between SGP and Knorr will be improved and technical contacts will be established during early stages of new product development, which ensures fewer errors, better quality, less development time, and consequently lower overall costs (including EC-cost). Understanding such early involvement and collaboration will give deep insight into SGP’s engineering processes, and consequently may lead to a better understanding of SGP’s requirements for collaboration and coordination with Knorr. Besides SGP objectives for collaboration, Knorr’s managers insisted on the mutual benefit (winner/winner strategy) that may be generated from early collaboration with SGP.

Interaction between SGP and Knorr has been serial and paper based, involving face-to-face communication. This had many shortcomings (problems of data management,
cooperation of changes and communication) from the SGP managers’ view. Using documents led to problems of data management (data inconsistency, data isolation, and data redundancy) especially when there are many ECs. Paper-based cooperation between SGP and Knorr can be slow when product data (geometric models, process models and workflow) and documentation notification must be exchanged frequently between several people involved from different business functions within Knorr and SGP (the problem of change coordination). When fixing (releasing) requirements of a new product, key managers, other than the technical, from SGP and Knorr meet in one location. This is usually conducted in a location other than the place where the people involved normally work. This process would be too expensive to include all of the people involved. Other expenses include the costs associated with flying people to a remote site and putting them up in hotels and feeding them for several days. Once those managers return to their companies, the agreed requirements can change for several reasons: technical specialists may feel they are infeasible or need adjustment or final end-users may change their requirements (problem of communication). Therefore, new meetings are required in order to evaluate the impact of changes. Accordingly, additional costs are generated. For these reasons, engineers from both sides are willing to be more involved in a remote process that could be Internet-based in order to overcome the previously mentioned problems of data management, coordination and communication.

The head of one Knorr department summarized Knorr’s goals regarding engineering cooperation with SGP within a CE framework by stating, ‘In order to avoid sub-optimal solutions, future [analysis] should not only be performed at the component level but at the entire product level with the involvement of the supplying companies.’ He also added, ‘At the time of order release, the data for components with a long fore-run are not yet complete.’ The involvement of suppliers (e.g. Knorr) in product development has therefore become a key issue in the SGP engineering process. However, such involvement raises difficulties.

4.2. Problems encountered during process analysis

The decision not to model the current state of engineering for SGP’s project business, but to start from product-based engineering design made this a business process re-engineering activity with all the associated challenges. See, for example, Cameron and Braiden (2003) for a discussion of BPR in an engineer-to-order setting. The following observations were reported in the Project’s Deliverable 1 (Schmitt 1999):

- Along with specifying the process specification and defining the requirements, SGP’s managing board discussed the future strategy and organizational structure. A stable organizational structure which could have been used as a baseline for process analysis was consequently not available during the project. Both organizational structure and process representation were therefore subject to possible changes.
- Even though the overall vision regarding the future engineering processes was clear, the detailed common view on the particular sub-processes still had to be generated.
- The generation of this common view required the participation of many persons. This was a greater challenge because the processes to be defined were intended to support CE with the involvement of several internal and external teams at SGP and Knorr.
- In interviews, people found it difficult to make their implicit knowledge explicit. Although the people knew what activities they had or would have to perform, and in what order, they found these very difficult to describe in terms of documents or graphical forms.

5. Results of the case study

The analysis of SGP’s engineering processes and possible Knorr involvement yielded the following lessons.

5.1. Engineering processes become unstructured at very low levels of detail

The initial approach adopted in this research, termed modular reference ‘process’ models, requires the specification of all process modules, which cover all SGP’s processes including those that interact with Knorr. The Workflow Management Coalition (WFMC) defines a ‘process’ as a formalized view of a business process, represented as a coordinated (parallel and/or serial) set of process activities that are connected in order to achieve a common goal. These processes are then stored in a process library. For any specific situation, the appropriate process modules are retrieved from the library and then implemented as workflow. The drawbacks of this strategy consist of (a) the necessity to pre-model all possible process modules that may be required, (b) the difficulty of finding and retrieving the most convenient process modules from the library according to the specific situation, and (c) the fact that the interfaces between the process modules must fulfill the needs of all possible combinations. Engineering sub processes vary significantly.

To test the applicability of the modular reference models, SGP’s engineering processes were analysed by means of the business process-modelling tool ARIS Toolset. Through function decomposition, using the ARIS Toolset, a process
hierarchy can be obtained which allows the illustration of very complex processes in a modular and therefore more comprehensible way (see figures 4 and 5).

For the analysed design phases, the ‘as is’ practice showed almost no supplier involvement at all. In addition, it was found that a complete set of process modules could not be predefined. Furthermore, the number of sub processes to be executed during a large engineering project (such as a bogie development) would require extensive human interaction to compose the overall process based on the process modules.

Process analysis discovered that engineering processes can be considered structured and stable, i.e. time invariant, only at a very abstract (high) level. Such high level processes include the global process of bogie design, platform development, engineering, system design, and determination of system parameters. However, it was impossible to represent the engineering processes at an adequate level of detail. The more detailed the analysis got the more unstructured the processes became.

Figure 5, which is part of the structured overview of the defined process model of a bogie design, illustrates the detailing problem. This figure is obtained after decomposing the Global Process, Platform Development, Engineering, System Design and Determination of System parameters in figure 4. The maximum level of detail that can be achieved by means of structured engineering process representation of a bogie design is limited. The functions shown in a horizontal line, for example ‘optimize frame and components according to internal requirements’, are unstructured processes. They are highly interactive, requiring frequent communication between functional areas, either at SGP, Knorr or between SGP and Knorr, to achieve an optimal engineering result. Optimization involves many activities such as:

- Check validity of requirements.
- Define target values for parameters and derive new start values for iteration.
- Communicate parameter values to external engineering unit and other internal organization unit (such as Knorr).
- Collect their feedback.
- Determine components requirements.
- Achieve consensus among involved engineering units with respect to the internal requirement.

This optimization process with the involvement of suppliers consists of ad hoc processes, which are performed according to specific circumstances in a given engineering situation. These ad hoc processes cannot be predefined in the form of ‘reference processes’ or a graphical representation. Therefore, the particular actions performed as part of the optimization process are added in textual form to the engineering processes shown in figure 5.

Reflecting the above findings, it was impossible to: (a) identify exactly when and how Knorr was to be involved in the CE process of the customer for a specific engineering situation, (b) model stable reference processes which may cover any possible engineering situation that includes a customer–supplier interface, and could be implemented into a workflow management system.

This part of the case study showed that even when a formal design process exists, the design process becomes harder to represent when the design itself becomes more detailed, which in turn makes active supplier involvement in design harder to achieve. This finding may be consistent with that of Culley et al. (1999) who found that 62% of the surveyed companies had official design process models, but only 35% thought these had the potential to aid and facilitate engineering designers in their decisions on supplier interactions.

Interviews with SGP engineers revealed that ad hoc processes, depending on the specific circumstances in a
given engineering situation, started to dominate the engineering activities. The characteristics of technical (i.e. non-administrative) engineering processes depend very much on ‘the specific circumstances’ in a given engineering situation. In such a case, the occurring events, the activities to be performed, their sequence, and the required participants cannot be pre-defined without the specific circumstances. The process is therefore purely ad hoc and would need to be specifically designed for each particular engineering situation, which is not feasible. This result supports the GIPP group finding (Kiessling et al. 1997).

Decisions on supplier involvement are taken in relation to these ad hoc processes. Moreover, early collaboration is performed with early data supplied by SGP and Knorr. As these early data can be vague and rough, many design iterations and ECs are necessary to reach a design consensus. To speed up this process, engineers have expressed the need for ‘rapid communication’ to replace paper-based communication, in order to avoid late decisions.

As reference process models cannot represent the complete engineering process, a different approach to CE was initiated. This approach will be discussed in the next section.

5.2. Parameters and their relationships match engineers’ thinking

In order to overcome the problem of extensive human interaction required to compose the overall process when using a process modules approach, a document-controlled workflow approach was considered as an alternative. Predefined document types, containing ‘sensitive’ document sections, retrieve the appropriate subset of process definitions, combine them and finally execute them as workflows. However, this approach requires the predefinition of not only the entire subset of processes but also of any document type and its variants if any change might occur. As far as engineering is concerned, the essential disadvantage of this approach is the use of documents. An engineering milestone checklist based on completed documents had been generated for use within SGP. Nevertheless, it was found during the case study that SGP’s engineers rarely used the checklist because: (a) the everyday business did not allow the engineers the time required to complete the documents or, (b) the engineers were simply not keen on completing the documents since the related work was not considered directly productive or providing them any further tangible benefit to their usual engineering work. In addition, meetings held between people from SGP and Knorr about bogie design cooperation are time consuming and costly (see section 4.1), and are subject to frequent requirement changes. A representative of a large automotive supplier summarized document disadvantages by stating during one seminar that ‘future engineering will no longer have the time to wait for documents’.

Based on the engineers’ experience and taking into account previous disadvantages, engineers reported they were less concerned about processes and documents. In a design setting, neither a document nor process view captures the essence of customer–supplier collaboration. Engineers see their work as making engineering decisions during ‘specific circumstances in a given engineering situation’, not as creating documents or as following processes. An internal SGP workshop revealed that the mentioned specific circumstances in a given engineering situation are defined by product parameters, especially those engineers referred to as the killer parameters.
Parameters capture well the way engineers work and think, and dominate most discussions and organized workshops. Depending on the type and the value of a specific parameter, engineers must communicate with other company and external engineers, either from the same or from other disciplines such as operations planning, manufacturing or purchasing. The term killer parameter had been mentioned various times during organized workshops within SGP. Parameters represent elementary engineering variables during engineering activities. They represent the specific circumstances in a given engineering situation. Killer parameters are critical component attribute values, which must be kept within a certain value range or below a certain maximum value because otherwise extensive reworking of the entire bogie system design would be required. These parameters have an extensive impact on both self-manufactured and supplied components and should be managed carefully by the customer and supplier. Therefore, the management of killer parameters requires intensive communication with the suppliers in order to achieve a consensus regarding the components geometric and functional properties.

The bogie development process is dominated by iterative procedures. Although some parameter values may be predefined by a requirements list (the one completed by the end-users), starting values must be estimated for most of the parameters at the beginning of the engineering process. While the engineering activities proceed, the parameters are subject to numerous iterations. The parameter values estimated at the beginning become more and more precise and stable.

The approach described here considers complex product development as a form of parameter processing. The engineering process is therefore approached as a network of activities that uses and produces parameters (figure 6).

An activity can start when all required input parameters are available and ends when the target parameters are stable. The control mechanism to upgrading parameters is based upon a workflow. This workflow is outside the scope of this case study and is the subject of a separate paper.

Parameters often share complex relationships. These relationships might be represented by mathematical equations such as

\[
\text{max\_axle\_diameter} = f(\text{max\_axle\_load}, \text{bear\_distance}, \text{track\_gauge}, \text{axle\_material}),
\text{wheel\_motor\_distance} = f(\text{gear\_transmission\_ratio}, \text{wheel\_diameter\_worn}, \text{max\_axle\_diameter}, \text{clearance\_to\_rail}, \text{gear\_steps}).
\]

Parameters represent the smallest elements for basic cooperation between the customer and its suppliers. The collaboration is therefore more easily based on parameters and their relationships since the engineers (from SGP and Knorr) subscribe to product interface parameters. In case of a parameter value change, subscribed engineers (either at the customer or supplier side) will be automatically informed in case of any ECs. Not all parameters impact the customer–supplier cooperation. Only a subset is required to satisfy such cooperation. For example, designing a bogie for a passenger railcar involves 300 killer parameters as described by SGP engineers. These parameters will be the subject of collective estimation and validation by engineers from both sides of the customer–supplier relationship.

During the case study a list of engineering parameters and their relationships, relevant to the bogie life-cycle was developed. In addition, using the parameter approach as a means of collaboration across company borders led to the establishment of links (a relationship matrix) among parameters, and between parameters and final end-user requirements, parameters and components, parameters and people, documents and components. The result of these combinations, as shown in figure 7, eases communication between engineers on either side of the customer–supplier relationship. In addition, it eases the transparency of engineering activities, helps assign values to parameters, and supports quality of design.

Table 2 shows an example of parameters linked to product structure items or components. This table is not meant to show all parameters. Confidentiality required by the two companies, limit the names of component types in the sample. This table is useful to support EC management. If there is a change of any parameter, the captured relationships may help to identify the snowball effect on associated items. Therefore, all people subscribed to any parameters or components will be informed.

### 5.3. Measuring design stability

During product design, engineering data exist in multiple levels of maturity, within different departments in the customer–supplier relationship. In order to ensure engi-
ing data validity all the time, SGP engineers capture the maturity level using the concept of hardness grade, noted HG. This concept originated at McKinsey Consulting and it was related to cost reduction measures. SGP uses five HGs. Engineers of SGP later adopted the terminology in order to show how secure and stable the value of a specific parameter was during the design process. During this project, SGP agreed upon an internal HG designation. The evolution of a parameter value through the five hardness grades controls the design process.

The five HGs are linked to the bogie life cycle (figure 8). For example, at HG 1 the parameter value has been estimated and depicts a start value for iteration. At HG 3 parameter values are specified based on more precise calculations in cooperation with other engineering groups; parameter values are checked and preliminarily approved by the supplier Knorr; parameter values are checked and preliminarily approved by internal organizational units in SGP other than engineering; and finally parameter values are checked and released by the responsible SGP project manager.

Parameter values may be explicitly or implicitly predefined by external (final end-users) or internal requirements (by engineers of SGP or Knorr). If a parameter is predefined by external end-users then it is set to ‘hardness grade = 5’. Otherwise, the parameter must pass through all HG transitions from 1 to 5.

Whereas the HG of a parameter already depicts one form of parameter state, the parameter has to pass various statuses within a particular HG level prior to its upgrading. Parameter values must be estimated, approved, and released. This forms the parameter life cycle. During bogie design, collaborative process of assigning values to parameters moves a parameter through several statuses and HGs.

Previous sections described new approaches to coordinating engineering design activities and placed these within a parameter framework of three dimensions (see figure 9).

Before using this parameter approach, several steps need to be performed.

1. Identify the product interface collaboration between customer and supplier to meet the specific end-user demand.
2. Ensure engineering transparency through assignment of parameters without input/output interdependence relationships, to bogie product life cycle (i.e. to each phase of product development).
3. Obtain external end-users’ specifications through interviews and marketing research.
4. Transform external requirements into internal functional requirements, and identify predefined parameters.
5. Link parameters to all components; parameters will now identify where suppliers and the main contractor collaborate.

5.4 Test results and end-user comments

The results of the test of the parameter-based approach to concurrent engineering coordination between Siemens SGP, and Knorr Bremse are described in detail in Schmitt and Frotmüller (2001). However, as that document contains company sensitive material, it is confidential. We can present some of the findings reported in that document. Those interested in greater detail are encouraged to contact the companies involved directly.

After testing, the end users were asked to evaluate several aspects of the parameter-based approach to concurrent engineering on the basis of potential value and value already achieved in the implementation. For all aspects the evaluations were quite similar. The users found the concepts of immediate potential value and the implementation ranked almost as high. The slightly lower score for implementation may be interpreted as the users finding value in the implementation but that there are still details to be improved.

The users found the five HGs to be convenient but did have some concerns as to ease of use in actual operations. They wondered whether parameters appearing in multiple change lists could make tracing changes difficult.

Specific concerns in implementation of the change management included the difficulty of distinguishing between first and higher-order relations resulting from the snowball effect, that the change procedure might be overly simplified, and that problems may emerge when parameters appear on more than one change list.

One of the goals of SGP was to support the migration from a project approach to customer-driven design to a product approach. This move is facilitated through the
As long as a new customer order shares similarities with at least one previous order, this creates a starting place. A variant of a previous order can be created by starting with the previous parameter checklist and network.

While parameter-based concurrent engineering control had been implemented, the value of the change will not be known until several customer orders for bogies have been met through the product variant approach. Only then can there be certainty that the parameter approach facilitates the cost and development speed improvements sought in the move from project to product design.

6. Conclusions and implications for future research

This paper has described a case study dealing with CE with ESI and its implications to the design of complex products in a collaborative environment.

The case study found unexpected difficulties in managing CE during the early product specification stage. The complexity and iterative nature of design made pre-definition of all potential processes infeasible. Basing the interaction between supplier and customer on document processing was also found to be unsatisfactory. Research showed that engineers think in terms of parameters and their relationships, rather than of following process or altering documents. Parameters represent the smallest elements where Knorr (the supplier) is integrated into SGP’s (the customer) engineering processes. From the case study it appears that SGP–Knorr engineering collaboration depends very much on the specific circumstances in a given situation, which are well represented by parameters. Parameters represent the essence of the collaboration in the customer–supplier relationship. This finding constitutes a new approach to managing concurrent engineering across company borders. Furthermore, this paper proposes clear and key concepts that might represent a new approach for workflow management and engineering change management between companies based on parameters.

The parameter approach was then tested and is being adopted by SGP and Knorr to improve collaboration, and facilitate communication early enough during product development. Engineers from both companies consider the parameter approach, in connection with the HG maturity measure, a very useful approach to achieve better quality assurance in engineering.

The test case showed that the parameter approach is indeed usable but did not indicate whether it would lead to the cost and time savings sought by the move from a project to a product variant approach to satisfying customer orders. These metrics will require the experience of several customer orders before the new approach can be judged against the old. Once the partners have satisfied several new orders by adapting previously used designs, as captured in parameter networks, answers to these questions should be sought.

The parameter approach could also provide significant support during the assessment of engineering change effects and would also document the engineering process. Direct access to product data across company borders is vital regardless of the actual type of project management organization. However, such benefits need to be tested and measured in future research and from observing actual practice.

Beyond these benefits, this research has limitations. First, according to Ullman’s (1997) six design methods, this approach best fits parametric design. Ullman’s methods include: selection, configuration, parametric, original, routine or redesign, and mature design. As configuration design consists of assembling components into a completed product and parametric design involves finding values for variables, or parameters, the approach described in this study fits parametric design and permits configuration design. It treats complex product development as a form of parameter processing. Second, the approach described here is most applicable to product families (not one-of-a-kind) where former product specifications can extensively be re-used for new designs. Third, the case study focused on only two companies. However, because many companies are facing the same challenges, the findings of this paper are not limited to SGP and Knorr. Finally, these two companies do have a
long history of cooperation. The parameter approach toward new product development uses parameters and values from previous variants as the starting point for a new product. This would be quite difficult to implement if the suppliers sought to be involved early in the design process did not have previous experience working with the main contractor.

Results of this research have several implications for both researchers and practitioners. From a research perspective, capturing parameter relationships is a form of knowledge management. For example, one participant suggested comparing the parameter relationship to knowledge capture used in other research areas.

Results also imply that outsourcing does not work effectively without extensive internal effort by the main contractor, in this case SGP. To gain competitive advantage from early supplier involvement, Takeishi (2001) suggests managers should, ‘ask not what your supplier can do for you; ask what you can do with your suppliers’. Consequently internal reorganization must be initiated to fully adopt such an approach.

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