ELSEVIER

Int. J. Production Economics 60–61 (1999) 251–260

international journal of production economics

# Concurrent engineering for global manufacturing

Hassan S. Abdalla*

*Department of Mechanical Manufacturing Engineering, De Montfort University Leicester, The Gateway, Leicester LE1 9BH, UK*

**Abstract**

This paper presents the state of the art of the research work carried out within the multi-national collaborative programme IMS-Test Case 3 "Global Concurrent Engineering". The project's aims were to identify the critical constraints with respect to global manufacturing, and to synthesise the best practices of concurrent engineering (CE) in a number of industrial sectors including automotive, aerospace, telecommunication, shipbuilding, and information technology. The consortium was constructed from a cohesive group of world class companies and research institutions from the USA, Canada, and Europe. The research outcome indicated that effective communication, a systematic involvement of customers, suppliers; distributors, powerful information infrastructure, and effective use of modern technology are vital key elements for success. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Globalisation; Concurrent engineering; Product life cycle; Organisational strategy; Communication infrastructure; Functions co-location; Multi-disciplinary teams

## 1. Background

Concurrent engineering (CE) is the consideration of the factors associated with the life cycle of the product during the design phase. These factors include product functionality, manufacturing, assembly, testing, maintenance, reliability, cost and quality. Concurrent engineering is important because it is at the design stage that such aspects as product quality and cost are specified. The essence of CE is not only the concurrency of the activities but also the cooperative effort from all the involved teams, which leads to improving profitability and competitiveness. The measures for productivity are usually based on time to market, product cost, market share, and quality. In reality, these factors are interrelated and CE strategy is to target a mix of all these factors to give an overall framework to organisations. For example, taking into account the design processes, as early as possible during the product life-cycle development, might expose alternative solutions that could provide remarkable quality improvement for an insignificant cost increase.

Over the last few years considerable research work has been directed towards investigating the techniques and tools needed for implementing concurrent engineering strategy. A premier effort was conducted at West Virginia University's Concurrent Engineering Research Centre (CERC) [1,2].

* Tel.: +44 1162 577097; fax: +44 1162 577052; e-mail: ha@dmu.ac.uk, http://www.eng.dmu.ac.uk/~prob/.

0925-5273/99/$ - see front matter 
PII: S0925-5273(98)00152-2

The objectives of the research work undertaken at CERC were to develop a system that facilitate data interchange so that design data from one system can be used by other systems. It also permits virtual meetings with voice, graphics, text, and video capabilities. The CE wheel-set which encompasses two wheels, the first "represents the integrated product and process organisation" issue and the second wheel "accomplishes the integrated product development theme" was presented by Prasad [3,4]. O'Brien [5] discussed different approaches for implementing CE strategy. He highlights the need for "better information systems, and decision support tools to support CE activities". O'Grady et al. [6] introduced an approach to CE using artificial intelligence constraint networks. The system uses constraint networks that can advise designers on improvements that can be made to the design. The advantage of this system that it is flexible enough to allow design problems to be approached from a variety of viewpoints. A system approach to the design of mechanical components where constraints associated with design attributes of a concurrent engineering environment was presented by Dowlatshahi [7]. The proposed approach is capable of reflecting the results in an optimisation model leading to the identification of product configuration. Finger and Fox [8] developed a system that surrounds designers with experts and advisors that provide continuous feedback based on incremental analysis of the design as it evolves. The system uses constraints as a language by which perspectives (e.g., comments on its manufacturability) communicate with one another and with the user. These perspectives are coordinated through blackboard architecture. Shekhar and Azadivar [9] present an expert system for information flow in a CE environment, their framework can be customised for a particular application. An open-system platform for integrating different engineering tools and management services in order to maximise engineering design and production planning efficiency was investigated within the framework of the ESPRIT project (CONSENS) [10]. The system has the ability to support designers by monitoring the manufacturability and estimating production cost of a designed part. A modelling approach for production costing estimation and continuous improvement of manufacturing processes was presented by Senechal and Tahon [11].

Glover et al. [12] described the significance of implementing the software tools "SYNTHESIS" to integrate Reliability and Maintainability (R&D) into the early stage of the product-life cycle development. SYNTHESIS tools enable each participant to productively contribute to concurrent engineering and design decision process. This system can be seen as an effective tool for supporting multi-disciplinary design teams which is a critical element of CE. A CE environment for micro-CAD systems, based on a commercially available local area network operating system, in order to provide adequate facilities for managing team-based design projects has been developed by Gay et al. [13]. Oh and Park [14] proposed an integrated decision model in which decisions on product and process design are simultaneously performed through economic evaluation at each stage. This approach minimises the product cost under a set of strategic constraints defined by the organisation. The model was tested on designing a printed circuit board to demonstrate the effectiveness of a concurrent product and process.

El-Gizawy et al. [15] described an approach for integration of product, process and tooling design and systematic method for acquiring and analysing information about capabilities and limitations of the manufacturing processes. The suggested strategy allows for the timely evaluation of the effects of changing product and process design parameters on the performance of manufacturing as measured by cost effectiveness and productivity indices. Similar approach for quality control planning of mechanical components was proposed by Abdalla [16]. A new methodology and tool based upon a process modelling and analysis technique, aimed at assisting in re-engineering of organisational processes and structures for a CE environment was introduced by Pawar et al. [17]. A human-oriented approach to computer supporting of CE in distributed enterprises was discussed by Rohatynski [18] and Fernando et al. [19].

Further studies still needed to address or develop more comprehensive methodology and tools to help designers conduct the CE discipline. A key aspect of this methodology is to assure that components are manufacturable for the lowest possible cost in specially designed manufacturing facilities such as manufacturing cells. However, the implementation of CE strategy has been shown to be non-trivial task inherent difficulties have to be overcome before the full benefits can be accomplished. Since designers need to be equipped with effective and integrated information technology tools, which act as a formal feedback route from the manufacturing phases. However, full realisation of a successful concurrent engineering practice requires cooperative team(s) to work on the product development. This task is a difficult one for a number of reasons: firstly, lack of a comprehensive model clearly describing the decision activities in simultaneous product and process design; secondly, lack of sufficient computer-based tools, capable of supporting cooperative decision-making activities.

The work undertaken in this project aims to develop a methodology for the development and manufacturing of products based on the concept of concurrent engineering, for organisations that operate on a global basis. Globalisation in this context means that the product or different parts of the product can be manufactured in different sites around the world for a number of reasons, such as technology and resource availability. This necessitates the fulfilment of some requirements as stated by Hayashi [20]: "a company may have various facilities located around the world and to manage those facilities effectively, and to handle its policy making and production planning, a company needs a communications network that interconnects its multiple manufacturing plants and sales offices as well as other facilities".

## 2. Project aims and objectives

The goal of this project was to demonstrate the improvement that can be made to Global Manufacturing capabilities through the implementation of CE techniques which have been generated, tried, tested and evaluated within companies operating in national and international markets. It was believed that this approach could improve designs, reduce product lead times, reduce costs and improve quality to ensure the future viability of manufacturing industries in a global market. The project objectives were: (i) to establish the extent to which CE is practised; (ii) to identify the critical constraints with respect to Global Manufacturing in terms of technology, technology management and human resources; (iii) synthesise the best practices of CE and to diminish the effects of the critical constraints; (iv) to design an architecture of a CE System for global manufacturing, which represents a model of the functional activities, and (v) to disseminate the results through Global Concurrent Engineering workshops. Researchers from a number of organisations within the EU, the US, and Canada carried out the research work as part of the IMS feasibility study. The collaborators of the feasibility study are listed in Table 1.

Table 1
IMS Test case 3 consortium members

| Organisation | Country |
|---|---|
| Northern Telecom | Canada |
| Nokia Corporation | Finland |
| Odense Steel Shipyard | Denmark |
| Trans Tec Ltd | UK |
| Syntax Software | Italy |
| North Carolina State University | USA |
| Carleton University | Canada |
| De Montfort University | UK |
| California Poly State University | USA |
| Technical Univ. of Denmark | Denmark |
| VTT Research Laboratory | Finland |

## 3. Research methodology

A world-wide benchmarking survey was carried out at the beginning of the project in order to provide the information needed to define the best CE practice and to build the GCE architecture. The methodology developed to gather the necessary information is illustrated in Fig. 1. Over 320 companies were identified, but only 150 distinguished organisations and companies were approached as suitable candidates to participate in the study. The selection of those companies was based on two major factors; firstly these companies were

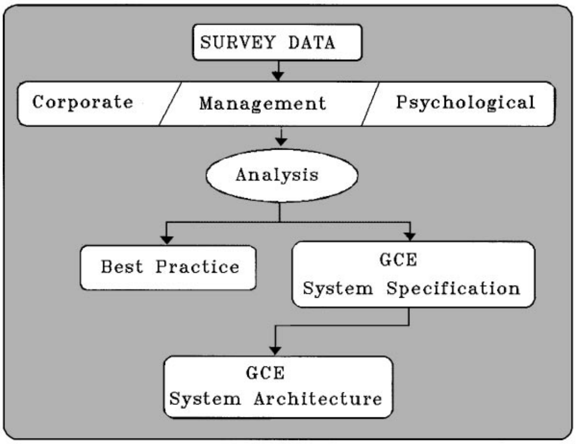


Fig. 1. Research methodology.

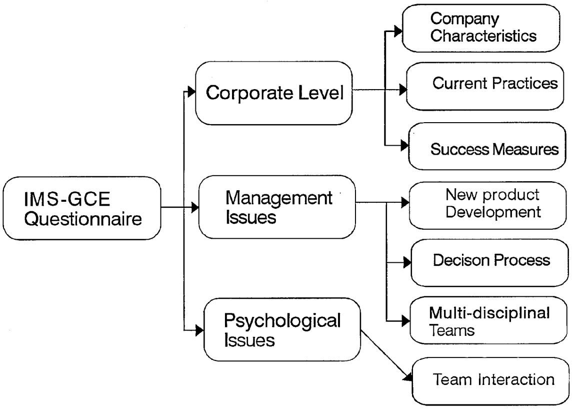


Fig. 2. IMS-GCE questionnaire structure.

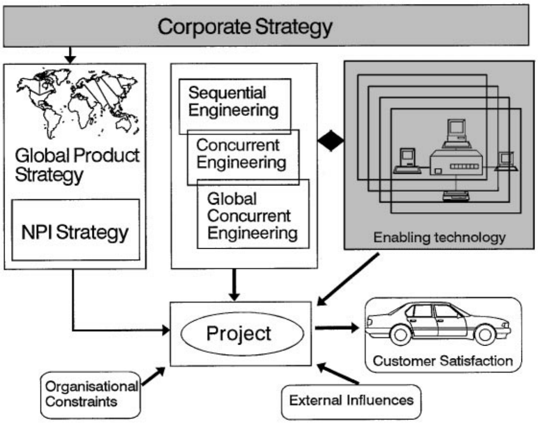


Fig. 3. The corporate strategy for a product development.

considered as market leader in their respective field and claim that their success is partially as a result of practising concurrent engineering. This claim was confirmed during the preliminary market analysis, which was carried out as part of this study and indicated that these companies, respond to the market demand much quicker than their competitors, and deliver a product at a competitive cost without any compromise on the quality. Secondly, these companies are actively manufacturing and marketing their products in different countries world-wide. Following the identification of the companies, questionnaires were designed to address a wide range of issues to establish how GCE is exercised in those organisations participated in this research. The questionnaires were also designed in such a way to allow examination of different factors for New Product Development (NPD) activities. To ensure that suitable feedback is achieved, logical and quantitative types of questions were addressed and included in the questionnaires.

The questionnaires consist of three parts: corporate level, management issue, and psychological issues, as shown in Fig. 2. The corporate level was addressed by a questionnaire which aims to examine corporate policies as shown in Fig. 3, strategies and practices during the implementation of GCE and the organisation of product development within those identified companies. The second level of analysis examines the relationships between management and project teams. This level of analysis focuses on factors determining the effectiveness of GCE practices at the development program and project level. It surveys project team leaders, design and manufacturing team members, and managers working directly with project teams. The third level of analysis was the infra-project level which examines the internal operation of teams in terms of how team members interact, communicate, and co-operate towards achieving the project goals.

The strength of this GCE research concept was to allow the linkage of these three levels of analysis within each company. Since corporate or business unit strategy was linked directly to project team decisions and processes, which in turn linked to measure team satisfaction, cohesion and commitment. It also allows for the hypotheses concerning the relative merit of different CE strategies and policies in influencing the outcomes of specific development projects, both in terms of meeting business goals and management satisfaction with the development process.

## 4. Benchmarking strategy

The essence of benchmarking is based on competitive performance according to other external perspectives. It is the process of comparing business practices and performance levels between companies in order to gain new insights and to identify opportunities for making improvements. The major benefit is likely to be achieved by focusing on those areas of the business that are critical in driving competitive success. Benchmarking enables companies to set strategy and identify new techniques and maintains the stimulus for continuous improvement. It also addresses problems encountered by companies during implementing new technology and techniques, and leads to better understanding of the customer expectations; fewer complaints and better customer satisfaction; faster

Table 2
The benchmarking data analysis approach

| | Background | 1. Strategies, visions | 11. The role of the project | 111. Miscellaneous | 111.a. Training | 111.b. Distances | 111.c. Initialization | Practices | 1. Use of methods, tools | 11. Interaction, participation | 111. Miscellaneous | 111.a. Duration of the project | 111.b. Overlap of design and | 111.c. Barrier to utilize CE | 111.d. Implementation of CE | Process | 1. Completion of the tasks | 11. Problems, conflicts | 111. Changes | Outcomes | 1. Benefit of CE | 11. Achievement of objectives | 111. Impact of CE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Background | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Strategies, visions | | | X | | | | | | X | (x) | | | X | | (x | | X | (x) | | | | (x) | |
| 11. The role of the project | | | | | | | | | X | (x) | | X | X | | | | (x | X | X | | | | |
| 111. Miscellaneous: | | | | | | | | | | | | | | | | | | | | | | X | |
| 111.a. Training | | | | | | | | | | X | | X | | | | | (x) | (x) | | | | X | |
| 111.b. Distances | | | | | | | | | X | X | | X | X | | | | X | X | X | | | X | |
| 111.c. Initialization | | | | | | | | | | | | | | | | | | | | | X | (x | X |
| Practices | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Use of methods, tools | | | | | | | | | | (x) | | (x | X | | | | (x) | (x) | X | | X | (x | X |
| 11. Interaction, participation | | | | | | | | | X | | | X | X | | | | (x) | (x) | X | | X | (x) | X |
| 111. Miscellaneous | | | | | | | | | | | | | | | | | | | | | | | |
| 111.a. Duration of the project | | | | | | | | | X | | | | | | | | X | X | | | | X | |
| 111.b. Overlap of design and | | | | | | | | | X | X | | X | | | | | (x | (x | X | | | X | |
| 111.c. Barrier to utilize CE | | | | | | | | | | | | | | | | | | | | | | | |
| 111.d. Implementation of CE | | | | | | | | | | | | | | | | | | | | | | | |
| Process | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Completion of the tasks | | | | | | | | | | | | | | | | | | | | | X | X | X |
| 11. Problems, conflicts | | | | | | | | | | X | | X | | | | | X | | X | | | (x | X |
| 111. Changes | | | | | | | | | | | | | | | | | | | | | | | |
| Outcomes | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Benefit of CE | | | | | | | | | | | | | | | | | | | | | | | |
| 11. Achievement of objectives | | | | | | | | | | | | | | | | | | | | | | | |
| 111. Impact of CE | | | | | | | | | | | | | | | | | | | | | | | |

awareness of important innovations and how they can be applied profitably; a stronger reputation within industry; improving skills and the general performance of company's workforce. The key for best benchmarking practice emphasises on understanding the actual performance of the business rather than just comparing results [21].

The collected data were analysed using the approach shown in Table 2 to identify differences in performance levels and practices according to the following benchmarking criteria:

1. Generic benchmarking investigates the strategy and practices of businesses in order to understand and learn from their experience.
2. Functional benchmarking compares similar functions in different industrial sectors such as the manufacturing or the design process in Automotive, Aerospace, and Telecommunications.
3. Competitor benchmarking compares between functions or performance and practices in similar industries. For example, the current NPD strategy between company (A) and company (B) in Aerospace industry.

Samples of the benchmarking findings, particularly the benefits, the barriers and the methods adopted by companies practising CE strategy are discussed in the following sections.

## 5. Some of the benchmarking findings

The results have shown that best practices of CE require the formation and support of multi-functional development teams that set product and process parameters early in the design phase, decisions made in the first 20% of the development cycle usually determine almost 80% of the product's performance, producibility, reliability, maintainability, schedule, and life-cycle costs. The ingredients of a successful development team require process management and organisation, team structure and dynamics, common information technology and integrated multi-discipline processes and development practices. Further discussion regarding some of the findings are presented briefly in the following sections including the steps and methods which are adopted by companies currently practising CE strategy. The benefits and barriers of implementing CE are also reviewed.

### 5.1. Steps taken for implementing CE

Due to the diversity of the data collected from the five industrial sectors involved in the benchmarking exercise, in terms of product nature, size of companies, and its objectives, the steps taken to implement CE varied from one company to another. The various common steps taken by the companies towards implementing CE strategy are shown in Fig. 4. Training for staff was regarded as the most vital step and ranked first with 56% of the companies have indicated the importance of this factor [22]. The management structure of 52% of the companies had to be reorganised in order to utilise a Concurrent Engineering strategy. Functions collocation was considered by 44% of the companies participated in the benchmarking as an initial step. IT tools were used by almost 30% of the companies to support CE, but was not regarded as the strongest factor as some might have expected. While innovation and globalisation were addressed as key strategic issues for GCE [23].

### 5.2. Barriers to CE implementation

The major barriers reported during practising CE were management reluctance and resistance to

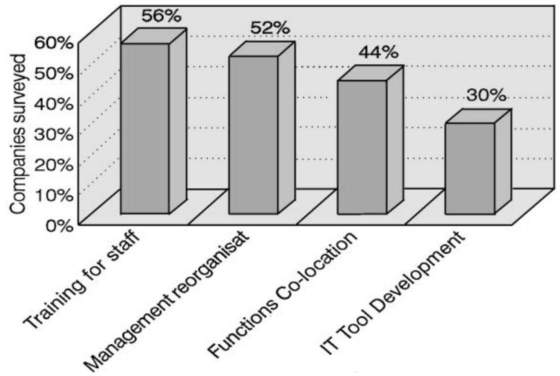


Fig. 4. Steps taken for implementing GCE.

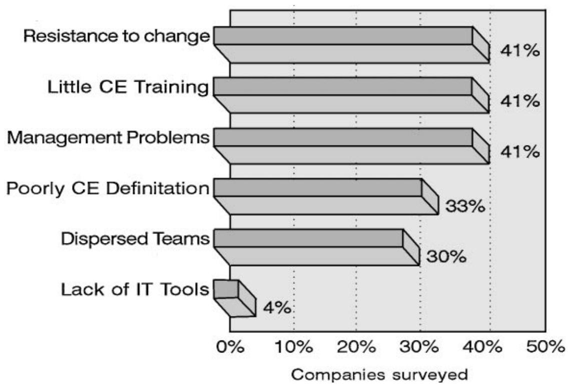


Fig. 5. Problems encountered during implementing GCE.

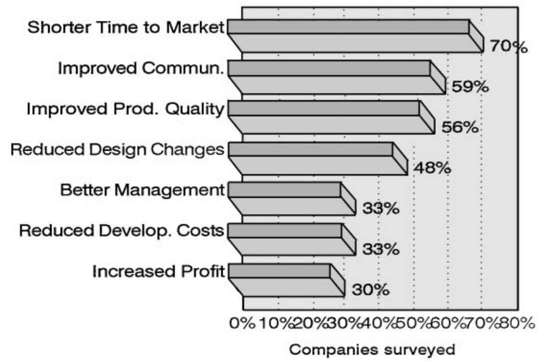


Fig. 6. Benefits gained during implementing GCE.

change, as 41% of the companies involved reported (see Fig. 5). Lack of expertise or information and poor definition of CE were highlighted by 33% of the participants as major difficulties to persuade employees of the philosophy. Similar outcomes were stressed in the British Design Council's survey where 70% [25] of the companies indicated that lack of information and difficulty in knowing where to start was crucial barrier to CE implementation. Lack of training was another obstacle and was reported by 41% of the companies. These results emphasise the necessity of training for management as well as employees in order to have a clear understanding of CE best practices.

Companies which have been practising concurrent engineering have also focused on team building skills and the use of total quality management (TQM), and quality function deployment (QFD) as successful techniques which entail the involvement of customers and suppliers as principal players with a key role in the success of the business. However, lack of IT tools was hardly mentioned as a major barrier as it was reported by only a few of the companies. This indicates that the implementation of concurrent engineering requires changes in the organisational, managerial, and cultural as well as technical aspects.

### *5.3. Benefits of concurrent engineering*

The outcome of this study indicated that CE enables industrialists to quickly bring quality products to market at higher quality and less cost. Through team working and the support of integrated information technology tools designers as well as manufacturing planners were able to cope with late changes, share data with other parties involved in the product development process. Some of the benefits gained by companies participated in this exercise as a result of implementing concurrent engineering best practise are illustrated in Fig. 6. Shorter time to market (70%), better communication (59%), and better quality (56%) were seen as direct reward of practising CE. Reduction in design changes, which means shorter ramp-up time and improving competitiveness, were highlighted by almost 48% of the participants [22]. Reductions in testing, quality failures, and life-cycle cost were also achieved through the consideration of concurrent product and process design.

## 6. Specifications of the GCE system

Developing a generic GCE system requires gathering information in specific areas including functional, informational, resources, organisational and cultural aspects at different levels. The functional area gathers specifications and constraints referred to product development process and projects. The product development processes have the meaning of grouping tasks and sub-tasks that organise, optimise, and define the guidelines to produce the information about products and their production process under the consideration of the whole product life cycle. The information area is tightly coupled with the functional area since it aims to bring together all specifications and constraints referred to production, exchange and share of information created during the performance of a product development process. The resources area gathers the specifications and constraints referred to the necessary support to realise the activities in a company and deals mainly with hardware and software supports, with human resources and financial capabilities. The organisational area focuses on the requirements that deal with a set of relations between people and the organisational structure within an enterprise. It also embraces specifications and constraints linked with multi-disciplinary teams. The cultural area investigates the way a group(s) of people who share same objectives and have some sort of cohesion think, can cooperate towards achieving those goals.

After gathering all information required, the analysis process was carried out and the system specifications and constraints were classified into three principal classes [24].

*Strategic level*: Specifications at this level refer to the product in terms of key success factors for a company. The requirements in this class are correlated to the objectives of high management level. Aspects such as shorter time to market, increase market share, reduce product development costs, and increase quality represent major concern at this level.

*Tactical level*: Specifications at this level refer to the product development process, and are directly linked to the intermediate management level. This class brings together specifications about functional, informational, organisational, and cultural areas. First the functional view: within this view, requirements for three different sub-aspects were addressed as follows: (i) Product development process which covers optimisation and standardisation requirements for the development process. The constraints include the limitation of available methods and tools, and costs. (ii) Requirements in the area of product which includes standardisation of products. Second, is the information view and the major focus in this view are to share consistent information as soon as possible to improve the level of paralellisation of tasks and to share the right quality and quantity of data when it is necessary.

*Operational level*: This level addresses the requirements of hardware and software needed to improve product development processes within the resources area. These requirements are:

(i) To harmonise product process development and tools or systems in a configurable and flexible way.

(ii) Simulation tools in all aspects of product development process, and production process.

(iii) Tools to generate geometrical data at early phases of the development process.

## 7. Lessons learned from the international collaboration

Working in an effective international collaboration provides industrialists and academics with a clear vision and experience that is necessary for improving global product management operations. There is no doubt that globalisation of manufacturing requires efficient transfer of manufacturing knowledge from various regions. The project participants have gained experience as a result of the benchmarking exercise, through monitoring their company performance versus others in similar industrial sectors. Other experiences include:

- Discovering the pitfalls of their business and learn more effective management strategies. The benchmarking exercise has given a better insight for improving productivity and quality of products.
- The international collaboration itself was an exercise in giving the consortium real insight on how multi-disciplinary teams could be managed, how data can be shared amongst teams from different domains, and how conflicts amongst team members can be resolved.
- The feasibility study has addressed a number of research areas, which need further investigation in order to fulfil the requirements for establishing a GCE environment. It has also identified some of the shortfalls and reasons for why visionary objectives could not be achieved.

The consortium members have learnt that dealing with this type of projects requires clear and strong project management strategy.

## 8. Conclusions

The study has shown that CE is a strategy which aims to increase market share, customer satisfaction, and reduces product lead-time. A key step towards implementing CE is effective cross-functional teams, which integrate the development process using both organisational and information management methods. Effective teams require a supportive managerial and organisational environment. The importance of managing teams and increasing responsibilities at teams level to convince people in advance with the benefits of the CE concept are substantial. An infrastructure for transferring technology together with the coordination of the product development processes is crucial elements for implementing concurrent engineering. The infrastructure would determine the degree to which data from customers, suppliers, and other business functions can be meaningfully organised and accessed by the development team members. This enables the team members to create a common understanding of the product and their related processes. This research area has shown its necessity and further study seems worthwhile.

## Acknowledgements

This research article describes the state of the art of the collaborative research work carried out by the consortium members of Test case 3 of the IMS programme. The author acknowledge the contribution of the following: J.A.G. Knight – De Montfort University, M.S. Ahmed – IMS Ltd, Andrew Young – Northern Telecom, Linda Moffat and Donald Gerwin – Carleton University, Peter O'Grady and Robert Young – North Carolina State University, Risto Lehtinen – Nokia Corporation, Johan Vesterager – Tech Univ. of Denmark, and Jan Tuxen – Odense Steel Shipyard.

## References

[1] F. Londono, C. Nichols, I. Karandirkar, R. Reddy, Co-ordinating a Virtual Team, CERC-TR-RN-92-005, Concurrent Engineering Research Centre, WVU, Morgantown, WV, 1992.

[2] Information Sharing Systems Manual (Release 1.0), CERC-TR-RN-93-026, Concurrent Engineering Research Centre, WVU, Morgantown, WV, 1992, pp. 107.

[3] B. Prasad, R. Morenc, R. Rangan, Information management for concurrent engineering: Research issues, Concurrent Engineering: Research and Applications 1 (1993) 3–20.

[4] B. Prasad, Concurrent Engineering Fundamentals, in: Integrated Product and Process Organisation, vol. I, PTR Prentice-Hall, Upper Saddle River, NJ, 1996.

[5] C. O'Brien, Organisational and methodological issues for concurrent engineering in extended enterprise, ESPRIT – Advanced Course on Concurrent Engineering: The Next Generation, Commission of the European Communities, (1992).

[6] P. O'Grady, R. Young, A. Greef, L. Smith, An advice system for concurrent engineering, International Journal of Computer Integrated Manufacturing 4 (2) (1991) 63–70.

[7] S. Dowlatshahi, Product design in a concurrent engineering environment: An optimisation approach, International Journal of Production Research 30 (8) (1992) 1803–1818.

[8] S. Finger, S. Fox, Concurrent design, Applied Artificial Intelligence 6 (3) (1992) 257–282.

[9] A. Shekhar, F. Azadivar, Customer driven concurrent engineering for manufacturing systems, Proceedings of the 14th, International Conference on Production Research, Osaka, Japan, vol. 1, 1997, pp. 1172–1175.

[10] CONSENSE (Concurrent/Simultaneous Engineering System), ESPRIT III: EP 6896, Commission of the European Community, 1994.

[11] O. Senechal, C. Tahon, A modelling approach for production costing and continuous improvement of manufacturing process, Journal of Production Planning and Control 8 (8) (1997) 731–742.

[12] J. Glover, R. Rolen, VanBibber, Expert R&D design synthesis an enabling technology for concurrent engineering, Computer-Aided Co-operative Product Development MTI-JSME, 1991, pp. 487–501.

[13] R.K. Gay, P.K. Seet, S. Lee, Network-based concurrent design environment for distributed-based CAD, Computing and Control Engineering Journal, 1993, pp. 253–267.

[14] C.J. Oh, C.S. Park, An economic evaluation model for product design decisions under concurrent engineering, Journal of Engineering Economist (USA) 38 (4) (1993) 275–297.

[15] A.S. El-Gizawy, J.Y. Hawang, D.H. Brewer, A Strategy for Concurrent Product and Process Design of Aerospace Components, Design Productivity Centre, University of Missouri, Columbia, MI, 1989.

[16] H. Abdalla, An expert system for concurrent product and process design of mechanical components, Journal of Engineering Manufacture (IMechE Part B), 208 (1994) 167–173.

[17] K.S. Pawar, B. Haque, R.J. Barson, Organisation improvement through process analysis for concurrent engineering using the 'PACE' organisational modelling tool, Proceedings of the 14th International Conference on Production Research, Osaka, Japan, vol. 1, 1997, pp. 1184–1187.

[18] R. Rohatynski, Human Oriented Approach to Computer Supporting for Concurrent Engineering in Distributed Enterprises, 1988, pp. 3–14.
[19] T. Fernando, P. Dew, F. Gao, Constraint-Based Interaction Techniques for Supporting a Distributed Collaborative Engineering Environment, Iowa City, USA, 1995, pp. 265–270.
[20] H. Hayashi, A preview of the 21st century, IEEE Spectrum (1993) 82–85.
[21] S. Chambers, I. Pickering, Competitive benchmarking: Progress and future development, Computer-Integrated Manufacturing Systems 4 (2) (1991).
[22] ESPRIT Project 7752, Deliverable 2.1 Data Analysis and Results, 1994.
[23] I.D. Marinescu, J.P. Lavelle, Innovation and globalisation of manufacturing 2000, Proceedings of the 14th International Conference on Production Research, Osaka, Japan, vol. 1, 1997, pp. 30–33.
[24] ESPRIT Project 7752, Deliverable 3.2 Architecture for Global Concurrent Engineering System, 1994.
[25] K. Nichols, A. Pye, C. Mynott, UK Product Development Survey, The Design Council Publication, London, UK, 1993.