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Practical Applications of Set-Based Concurrent Engineering in Industry

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Set-Based Concurrent Engineering is sometimes seen as a means to dramatic improvements in product design processes. In spite of its popularity in literature, the number of reported applications has so far been limited. This paper adds new information by describing implementations of Set-Based Concurrent Engineering in four product developing companies. The research took a case study approach, with the objective to investigate if the principles of Set-Based Concurrent Engineering can improve the efficiency and the effectiveness of the development process. The study shows that set-based projects can be driven within an existing organization, if given proper support. The participants claim that a set-based approach has positive effects on development performance, especially on the level of innovation, product cost and performance. The improvements were achieved at the expense of slightly higher development costs and longer lead time. However, the positive effects are dominating and the companies involved intend to use Set-Based Concurrent Engineering in future projects when appropriate.

Keywords: set-based concurrent engineering, set-based design, design method verification, lean product development, case study, industrial collaboration.

0 INTRODUCTION

Set Based Concurrent Engineering, SBCE, is a product development methodology that has been subject to considerable interest [1] to [9]. Some authors claim SBCE to be four times more efficient than traditional phase-gate processes [4] to [6]. In spite of the vast body of related research, the published applications of SBCE have so far been limited to the primary study at Toyota Motor Corporation where the methodology was developed and discovered [1].

According to literature [1] to [11], SBCE has many organisational implications, requiring most processes and working methods to be changed. It is considered a highly integrated part of the “Lean Product Development System” [4] to [6]. The lean development system uses different means for management of staff and projects and decision making. In the lean development context, “set-based” is synonymous to working with multiple solutions simultaneously, systematically exploring trade-offs between different alternatives and the use of visual knowledge.

In the view of traditional development, a Set-based approach can be considered inefficient [7] which requires a shift in the view of design: SBCE starts with multiple design alternatives, but opposed to traditional design, it allows more than one the design to proceed concurrently. Decisions are made by eliminating the weakest designs, allowing the process to narrow in slowly on a solution. Since SBCE is usually considered incompatible to traditional models [4] to [6], practical applications of SBCE in companies using phase-gate model could be challenging.

1 RESEARCH APPROACH AND RELATED LITERATURE

The framework for research was based on six pilot cases in four firms. An active research strategy was used with workshops at the participating companies, studying the development costs and use of resources, the characteristics of the resulting products and development process metrics.

The purpose was to improve the product development processes of the companies. The objective was to investigate if the Set-Based Concurrent Engineering principles could be implemented successfully in different environments, and to observe the effects on the development process.

1.1 Research Approach

The research approach was inspired by DRM; Blessings framework for Design Research

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Methodology [12]. In the study, the first three steps of DRM were already carried out through the discovery and formulation of SBCE. One difficulty was that the original success criteria were not known. However, in DRM most criteria are formulated in order to support the initial research process: the descriptive study was already published by Ward [1] and [8], and the prescriptive study resulted in the formulation of the principles of SBCE [7]. The remaining criteria are formulated to verify the findings in the prescriptive study. In this case this meant to find criteria that show to what extent the three principles lead to more successful products, and/or a better development process, and at what expenses.

1.2 Related Applications of Set-Based Concurrent Engineering

The research process started with a survey of academic and other literature, concluding that the SBCE- principles are not widely used. Except from the original case [1] to [3], only the use of single principles has been recorded in industry. The first theoretical description of Set-based design was made by Ward [13]. Through studies of Toyota's product development processes, the term SBCE was established [1]. Later, the research diverged into different directions and the term "set-based" now has a different meaning for different authors.

A common application is the mathematical modelling or optimisations of some aspects of product development [14], sometimes in an industrial collaboration [10]. Another application is the management of product development. According to Morgan [5], SBCE is an important component of the lean framework. Ward [4] and Kennedy [6], characterise SBCE as one of four components of Lean Product Development. Different branches of "Lean development" have evolved, based mainly on results from the primary SBCE research, and on the work of Womack et al. [15] and [16].

There are also prior scientific studies of related industrial implementations in the "Lean Aerospace Initiative" [17], but is does not address the same questions as the SBCE principles. The focus in these projects has been to re-engineer the development process by identifying waste and maximizing value-adding activities, or improving the information flow and the reduction of engineering cycle times.

So far we have not found any scientific studies of SBCE implementations in companies except from the original case [1] to [3]. However, one article [10] uses input from industry to model and optimise a product and hereby apply parts of SBCE in the form of multiple solutions and broad specifications. A comprehensive survey of Lean engineering in industry is written by Baines et al. [18].

1.3 Project Management of Set-Based Concurrent Engineering

Project management in SBCE is different from the practices of Concurrent Engineering, using a strict functional organisation [1] to [6]. The author would like to emphasize that this is a contradiction to the Concurrent Engineering approach [2] and [19]. Here, constraints from all departments are considered at the beginning of the process and projects take over responsibilities traditionally owned by the functional units.

The Set-based development process converges step-wise towards a solution acceptable by all stakeholders through a series of "integration events". These are decision points equivalent to traditional gate-reviews, however the purpose is not to report and act on project status but rather to trade-off and to eliminate solutions by using available data and knowledge of the product. If there is not enough information available to exclude a solution confidently, it will remain in the set to be further investigated. Contrary to gate-reviews, integration events can be held at different times or locations for different subsystems.

1.4 The Three Principles

SBCE relies on three principles [7]. This implies that SBCE needs to be adapted to each individual firm. Even though the principles are simple, they provided a useful guideline for the practical adaption of the firms design processes:

1. Map the design space:
   - define feasible regions,
   - explore trade-offs by designing multiple alternatives,
   - communicate sets of possibilities.
2. Integrate by intersection:

- look for intersections of feasible sets,
- impose minimum constraint,
- seek conceptual robustness.

3. Establish feasibility before commitment:
   - narrow sets gradually while increasing detail,
   - stay within sets once committed,
   - control by managing uncertainty at process gates.

The first principle implies a wide search for possible solutions without taking the needs or opinions of other departments into account.

The second principle integrates different solutions by eliminating those that are not compatible with the main body of solutions.

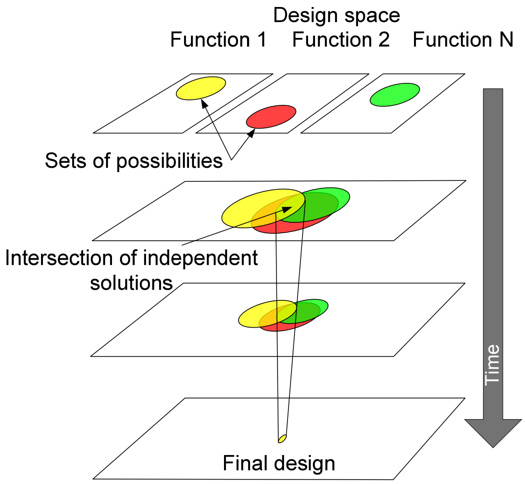

Fig. 1. *The principles of Set-Based Concurrent Engineering (adapted from[9])*

The last principle is a commitment to develop solutions that both, matches the other sets and fulfils current specifications. Elimination of remaining solutions is done by repeated development, tightening of specifications and application of the second principle.

In Fig. 1, a "set" represents a palette of different solutions to a specific function or problem and can be seen as a family of design proposals. This is opposite to the widely used traditional "Point-based" [1] development methodology, where the selection and approval of one "best" specific product solution is done early when the knowledge of the product is shallow.

1.5 The Decision and Specification Management Process of Set-Based Concurrent Engineering

SBCE uses a different approach than traditional point-based selection: instead of using different methods for ranking and selecting one or a few concepts for further development, the SBCE decision process is based on a rejection of the least suitable solutions. Rather than making an educated guess of the performance of a future design, SBCE carries forward all implementations that cannot yet be eliminated. This is a robust process since the consequences of an incorrect choice are fairly small. Rejecting the third worst solution instead of the worst is less critical compared to the magnitude of failure if the third best alternative is picked for development instead of the best.

An industrial case study [11] described the SBCE decision process and concluded that the method gives different results compared to a traditional Pugh method of controlled convergence.

Another aspect is the efficiency of the SBCE decision process. Contrary to the selection of alternatives, the elimination of alternatives can be done confidently from incomplete information, as long as it is based on facts of what is not possible.

The management of specifications is also an important distinction from traditional development [2]. This approach aims at an optimal system design, rather than an optimization of components under fixed constraints. In SBCE, the individual requirements are not fixed numbers but rather a range of upper and lower limits representing the design space.

This extra degree of freedom allows designers to compromise on different aspects. The requirements are gradually narrowed down to a final value, but are flexible during the process.

2 CASE STUDY SETUP

The study was a three year joint-venture between Swedish industry, the School of Engineering in Jönköping and the Swerea IVF research institute.

Information was collected from semi-structured interviews with managers and design engineers, through studies of documents, and by a questionnaire at the end of the projects. Other data sources were the working meetings at individual companies between project members and researchers.

2.1 Company Characteristics

The companies have different sizes and represent different types of businesses, as seen in Table 1. One common characteristic is that all of them have a large proportion of engineers compared to other types of employees. The companies also have a small share of outsourcing of design and none of them was using Lean Product Development tools to a significant extent.

Company A designs, sells and produces electronic equipment for traffic monitoring and control. The systems consist of mass produced units placed in vehicles plus an infrastructure that collects data for invoicing. The customers are cities or governments and the systems are tailor made for each application. All manufacturing is outsourced, but most of the design and software development is done within the company.

Company B designs, sells and produces equipment for paper mills and graphic industry on the international market. The products are customized and manufactured in low volumes, where local suppliers make components and modules. The final assembly, programming and testing is done in-house prior to shipping. Installation at the customer sites is usually done by the same people that assembled the product at home.

Company C is a first tier automotive supplier with in-house production and design capabilities. The products are built to manufacturer specifications around a core technology. The customers select suppliers by quoting and usually the lowest bidder wins the deal. Most of the production is highly automated with manual final assembly according to Lean Production principles.

Company D is a manufacturer of heavy trucks and engines and the majority of the design work is done on one central site. The company is refining its product development methods and has continuously invested resources in different improvement projects. Manufacturing is carried out with Lean Production practices in plants around the world.

Table 1. *Company characteristics and project goals*

	Company A	Company B	Company C	Company D
Business	Electronic systems	Graphic industry products	Automotive supplier	Heavy trucks
Business size	Small	Small	Medium	Large
Type	Orig. Equipm. manuf.	Orig. Equipm. manuf.	First tier supplier	Orig. Equip. manuf.
Customer adaption	Tailor-made	Modular design	Tailor-made	Modular design
Manufacturing volume	High	Low	High	High
Outsourced mfg vol.	Large	Large	Low	Low
Business tech. speed	High	Low	Low	Low
End user adaption	Mass produced, individually programmed	No	No	Modular adaption
Number of pilot projects	1	2	1	2
Pilot project purpose	Develop product	Develop product	Pre-study	Develop subsystem
Project 1 results	Product on the market	Product on the market	Product knowledge	Under development
Project 2 results	-	Product knowledge	-	Under development

2.2 Project Setup

For each participating company, a strategy for implementing SBCE was developed based on the current process. The projects were supported from upper level management, and the teams were allowed to bypass the ordinary development processes whenever appropriate for the project. A core team of managers and engineers from across the organization was given an introduction to SBCE. This created a broad acceptance for the methodology and served as a platform for finding appropriate pilot cases.

Based on the company's current development practice an outline for the implementation of SBCE was suggested by the researchers'. In cooperation with the firms, the outline was further refined and adjusted to individual cases. The researchers also introduced the companies to tools and methods for different tasks in the projects, and information of practices from the parallel cases was spread between the firms.

The current development practices were already documented in design manuals or in the project models. It was found that the participating companies used phase gate development models, freezing the concept or product structure at early stages of development. This indicated a commitment to an early design which did not fit the SBCE principles, and changes to the project models were made.

2.3 Development Metrics

To be able to evaluate the effects of SBCE with a reasonable effort, it was decided to explore readily available information. In our case, the companies were interested in two questions:

1. Is SBCE improving the chances of creating successful products compared to the current development model?
2. Is SBCE improving the efficiency of the design process compared to the current development model?

The intentions were that the metrics should cover different aspects. Some metrics were already used in current development, such as project cost, product cost and project lead time. Other familiar aspects were the risk of project failure and the performance of the product in relation to requirements.

Two metrics were found in literature [20]. These were the number of unwanted engineering changes and warranty costs. The two last metrics were suggested by the researchers, evaluating the robustness to specification changes and the level of innovation.

The future expectations on the methodology were also investigated. The purpose was to understand why the participating firms believe that SBCE will affect the product development performance in subsequent projects.

3 IMPLEMENTATIONS AND RESULTS

In order to apply the principles of SBCE on the pilot cases, changes were made to the product development processes. The purpose was to match the intentions of the principles to the different models of development in each company. The implementation also included changes of practical working methods and decision-making.

3.1 Adapting Current Design Processes to the Set-Based Concurrent Engineering Principles

Map the design space: The first two steps, "Define feasible regions" and "Explore trade-offs by designing multiple alternatives", was not new to the designers. Innovative exploration of the design space was seen as the natural start for any design work. However, in SBCE this extends to the design space of all technical disciplines. Exploring trade-offs is not a specific SBCE tool but is used systematically. Nevertheless, it was not a common practice to systematize project-specific results of tests and simulations into general graphs.

Communicating the sets of possibilities by sharing unfinished designs was somewhat awkward in the sense that designers are used to present one well-founded technical solution.

Integrate by intersection: Looking for intersections of feasible sets was a straightforward task in most cases. In some pilot projects the sets were developed by different organizational functions such as electronics, software or mechanics. When the sets of different functions were brought together it was possible to identify solutions incompatible with the main core. Imposing minimum constraint meant to start with setting a broad target for the most important specifications of each set and leave the rest unconstrained. The conceptual robustness was achieved by promoting solutions to sub-systems that were insensitive to changes in other sub-systems.

Establish feasibility before commitment: Narrowing the sets is a key feature of SBCE, which can be carried out in different ways depending on the maturity of the evolving product. This corresponds to the "screening" and "scoring" events found in textbooks on product development. In the projects, narrowing was typically done by the results of tests and by the adjustment of specifications. When the number of solutions in the sets decreases, more effort is put on each solution to increase the level of detail. When many solutions can satisfy the specifications, more constraints are added and alternatives eliminated.

Staying within the committed sets ensures that all solutions match the sets developed by other departments, and that no expansion outside the specifications will occur.

Control of the development process was done by a gradual review of specifications, continuously or at the process gates. Since requirements are tightly integrated with each other, and evolve with the product, there is no way of knowing all the final values in advance. In one pilot project, there were three final designs and the choice was made after producing three different series of products and evaluating their performance.

3.2 Data Acquisition and Processing

Information gathered from interviews and the questionnaire were compared to the company standard development. The respondents were senior designers or managers with extended experiences of product development. On each parameter, the results were given 1 point if SBCE created a better result than current development practice, 0 points if the output was equal and -1 point for an inferior output. The average and individual values were plotted in diagrams, and the average value will be one point if all companies are experiencing improvements on a parameter.

In some cases, parameters had to be estimated since not all projects have yet reached the market. The estimates were made by experienced engineers and managers based on the project results thus far, assuming that the remaining part of the project would follow the same path as the first.

3.3 Effects on Costs and the Use of Resources

The effects on project lead time, development costs and product cost is displayed in Fig. 2.

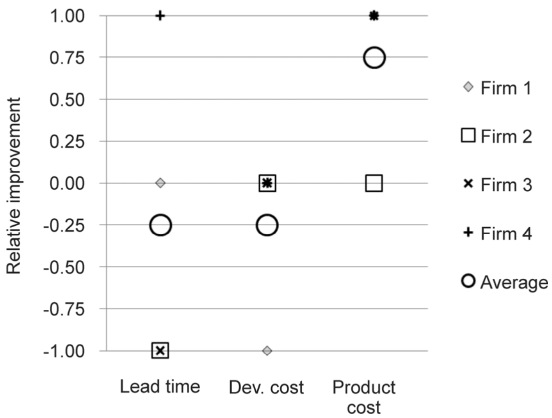

Fig. 2. *Costs and use of resources; a positive result indicates an improvement compared to the current development practice*

Lead time: The pilot projects had slightly longer lead times than comparable projects. There could be many reasons for this, but one reason mentioned by the engineers is that they are not used to this way of working. An extensive documentation also took more time than usual.

Development Costs: In all projects extra resources were allocated to enable thorough exploration of parallel solutions in early phases of development. This caused the pilots having slightly higher average development costs compared to standard projects. One manager commented that the budget increase was surprisingly small compared to the increased knowledge of the product.

Product cost: In all but one project, the product costs were reduced. One of the companies reported a 40% decrease in product cost compared to the initial calculated cost. This was achieved by having high-risk product architecture with inexpensive components in parallel to safer alternatives. The thorough evaluation of multiple combinations proved that the low-cost solution was good enough.

3.4 Effects on the Product Characteristics

The effects on product performance, the robustness to changes of requirements and on the level of innovation are displayed in Fig. 3.

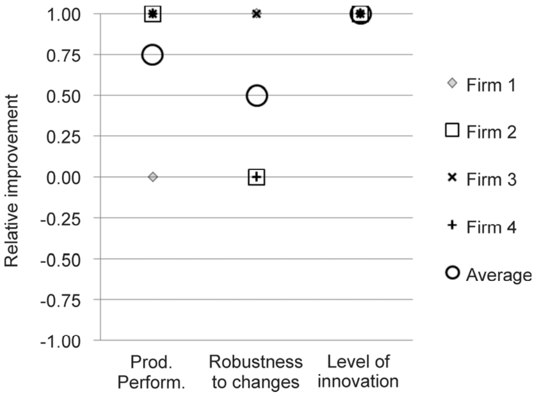

Fig. 3. *Product characteristics*

Product performance: In all but one case, the performance was improved compared to the output of their regular methods. In the case where performance was not improved, the company responded that once the specifications were met, the focus was to decrease the cost of the product.

Robustness to changes in specifications: In the study, the robustness was improved by the SBCE decision principle, and by the knowledge of key characteristics gained through the evaluation of different solutions.

Level of innovation: All companies responded that the innovation level of their projects was improved. Again, the main reason mentioned was the parallel solutions. Carrying a safe option in the set as it makes it easier to also develop an innovative version.

3.5 Estimated Effects on the Development Process

Based on the project results thus far, the effects of SBCE on the development process were evaluated (Fig. 4). These parameters are a result of the product development process, but are not available until the product has been produced and used. Therefore, estimations had to be made in the cases where the products were not yet manufactured. The firms estimated the project risk, warranty costs and the number of engineering changes in ongoing production.

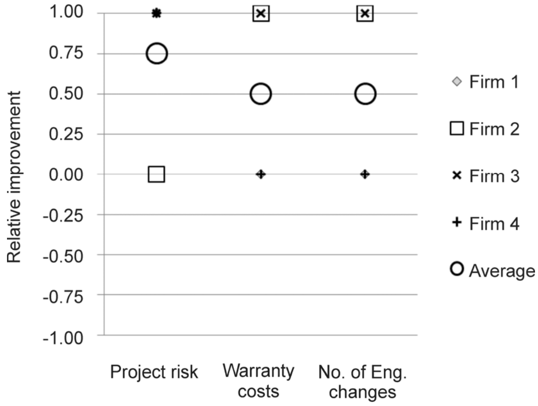

Fig. 4. *Estimated development process metrics*

Project risk: The estimated risk of project failure was considered to be improved in all but one case. In the last case, the manager argued that SBCE does not improve the level of risk in cases where previous knowledge cannot be used, so the project risk is equal to the risk of the current practice.

Warranty costs: Based on the confidence in technical solutions created in the projects, the participants answered that their warranty costs would improve moderately in the future.

Number of engineering changes: The amount of unwanted design changes to ongoing production was also estimated to be better than current practice. One comment was that all the solutions were evaluated from different points of view, rather than selecting one alternative for review.

3.6 Future Expectations

Another way of investigating the usefulness of Set-based principles is to see if the companies intend to use SBCE in future projects. The view is optimistic (Fig. 5), and all participants will use the methodology in upcoming projects where appropriate.

Lead time: Most companies expect that SBCE will give them shorter lead-times in the future. One reason for this is the improvement in failure rate seen in the pilot projects, and the fact that the organization will learn the different practices and, therefore, work faster. Most companies also argued that the increased amount of reused experiences from prior projects would also speed up the projects, but none of the pilot companies had implemented new routines for capturing design knowledge.

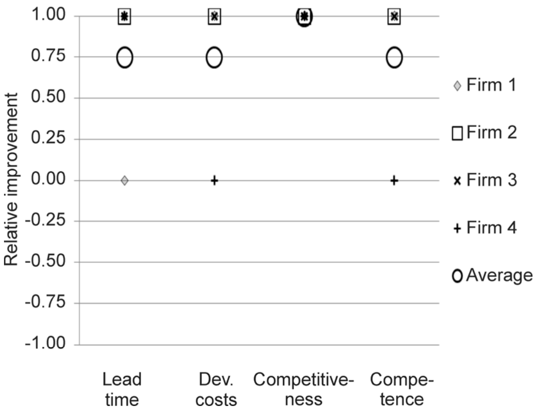

Fig. 5. *Future expectations on SBCE*

Development costs: Future development costs are also considered to be lower than today. One company commented on how SBCE gave stability to the product development process that helped them to avoid expensive mistakes.

Competitiveness: All companies expected their competitiveness to increase in future projects.

Proficient personnel: The companies believe that SBCE in the future will create more proficient engineers. This optimistic view is based on the assumption that the engineers will somehow capture more useful knowledge form the exploration of parallel solutions.

3.7 Comparison to Earlier Studies

A study introducing Concurrent Engineering in industry [19] arrived at the conclusion that a change in development practices must be backed up by the management. This statement is also found in other literature [4] to [6], [9] and [18], and our projects arrived at the same conclusion.

No firms had Set-based development processes before the pilot projects. This observation is well-aligned with earlier surveys [9], concluding that Set-based practices are not well established in industry.

Another feature of SBCE is the reuse of design knowledge [1] to [6]. In our study, the documenting process was ad hoc, depending on individual incentives. There is, therefore, no support for a higher degree of knowledge reuse, or more knowledgeable employees.

A Set-based strategy is recommended for complex systems [2], and a Point-based strategy for stable, well-understood environments. In the study, the designers state that a Set-based approach is preferable at most times, not just for complex problems. This gap in opinion needs to be resolved in order to find reliable criteria for choosing between these different development strategies.

4 RECOMMENDATIONS FOR THE INTRODUCTION OF SET-BASED CONCURRENT ENGINEERING

At the beginning of the study, there were six participating companies. Two of them were not successful. The reasons could be that the implementation of SBCE did not give expected results, but in the opinion of the author, the main reason was that none of the companies had ensured commitment from the management. Hence, to introduce SBCE, a prerequisite is an appropriate support from within the organization. A full scale introduction in a firm is more complicated than a pilot study: it requires fundamental changes in development- and business processes as well as training for all personnel. A summary of the recommendations for introducing SBCE is found in Table 2.

4.1 When Should Set-Based Concurrent Engineering Be Used?

In the opinion of the designers, a Set-based approach could, and should, be used at most times. The exceptions are very small projects, with an obvious solution and tight schedules.

The participants mentioned applications where SBCE would be extra valuable compared to the processes used today: Projects containing unproven or new technology were seen to have a large potential for SBCE. Two main reasons were mentioned: The parallel development of members in the different sets reduces the statistical rate of failure. The robust method of selection increases the chances of developing the right alternative. Another suitable application is the case of unstable market requirements, or when the customer provides unclear specifications. Also, for situations where there is a potential for innovation was mentioned: SBCE enables the introduction of innovations in products by eliminating the trade-off between risk and innovation.

4.2 Barriers for the Implementation of Set-Based Concurrent Engineering

One of the barriers found in the study are the tight schedules from current parallel projects, resulting in focus on short term necessary activities. Allocating time and resources on implementing new methods is not sufficient to achieve success; priority from management must also exist.

The current design processes can also hinder the implementation. The first implementation of SBCE in Company C by a re-engineering of the design process was not successful. The approach was to add checklists and tasks derived from the SBCE principles to the standard development process. In the next attempt the designers only used methods that seemed to suit the tasks at hand, with satisfying results.

Another barrier is the attention to the wastes occurring in the design of many parallel alternatives. Designing one fair solution is enough for most applications, however, it is based on the assumption that it is possible to find and select the correct solution before actual development.

The case of not controlling the specifications is a hard barrier for the introduction of SBCE. For company C the value of the SBCE project was to identify the knowledge gaps in their core technology. Knowing the limits of their technology will make it possible to have an appropriate set of solutions ready for future offers.

Also, human barriers were identified: some people may not be interested in changing the way they work, for example to communicate unfinished designs.

5 CONCLUSIONS

This study shows that Set-based projects can be implemented within an organization practicing traditional product development with phase-gates.

The participants claim that SBCE has positive effects on product development performance and on the resulting products. The improvements are especially dominant on the level of innovation, product cost and product performance.

Table 2. *Recommendations for the introduction of Set-Based Concurrent Engineering in pilot projects*

Recommendation	*Description*
Sidestep current dev. Practices	Allow teams to bypass the standard development processes whenever appropriate. Avoid freezing concepts or product structures at early stages of development.
Train engineers and managers	Create a broad acceptance for the methodology by training a core team of managers and engineers. Only select individuals that are willing to participate.
Adapt and use the three principles	Match the intentions of the principles to the tasks at hand, without taking any short-cuts.
Allow flexibility in specifications	Set broad target initially for the most important specifications and leave the rest unconstrained. Use loosest possible constraints to create flexibility.
Narrow sets step-vice	Gradually reduce the size of the sets as soon as information is available.
Decisions by elimination	Reject solutions on tangible reasons only. Base decisions on results of tests, simulations, technical data, trade-off curves or other knowledge.
Include a low-risk member in each set	Use back-up solutions for innovative or low-cost members of a set.
Avoid process design	Postpone the formulation of a new development process until the experiences of SBCE are clarified.

The improvements were achieved at the expense of slightly lower efficiency, measured in terms of development costs and lead time. However, for future projects, the firms are also anticipating SBCE to create more proficient engineers. This opinion cannot be supported by this study: no firm has implemented new means for capturing and reusing knowledge and experiences.

At one point the project results differ substantially from the results in literature: some authors claim that SCBE and other practices from the Toyota product development system can quadruple the productivity of the design process [4] to [6]. Even though improvements of this magnitude were not seen, the companies will continue to use SBCE in the future. At present, one of the firms has started to implement SBCE with the goal to put it into practice in the whole of the organization. Future studies will show if SBCE can live up to the high expectations for projects to come.

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