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Inter-organizational concurrent engineering: A case study in PCB manufacturing

Robert de Graaf^{a,*}, Luuk Kornelius^{a,b}

^a Eindhoven University of Technology, Faculty of Technology Management, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

^b Bakkenist Management Consultants, Telematics and Logistics Section, P.O. Box 23103, 1100 DP Amsterdam, The Netherlands

Abstract

Concurrent Engineering (CE) is mostly applied within an organization. Due to the focus at core competencies, suppliers need to be involved. Focusing on core competencies requires manufacturers to involve suppliers in the development of complex products, especially in electronic design. Consequently, an inter-organizational approach is necessary to reduce throughput-time, improve quality, and lower costs. Analysis of a European PCB supplier's difficulties in implementing CE, with the Readiness Assessment for Concurrent Engineering (RACE), led to a maturity model for supplier involvement in electronic design. This framework's first step is effectuation of basic CE principles within the organization, which has been recommended for the PCB supplier. Further progress requires customer involvement, ultimately leading to virtual customer–supplier-teams striving end-user satisfaction, supported by enhanced, ethernet-based application tools. The lack of customer effort, to achieve Inter-Organizational CE, proved to be the major road-block for the PCB supplier. Nevertheless, suppliers have a strong competitive edge, since they are capable of entering customer–supplier-networks can therewith be established instantaneously.

Keywords: Concurrent engineering; EDI/PDI; Customer supplier relationships; Extended enterprise; Virtual team

1. Introduction

Difficulties in implementing Concurrent Engineering (CE), in a situation where customer–supplier-interaction is considered, have led to this paper. A case study was carried out at 'X-Circuit', a medium-sized PCB manufacturer from North-Western Europe. X-Circuit features multi-layered circuits on both conventional and new materials. Most of X-Circuit's customers can be found in the telecom business and develop products for niche markets. Mass production advantages cannot be achieved for components used

in these products. Womack et al. made clear that, in the automotive industry, this niche approach called for a redesign of the business process, including engineering [20].

X-Circuit identified CE as the engineering philosophy for the cooperation between customer and supplier, because of its emphasis on simultaneously developing the product and its related processes. CE enables a short lead-time in engineering activities, one of the major drivers in electronic design markets. Furthermore, CE strives for end-user satisfaction, by deploying the end-user requirements to all parties in the chain. This enables creation of specific niche products. Finally, CE forces all parties to communicate their progress and problems to ensure the whole

* Corresponding author. Email: r.d.graaf@tm.tue.nl

product is right the first time, so no costly rework is needed to make the parts fit and work together.

CE is generally regarded as a way to improve the internal organization [17]. From the CE viewpoint, experts need to work concurrently, ensuring their discipline's input during product and process design [3]. In PCB manufacturing these experts cannot be found in one organization, because PCB manufacturing technologies are often beyond the Original Equipment Manufacturers' (OEMs) capabilities. Hence Inter-Organizational CE is required to address customer–supplier-interaction.

The Readiness Assessment for Concurrent Engineering (RACE) was used to analyze the difficulties X-Circuit was experiencing in implementing CE. The major findings were that the organizational structure was not supporting CE, and that communication within the company and with customers was slow. Furthermore, the planning was not visible to all disciplines involved in the process. Extended cooperation and coordination between customer and supplier as well as some internal improvements were needed to achieve the Concurrent Engineering advantages. The necessary changes addressed both organizational issues and supporting information technology (IT).

Proper use of information technology is a key issue when customer and supplier form a virtual company [8]. In the aerospace industry, first steps towards connecting remote supplier engineers have been set [15]. Developing and choosing the right tools requires a clear definition of the processes to be supported. We used our case study to develop a maturity model for supplier involvement, illustrating the consecutive stages that ultimately enable Inter-Organizational CE. This model includes the communication between the organizations and the information technology to support it.

Section 2 portrays the difficulties customers and suppliers of PCBs face, due to new technologies and the growing divergence in end-user products. Section 3 introduces RACE, that was used to investigate X-Circuit's engineering process. The results of this investigation and the consequences for X-Circuit and its customers are presented in Section 4. Section 5 displays the maturity model that was developed for supplier-involvement during PCB engineering. Section 6 discusses the applicability of RACE at X-Cir-

cuit and the use of the supplier-involvement maturity model outside electronic design. Finally, in Section 7, conclusions are drawn considering the difficulties X-Circuit was facing in implementing CE, the need for Inter-Organizational CE and the role that suppliers should play in it.

This study emphasizes the relationship between PCB manufacturers and their clientele. Hence we have chosen to refer to the PCB manufacturer as 'supplier' and the clientele as 'customer'. With customer we therefore explicitly do not mean the user of the final product. If these users are meant, we will refer to them as 'end-user.'

2. Inter-organizational developments in PCB manufacturing

PCBs are generally considered as mass production goods. However, PCBs are now often used in products that serve niche markets. This means PCBs cannot be manufactured customer-independently. End-user specific components require the customer set up an engineering process for each end-user order, using end-user requirements as input. The customer desires to use the components in its products immediately. Consequently, long lead-times will not be accepted even though engineering is now part of the lead-time and has become critical to on time delivery.

Complex PCBs are often beyond the capabilities of the OEMs. This means suppliers need to be involved to create reliable products. At the same time, OEMs today are looking for help from their suppliers to handle the shortening product life-cycle [9,18]. This calls PCB suppliers to restructure their manufacturing processes and equipment, allowing smaller batch sizes at reasonable costs. Developing process technology has consequently been a major driver for PCB suppliers. In doing so they have become specialists in their specific field of industry. Highly automated flow-lines are necessary for efficient manufacturing and about 10% of annual turnover need to be invested in further development of the process.

Manufacturing specialized products also requires specialization in engineering processes. Consequently customers can hardly generate the right tech-

nical specifications on their own. This has become even more difficult because both the PCB and its components influence the final product functionality. Customers must accordingly involve their suppliers in defining their new products. However, customers still consider specifying the complete product as a core activity. Customers are thus reluctant to simply hand over the specification process for their products to their suppliers. This creates a dilemma in which the customer is forced to choose between cost effectiveness and core business.

In this situation customer and supplier share core activities that can hardly be separated. The risks involved in sharing proprietary information are eminent. The risk is outweighed, however, by cooperating intensively in the engineering process in order to create a well-designed product. If this cooperation is not structured effectively, the common final product will be sub-optimal if not non-competitive.

Customers therefore have no choice but to cooperate with their suppliers. The supplier holds the knowledge to develop and manufacture the PCB and is able to do so at lower cost than the customer. Suppliers have to be involved in the engineering process as soon as possible as the customer needs chain information to efficiently manufacture its products [2,16]. This development leads to manufacturing networks with independent customers and suppliers that develop and produce the same end-user order. Such networks are referred to as 'Extended Enterprises' or 'Virtual Corporations' [1,4].

We believe that a supply chain oriented approach with structured cooperation between all parties involved, is essentially necessary for all niche products. Customer and supplier have to redesign their engineering processes according to Inter-Organizational CE principles. Inter-Organizational CE demands extensive communication between the organizations involved. Inter-Organizational processes need to be fine tuned with each other. This means all organizations involved need to be CE focused themselves and need to have proper support tools in place. However, new technologies require new design rules and therefore standard tools fall short in optimizing PCBs that utilize new materials [11]. Furthermore, increased involvement of suppliers will lead to a need for supplementary communication tools [13].

3. Readiness assessment for concurrent engineering

The Readiness Assessment for Concurrent Engineering (RACE) displays the current practices of the engineering process seen from a CE standpoint [14]. Furthermore, it is used to develop improvement plans for the engineering process. RACE highlights obstacles that prevent progress towards CE. These bottlenecks can be caused by an insufficient process or deficiencies in the technological infrastructure.

RACE was chosen for the investigation for sev-

Fig. 1. The RACE model

eral reasons. X-Circuit needed insight in its engineering process from a CE point of view. X-Circuit's engineers were convinced concurrently executed activities could enhance the engineering performance, however, a strategy to implement CE was not formulated yet. In addition, RACE involves the engineers in establishing what steps are to be taken. This way organizational recognition for the necessity of change is acquired. Finally, X-Circuit was eager to test RACE for application small and medium sized enterprises, as RACE had been illustrating its applicability for larger manufacturing companies [10]. Some of X-Circuits potential customers had even been using the tool before.

The RACE method features a model that addresses 14 critical elements for engineering, divided into a Process and a Technology part. The critical elements and levels are briefly explained in [14]. Process elements are defined at 5 levels; the Technology elements have 3 levels. The RACE model is illustrated in Fig. 1. Currently, the RACE method is being expanded. New critical elements – Strategy Deployment and Support for Product Architecture – are added to the model as they have proved to be of importance in setting up CE in four previous cases [10]. Furthermore, a structured deployment technique of the improvement initiatives is being developed to support implementation.

RACE features 7 basic steps in assessing the engineering process and identifying improvement plans:

1. Interview management to establish the Business Drivers for the next 1 to 2 years.
2. Study corporate documents to get acquainted with the internal practices.
3. Interview engineering related employees to identify bottlenecks that restrain the realization of the Business Drivers.
4. Guide a group session with engineering related employees using Nominal Group Technique to identify, cluster, and prioritize present process bottlenecks [6].
5. Apply a questionnaire concerning the critical elements of the RACE Model to establish the current state of the engineering process in the model.

6. Interview management to establish the desired state in the model.

7. Linking business drivers, desired state in the model, and remedial initiatives in a double matrix, to select powerful remedies for improving the engineering process.

These steps are usually performed by 2 academic consultants.

4. Results

4.1. Assessment results

X-Circuit's major business drivers are reliability and flexibility. Furthermore, throughput time and productivity are considered important issues for the success of the company. According to the organization, the most significant bottleneck that prevents improvement of the business drivers was the organizational structure with strict separation of commercial and technical departments. The path of communication with the customer was also considered inconvenient. Planning was identified as a major bottleneck too, especially its poor visibility in the organization and its rigid lead-times. Finally, the lack of harmony between sales and technology departments was questioned.

The current state in the RACE model was established using the RACE questionnaire. The results are depicted in the RACE model in Fig. 2. Three parts on the Process side are well supported. Product Assurance is Characterized; Agility and Discipline are rated Repeatable in the current state. Relative to other assessments, these scores equal the highest levels found so far [10]. Customer Focus and Process Focus are relatively weak; Team Formation and Teams in Organization are insufficient; Leadership and Management Systems are more or less unaccounted for, as X-Circuit is just starting to implement CE. On the Technology side Application Tools and Coordination are ranked at Intermediate; the other parts are Basic.

The desired state for the engineering process and its IT-support was set by X-Circuit's general manager. Improving Team Formation and Teams in Organization got high priority; Customer Focus, Lead-

ership, Agility and Process Focus got medium priority. The grey line in Fig. 2 represents the desired state. At the Technology side a desired improvement in Communication was added to provide the means for electronic data interchange with customers.

The remedies generated during interviews and group session have been linked to the desired state and the business drivers. The most powerful remedies came out to be:

1. Introduction of market teams with commercial and technical people at the operational level.

These teams will handle market specific order flows and will be held responsible for the on time delivery to the customer.

2. Integration of engineering and sales at the tactical level

This integration will enable X-Circuit and the customer to discuss long term boundaries of financial and technical nature. PCBs can then be ordered from between these boundaries.

3. Electronic communication with customers.

This communication will provide consistent and up to date data to both X-Circuit and its customers on both orders and products in development.

All chosen initiatives indicate the importance of providing the organizational functions with the proper translation of the customer requirements. Remedies 1

and 3 improve the interpretation of the customer requirements. Remedy 2 improves the internal communication so the customer requirements can be translated into information that can be used to plan and control the engineering and manufacturing activities.

4.2. Consequences

4.2.1. Internal

Before X-Circuit deployed the initiatives listed above some adaptations in the current procedures of the company were required. First, the planning had to consider engineering and purchasing activities next to production, as these activities have become part of the customer order lead-time. Second, communication between engineering and sales staff had to be improved. Initially, informal communication within teams was essential. Besides, some formal meetings had to be scheduled to monitor the order delivery chain. Finally, the market team's members needed to be trained in working together as a team. They had to acquire knowledge concerning the whole order flow process, i.e. sales, engineering, planning, purchasing, production and delivery.

4.2.2. External

Not only X-Circuit had to adapt its organization and focus in order to achieve inter-organizational

Fig. 2. Current and desired state of X-circuit in the RACE-model

integration in engineering processes. Customers were to create supplier focus in their organization, at least to ensure manufacturability, but preferably in order to achieve optimal use of the supplier's competencies. Component specification and design should then be judged against yield, capacity and lay-out [5]. Only when this cooperation is achieved, customer and supplier can work towards their final goal: end-user satisfaction.

4.2.3. Interaction consequences

The engineering process must show frequent instead of occasional interaction between customer and supplier. This is the foundation for X-Circuit's inter-organizational engineering process. Each phase in the customer's process will have its counterpart in the supplier's process. This interaction should start at the earliest moment possible, enabling continuous knowledge transfer, and avoiding redundancy in activities so both customer and supplier can at all times focus on their specific competencies.

X-Circuit's business process will change due to the Inter-Organizational CE approach. Subsequently parts of the customer's business process will also change. The main difference is the sequence of the activities. The proposed ideal model of interaction with the customer is presented in Fig. 3. The figure shows a high degree of concurrency between customer and supplier activities. One of the essentials of

this new process is the continuous transfer of knowledge. Considering this knowledge the customer can draw up the PCB definition. If specific questions come forward, interaction with the supplier is possible before any order is given. The new process model distinguishes 3 major steps in acquiring new products:

Exchanging conditional information. The approximate batch size, base materials and components are forwarded to the supplier (1) (numbers in parentheses correspond to the encircled numbers in Fig. 3), so purchasing can check availability of these materials and a rough capacity check can be made for production (2).

Prototyping. Based on the information that is fed back to the customer (3), the lay-outs can be designed to fit the specified base material (4). These lay-outs are forwarded to the supplier (5) for design rule checks, yield optimization, tool specification and planning of engineering and production capacity (6).

Ordering. Suggestions for improvement are communicated to the customer (7), so its drawings can be harmonized with the supplier's capabilities (8). The final order – with specific quantity and lead time – is given with the final drawings (9). The supplier can now fine tune its planning (10) and process the board (11).

A major advantage of this process model is the

Fig. 3. Optimal design of X-circuit's inter-organizational engineering process

ability to respond to changes in the market place. The customer can specify the final product gradually during the process, using inputs from its supplier to produce a cost effective and high quality design. Changes in the definition of the order, lay-out, and drawings can be taken into account until the final test and evaluation is done. The time between the final requirements and production of the PCB is dramatically shortened this way.

4.2.4. Infrastructure

Electronic Data Interchange (EDI) and Product Data Interchange (PDI) can play an important role in keeping the communicated information in Fig. 3 up to date and consistent. EDI handles order information, where PDI focuses on engineering information. The current facilities on Internet, or private networks that are alike, seem promising. Such systems could reduce the necessary investments in dedicated applications. Currently, Internet applications are not yet as well supported as dedicated network services for EDI and PDI, but they might become available within five years from now.

4.2.5. Deployment

X-Circuit's current customers could not be convinced of the proposed Inter-Organizational CE approach yet. They were quite satisfied with the current approach, and not willing to adapt their engineering process to one supplier. Issues like core competence protection and the lack of senior management attention at customers are the main reasons for this dead-lock situation. X-Circuit could therefore only improve its engineering efficiency through introducing market teams and developing knowledge based checklists. Yield and lead-time can only be improved marginally this way. To further optimize yield and reduce lead-time, customer cooperation is required.

5. Supplier involvement maturity model

5.1. Towards virtual teams

Concurrent execution of engineering and production activities requires intensive cooperation between the supplier and its customer. Table 1 illustrates the consecutive maturity levels of supplier involvement.

As long as the customer's purchasing department sends specifications to the supplier's sales department, all activities will be sequential. The total lead-time will equal the sum of the lead-times of the respective activities to be completed. In such situations, the customer can only reduce costs by tough negotiation, forcing the supplier to reduce its prices. IT support at the customer's side as well as at the supplier's side will be limited to non-communicating systems, supporting internal processes.

The introduction of market teams at the supplier, in which engineers and sales people are equally important, creates customer focus at the supplier. This is especially the case when the customer's purchasers can directly communicate with the engineers in the team. The engineering process can then be improved by reusing existing knowledge and experience efficiently, so yield and cycle-time can be improved. The supplier typically uses knowledge based systems to check whether the PCB is within the capabilities and CAD-CAM integration for production preparation. This way the customer focus is enhanced.

Dedicating an engineer to the customer and posting him physically at the customer's site does not only stimulate customer focus, but also supports creation of supplier focus among the customer's engineers. The customer's engineers use knowledge based systems to check supplier specific design rules. The dedicated engineer can explain the supplier's specific problems, ensuring manufacturability of the component and thus optimize yield. The customer's CAD system and the supplier's CAM system can be coupled to transfer data.

In those cases where supplier competencies are essential to the quality and lead-time of the final product, the customer can allocate one of its engineers to the supplier. This dedicated engineer must ensure the optimal use of the supplier's competencies in the final product. This requires supplier involvement in product architecture decisions. The supplier can access the customer's CAD system and product data interchange facilities are implemented. Feedback to sales and marketing will stimulate product innovation and facilitate the division and adjustment of activities carried by the customer and its supplier [7]. This way the lead-time is optimized.

The final step is to consciously focus on the

Table 1
Maturity in supplier/customer cooperation

Maturity level	Focus	Customer			Supplier	
		IT support	Departments involved	Communication	Departments involved	IT support
1. Ordering	• Product cost reduction	• Stand alone CAD	• Purchasing	• Reactive	• Sales	• Stand alone CAM
2. Capability checking	• Yield improvement	• Connected CAD	• Purchasing	• Market team	• Sales	• Capability base
	• Cycle-time improvement				• Engineering	• Connected CAM
3. Outsourcing	• Yield optimization	• Design rule base	• Engineering	• Dedicated engineer	• Engineering	• Coupled CAM
		• Coupled CAD		(Supplier at customer)		
4. JIT II	• Cycle-time optimization	• Dial in CAD	• Sales	• Dedicated engineer	• Engineering	• Product data interchange
		• Product data interchange	• Engineering	(Customer at supplier)		
5. Inter-organizational Concurrent Engineering	• End-user satisfaction	• Ethernet applications	• Sales	• Virtual team	• Engineering team (Suppliers)	• Ethernet applications
		• Common information base				• Common information base

end-user. All activities to be carried out should be directed towards market demand and customer orders. The customers translate their end-user order information directly to the suppliers' engineers. Engineers of several suppliers will cooperate in virtual teams, communicating through ethernet applications and working with a common information base. The customer and its key suppliers should agree on a division of tasks and responsibilities and develop a communication infrastructure for ongoing end-user focused interaction. This way both customer and supplier are end-user suppliers analogous to Hoppenbrouwers et al. [12].

5.2. *Enabling consortia*

In the previous sub-section we stated that focusing on end-user satisfaction requires the cooperation between the customer and its entire supplier network. Not only customer and supplier should communicate and cooperate, miscellaneous suppliers contributing to the same end-user order will also need interaction for product and process adjustment. One of the customer's main tasks is therefore to establish a supplier network. Such a consortium of organizations should contain all competencies required for engineering and manufacturing the final product. This consortium might only exist during the fulfillment of one end-user order, similar to Davidow and Malone's suggestion in *The Virtual Corporation* [4].

Establishing such a consortium and making all the actors involved cooperate is not an easy task. Each supplier is independent and has a specific agenda. While the consortium is in place, the customer must nurture sound relationships. However, in order to be able to rapidly establish or adjust the consortium, the customer must constantly keep in touch with the supply market, stimulating innovation and investments in knowledge, machinery and information technology. At the moment an end-user order portfolio can be acquired, it must be clear instantly which suppliers are to be involved. Traditional purchasing activities such as price-negotiation and supplier selection cannot be executed within the required timeframe. Suppliers that can immediately become part of an additional or existing consortium will thus be preferred. Establishing and maintaining the capabilities and information technology required for Inter-

Organizational CE is consequently an important asset for suppliers.

The communication infrastructure must enable the continuous interaction that is vital for Inter-Organizational Concurrent Engineering. Inter-organizational information exchange has long relied on media such as mail, facsimile and telephone. Such communication media do not enable concurrency. Technologies such as EDI/PDI and Ethernet enable continuous communication. Computers of different organizations can be linked and files can be transferred and used immediately. This allows different organizations to use the same files or even collaborate electronically during the engineering process. Clear definition of tasks and responsibilities and their dispersal between customer and supplier is then required.

6. Discussion

The applicability of our findings is argued in this section starting with the use of RACE at a small enterprise. Following, the deployment of the most powerful improvement initiatives at X-Circuit is discussed. The use of the maturity grid beyond the PCB manufacturing domain concludes this section.

The use of RACE to identify suitable improvements for the engineering process of a relatively small enterprise like X-Circuit worked well, yet the effort per individual was quite high. Bottleneck identification in the X-Circuit case did not consider Strategy Deployment and Product Architecture Support, the proposed new critical elements of the RACE model. From our observations in interviews and group session, we conclude that X-Circuit's strategy was deployed adequately to the employees involved. Therefore Strategy Deployment would not have been identified as a bottleneck. Product Architecture Support would not have been regarded a bottleneck for X-Circuit either, as product architecture is not an issue for the supplier, until level 4 in the Supplier Involvement Maturity Model is reached.

Application of RACE led to a well-motivated crew that was certainly ready for a change toward CE. This commitment diminished when the selected improvements could not be executed in full, because customers did not commit to the suggested improvements. RACE should consequently only be employed

in environments where all changes can be carried out by the assessed organization itself. Involvement of one or two customers – especially in determining the business drivers – could have overcome this problem.

Still, X-Circuit should fully implement selected improvements and use its increased knowledge of concurrent processes in approaching new customers. Certain potential customers have improved their product development cycle-time internally and recognize that suppliers have become part of the critical path [9]. These companies approach their suppliers to speed up engineering and manufacturing process. Not all suppliers can achieve such a goal in a short time. Furthermore, X-Circuit could suggest innovations to its current customers, for example in the fields of cost reduction or reliability improvement. X-Circuit could thus fulfill the need for supplier initiated innovation, as identified by companies such as Chrysler [19]. X-Circuit can market itself as an innovative, reliable, short lead-time supplier for end-user specific PCBs, which require both engineering and production activities.

The maturity grid for customer–supplier-interaction, that was developed during this case study, is not specific for PCB manufacturing. Complex components that require sound process knowledge beyond OEM capabilities or that are not considered core by the OEMs will follow the same grid. The grid cannot be used for co-development in strategic alliances as customer and supplier cannot clearly be separated there.

7. Conclusion

We have made clear that shifting specialisms call for inter-organizational integration in engineering processes. Customers need specialized suppliers to support important elements of their core activities. Outsourcing used to be cost driven; currently customers often have no other choice but to involve suppliers in engineering and production activities. The supplier is the one with the required knowledge to influence the output of the production process in terms of yield, quality, and cost.

Being ready for Inter-Organizational Concurrent Engineering implies having adopted the basic princi-

ples of CE. Two of the eminent prerequisites are therefore to form market oriented teams and to implement means for electronic communication with the customer. Market teams result in less formal communication and provide a better concept of how the formal communication needs to be structured. Electronic communication provides consistent and up to date data related to products in development and orders.

X-Circuit has identified the importance of these initiatives for its organization, but just implementing CE principles internally could not solve all associated bottlenecks; customers needed to be involved. The lack of customer commitment to engage in Inter-Organizational CE limited the success. The case made clear suppliers can work themselves up to level 2 in the model, mainly improving engineering efficiency. Level 3 and higher only work if both supplier and customer desire to be at the same level.

This does, however, not imply that suppliers should postpone the required investments in the organizational and information technology changes, if their customers have not committed themselves to supplier involvement in engineering. It is to be expected that outsourcing customers will increasingly demand their suppliers to be able to participate in a manufacturing network. The capability to engage immediately in such a network is an important asset.

The X-Circuit case shows it is difficult for a supplier to initiate CE oriented changes at a customer. Suppliers should put their effort in making clear what their competencies are and convince the customer of the need for these competencies in fulfilling the end-user's need. Neither the customer nor the supplier can fully meet the end-user's demand without cooperating with the other. This does, however, not imply that they should both sell the final product. The end-user will still perceive one of them as the manufacturer, perhaps not even knowing the other. Knowing which suppliers have the right competencies allows the customer to establish a network. Establishing a network also means temporarily connecting computer systems. Consequently the proper information technology should be in place, both at the customer's side and at the suppliers' side.

Currently, most information technology tools used in electronic design check basic manufacturability issues. For complex PCBs these tools fall short.

Suppliers can provide some of their expertise in knowledge based tools, but still need to be involved in the engineering process to optimize yield, lead-time and product quality. CAD-CAM integration tools between customers and suppliers are the starting point, gradually evolving to ethernet applications that support product and order data exchange and real-time collaboration. Standardization is an important issue here, because the customer–supplier-networks can exist for just one end-user order. Internet based tools are promising, because they are already partly standardized and do not require large infrastructure investments.

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Robert de Graaf received his M.S. in 1992 from Eindhoven University of Technology, The Netherlands. He majored in Industrial Engineering. Currently, he is a member of the Manufacturing Technology Group at the Technology Management Department of the same university. He hopes to receive his Ph.D. in Concurrent Engineering this summer. During his Ph.D. work, he has cooperated with several large industrial firms in North Western Europe, assessing

and improving their product development processes according to Concurrent Engineering principles. This work was done in close collaboration with the Concurrent Engineering Research Center at West Virginia University, Morgantown, WV, USA.

Luuk Kornelius received his M.S. in Industrial Engineering from Eindhoven University of Technology, The Netherlands in 1992. At the moment he works within the Information and Technology Group under the supervision of prof.dr.ir. Hans Wortmann and prof.ir. Piet van der Vlist. He hopes to receive his Ph.D. in Industrial Engineering early 1997. During his Ph.D. studies, he has been working on supply chains and extended enterprise issues. Since 1992 he

also works as a management consultant in the field of inter-organisational logistics with Bakkenist Management Consultants in Amsterdam, The Netherlands.