Set-based design – the lean tool that eludes us; Pitfalls in implementing set-based design in Kongsberg Automotive

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Abstract. This paper is based on a five month research project performed at the company Kongsberg Automotive (KA). It describes a study of the implementation of set-based design in project processes in KA, results from the study, and evaluations of these results. The focus has been on knowledge gaps in relation to the implementation of set-based design. Data has been gathered through observations, discussions with and feedback from employees, interviews and surveys, as well as literature research in order to evaluate the implementation of set-based design. A set-based approach has also been used in this research through the development of a set of theories that were investigated in an effort to disprove them or create a basis to support the probability of the theory being correct.

Through this project it has become clear that there are variations in the employees' knowledge on what set-based design entails. Data show that there is far more agreement on potential goals and benefits of the implementation. This indicates that the employees know where they are going, but that there is some ambiguity as to how to get there. This could be resolved through clarification of the elements of the process and clarification of how the company wants to achieve its goals.

Introduction

Toyota has been applying set-based design for decades, and the positive results have been reported in several books and articles (Kennedy, Harmon and Minnock) (Sobek and Ward) (Sobek, Ward and Liker) (Ward, Liker and Cristiano) and (Zayko). There is however a lack of research and knowledge concerning the challenges and pitfalls of implementing set-based design in other companies.

KA employees have been introduced to the concept of set-based design as part of the company's new Knowledge Based Development (KBD) processes. Three pilot projects are currently applying and "testing" these new processes. These projects have created a great stage for doing observations and research on the implementation of set-based design in a company that is different from Toyota in many aspects.

Kongsberg Automotive

Kongsberg Automotive is a global provider of engineering, design, and manufacturing for seat comfort, driver and motion control systems, fluid assemblies, and industrial driver interface products. Its product line includes systems for seat comfort, clutch actuation, cable actuation, gear shifters, transmission control systems, stabilizing rods, couplings, electronic engine controls, and specialty hoses, tubes and fittings. It targets the automotive, commercial vehicle and industrial markets (Kongsberg Automotive).

Figure 1 Kongsberg Automotive Organizational chart (Kongsberg Automotive)

The three pilot projects that are testing the new processes are all projects within the Actuation and Chassis business area (Figure 1). However the projects belong to different sub-groups within this area. The first project (project A) belongs to the Driveline Control Systems group, the second (project B) belongs to the Concept and Strategic Product Assessment group, and the third (project C) belongs to the Vehicle Dynamics group. All three projects are in different phases of development, and two of them were already well underway in development when they were chosen as pilot projects for the new processes.

The focus of this research has been on problems and challenges the company is faced with in the implementation of set-based design, since in many cases that is where one can learn the most valuable lessons. What should the company look out for, and how could it adjust the implementation to fit this company in particular? In order to answer this question, a decision was made to focus on what could stop the company from getting the desired results from implementing set-based design. That way, the company will hopefully have a better chance of avoiding the pitfalls in order to get the full benefits of using set-based design.

Therefore, the final goal of this project was to answer the question: "What can inhibit successful implementation of set-based design in KA?" Part of the goal was also to make recommendations based on the results from the study, and point out issues for further study.

A general overview of set-based design

Set-based design is often compared to what is called point-based design. In essence, these are methodologies in the product development process, and describe two different ways of arriving at the final concept design.

Point-based design can be described as a process where the development team either starts with or quickly narrows down to one design solution. It is called point-based because the first chosen concept is considered a "point" in the solution space (the solution space being the range of possible solutions that satisfy all constraints). Through iterations of the concept design the development team tries to move the point closer to the concept that satisfies all stakeholder needs and requirements (Ward, Liker and Cristiano). Sometimes development teams encounter problems that halt the progress, and having only one concept they have to go back and re-design. This is called loop-backs. The later in the project this happens, the more cost it entails.

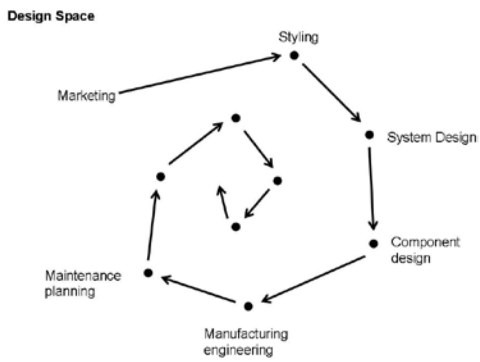

Figure 2 Point-based design, based on (Ward, Liker and Cristiano)

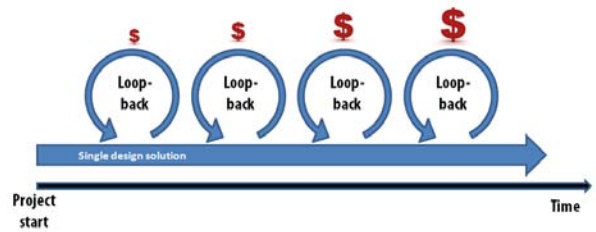

Figure 3 Point-based design with a single design solution with possible loop-backs

In set-based design, on the other hand, more effort and resources are used in the process of narrowing down to the final concept. Allan Ward states that multiple alternatives for both system and subsystems are to be explored, and narrowed down through aggressive test and analysis to "kill" the weak concepts. The theory is that through this process, only robust solutions will remain, and the development team will dramatically increase innovation and reduce risk (A. C. Ward).

Set-based design is often referred to as "set-based concurrent engineering" (SBCE), which is the term introduced by an academic team from the University of Michigan in 1995 (Ward, Liker and Cristiano). Ward et al. made an effort to clarify how concurrent engineering was done at Toyota. The authors detailed the following approach:

1. The team defines a set of solutions, rather than a single solution, at the system level.
2. They define sets of possible solutions for various sub-systems.
3. They explore these possible sub-systems in parallel, using analysis, design rules, and experiments to characterize those parts of the design space.
4. They use this analysis to gradually narrow the set of solutions, converging slowly towards a single solution. In particular, they analyze the possibilities for the subsystems to determine the appropriate specifications. Both Toyota's engineers and Toyota suppliers described an extensive negotiation process.
5. Once they have established the single solution for any part of the design, it is not changed unless absolutely necessary; in particular, the single solution is not changed to gain improvements (i.e. to climb the optimality hill).

In working this way, Toyota is not only front-loading its development process, but also delaying key decisions, which, paradoxically, results in faster product development. The purpose of the front-loading is to identify all possible problems and to resolve them early on in the process, long before "the clay freeze". By nature, it is a messy process, given to ambiguity and negotiation. Ultimately, conflicts tend to be resolved by returning to "customer satisfaction" criteria (Ballé and Ballé).

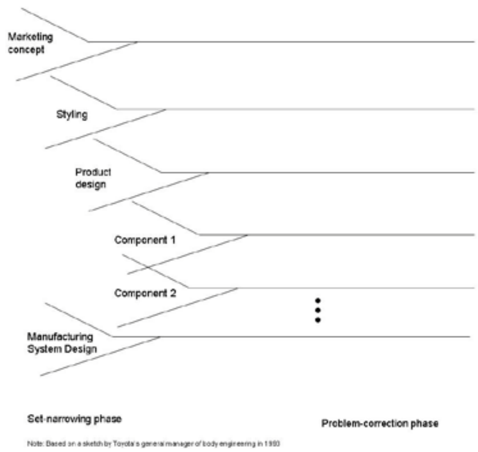

Figure 4 Toyota's parallel set-narrowing process, based on (Ward, Liker and Cristiano)

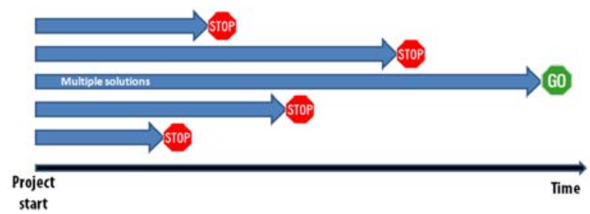

Figure 5 Set-based design – exploring multiple design solutions

SBCE considers the design perspectives proposed by different functions, and converges towards the acceptable range of overlapping sets before selecting the best one. The following Venn diagram illustrates this perspective. "By front-loading the design phase, overlaps are identified in the acceptable range, minimizing future design and engineering changes further downstream, as well as eliminating a great deal of waste in the early stages of product design" (Zayko).

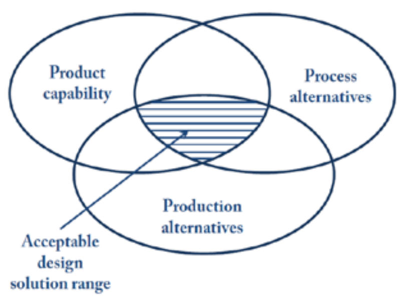

Figure 6 Set-based considerations of different parties, based on (Zayko)

Pit-falls in the implementation of set-based design

It is currently a challenging task to find literature describing the pitfalls of implementing set-based design. In general, most of the relevant literature provides support for the notion of set-based design, but the studies of industry provide minimal guidance on how actually to perform it (Malak, Aughenbaugh and Paredis). Usually the texts describe how different elements of the method can generate various positive outcomes. The idea that development processes need to be loaded up-front in order to avoid the usual delays and overspending at the tooling and Start Of Production phases has been around for a long time and tried many times, but it is often unclear in traditional development processes exactly how this should be done (Ballé and Ballé).

Even though it is a challenge to find literature that says something explicit about pitfalls in the implementation of set-based design, review of literature that is to a greater or lesser degree related to the subject, reveals some pointers on possible pitfalls.

One of these pointers relate to how people often deal with problems. "People tend to naturally try to "go around" problems, which means find a quick fix so as to continue to work, rather than try and sort out the fundamental issue" (Ballé, Beauvallet and Smalley). In set-based design, the problem-solving strategy used entails a learning cycle that enables decisions to be based on knowledge instead of assumptions. One could assume that if problems are not dealt with the right way, this learning will never occur. This will in turn affect the possible benefits of working set-based, given that one of the benefits of working set-based is efficiency in development due to previously acquired knowledge. This knowledge can also be helpful in establishing baselines (i.e. a safe solution that is known to work, which can be used if alternatives fail). In addition, establishing baselines contributes to reducing risk when developing new products, so this benefit would be lost as well. In other words, "going around" problems can be particularly counterproductive when it comes to set-based design.

Repeated attempts by western automakers at encouraging concurrent engineering have failed in the past. Designers are often blamed for their apparent lack of concern for manufacturing issues, but it turns out that during "concurrent engineering" efforts to get functions to discuss the concept upstream, manufacturing engineering tends to expect drawings to be able to voice its opinion of the design – something of a catch-22 (Ballé and Ballé).

Allan Ward also suggests the use of comparison matrices in eliminating concept designs. This is a tool which can be compared to selection matrices, in which one compare concepts based on a given set of criteria, and choose one (or several) to develop (Ulrich and Eppinger) (SDOE 625). Several papers have been written on the subject of concept selection, and methods and tools have been proposed in order to enable designers and engineers to make the best selection possible. However, given that a design concept is an incomplete product description, the performance of a concept can only be characterized imprecisely (Malak, Aughenbaugh and Paredis). Therefore, comparison matrices will have to be based on the same imprecise knowledge, and reciprocal comparison and judgment might become difficult.

Another issue which has been pointed out in "The thinking production system" by Michael Ballé et al. on the implementation of lean tools (like set-based design) is that it is not enough to apply lean tools and principles to every process. The result would be a limited potential for lean transformation. It is argued that to achieve the full potential of the transformation one has to change the thought processes of every employee to develop kaizen (continuous improvement) consciousness. The paper discusses "frames," or "frameworks" which are the mental constructs through which we see, interpret and act on the world. The authors believe deep frames pervade the Toyota Production System (TPS) that fundamentally alter how the system is understood and therefore how to proceed with implementation. They argue that if managers and program leaders fail to understand the frameworks underlying TPS, they consequently miss the point of the tools and therefore fail to achieve the expected results.

The problem of successfully implementing set-based design in Kongsberg Automotive

Literature on the processes used by the Toyota Motor Company suggest that set-based design can make product development more efficient, reduce costly design iterations, and improve design quality, while reducing risk and time to market for the product (Ward, Liker and Cristiano) . One of the problems is that Toyota has used decades to develop and refine their processes to the state in which they are today, while other companies that have become aware of Toyota's successful methods would like to get the same results in a fraction of that time.

In order to increase the likelihood of success when implementing set-based design, it seems logical that the focus should be on what we do not know about this process and what challenges we might face; in other words a focus on knowledge gaps. Therefore, this thesis will try to answer the question: “What can inhibit successful implementation of set-based design in Kongsberg Automotive?”

The fact that people tend to “go around” problems could to some extent give an idea as to what could inhibit the implementation of set-based design. As explained earlier, Toyota front-loads its development process in order to identify all possible problems and to resolve them early before “the clay freeze”. They also use analysis, design rules, and experiments to characterize the design space (i.e. learn about possibilities and limitations). In other words, if people consistently “go around” problems and make decisions on e.g. gut feeling, this could have many adverse effects. For example, “going around” a problem could potentially solve the issue there and then if one is lucky. However, not knowing the root-cause of the problem and how to properly resolve it can lead to the problem reemerging at a later stage. In addition, the problem could turn up in other current or subsequent projects, and that could lead to the same problem having to be dealt with repeatedly. This “reoccurring problem”-issue is one of the inefficiencies that set-based design is said to counteract. However, declaring that people tend to “go around” problems is a very general statement. In addition, as part of the new processes, employees of Kongsberg Automotive have started using A3 analysis as a problem solving tool. “A3 analysis is considered core to the Toyota management system, and is a tool to identify the current situation, the nature of the issue, the range of possible countermeasures, the best countermeasure, the means (who will do what when) to put it into practice, and the evidence that the issue has actually been addressed” (Shook). Therefore the issue concerning “going around” problems does not answer the question of the thesis since it cannot be shown as being an inhibitor of successful implementation of set-based design in Kongsberg Automotive.

The catch-22 situation regarding designers’ lack of concern for manufacturing issues, and manufacturing engineers expecting drawings in order to voice their opinion on the design, describes a situation where lack of communication between design engineers and manufacturing engineers can cause hidden problems to emerge very late in the development and hence increase costs significantly. However, given the proximity of the production facilities to the design engineers in Kongsberg Automotive, the different means of communication, and observations of successful early communication between design and manufacturing engineers in this company, this is seemingly not a big issue. Therefore the probability of this occurring in this company is lowered, and hence this does not answer the question of the thesis.

As mentioned earlier, comparison matrices are suggested by some as a tool to be used in set-based design. Hence, problems concerning the use of comparison or selection matrices could also contribute to the failure of the implementation of set-based design. Following are some of the problems related to the use of these matrices that were experienced first-hand in one of the pilot projects. Choosing the *right* criteria is an initial challenge. In addition, rating was not straight forward since not all concepts were at the same level of “refinement”. Several people also expressed that it can easily be viewed as a calculation where one sums up the scores of the different concepts and the “winner” is the concept that gets to be developed further. This is a problem since a main benefit of such matrices is a gained awareness of strengths and weaknesses of the concepts, which you do not get from merely looking at the bottom line score.

Based on the experience the team had with the use of such matrices, the learning suggested that if misunderstood or used wrong, these matrices can in the worst case do more harm than good. But even though Alan Ward suggests this as a tool in set-based engineering, and several authors point out challenges concerning the use of such matrices, it has not been proven that this is an essential part of set-based design. It therefore does not create the basis needed to answer the question of the thesis.

What about the statement: “without the right framework to view the world, people will not reap the benefits of set-based design”? It does not sound unreasonable, but it cannot shed more light on the answer(s) to the question of the thesis without further investigations in the company of interest. Even though the preceding statements could be valid in many companies, they cannot necessarily be said to be valid or invalid in Kongsberg Automotive.

Implementing new processes in a company can be a challenging and risky task. There are many considerations to be made, and one should be fairly certain of resulting benefits that make it worth the time and effort. Implementing new processes entails an exploration of unknown territory where you can never be completely sure of the outcome. However there are steps one can take to reduce the risk. One of these steps is to investigate what could go wrong, and map out where there is a lack of knowledge with regard to the process that is being implemented.

In product development, risk reduction is a common challenge. It is inherently difficult to avoid the things we do not see, so the mere awareness of what to look out for can possibly determine whether or not one succeeds. Hence, tools are being used with the aim of looking at the element of interest from different viewpoints in order to reveal issues which one were initially not aware of.

The same principle of risk reduction can be used in the investigation of a new process, and that has been the effort of this project. If this study is able to reveal some of the pitfalls in implementing set-based design, that knowledge can be used to increase the likelihood of success in the implementation. It can also be beneficial to other companies that are thinking of, currently trying to, or might have failed at the same implementation. It might not be possible to use the results directly in other companies, but issues revealed can give companies pointers to what should be investigated, and also create an awareness of the hidden tripwires in this unknown landscape. With so little literature describing these issues, this paper could be a valuable piece of knowledge not only to Kongsberg Automotive, but also to everyone interested in applying set-based design.

Research at Kongsberg Automotive

The research has been inspired by the company’s focus on lean and knowledge based development, where one searches for knowledge gaps and where the value of the work has a direct connection to what is valuable to the customer. Therefore, throughout this research, the main aim has been to gather information and data that can contribute to valuable knowledge that can be beneficial to the company in its effort to implement set-based design.

Method of investigation

In the investigation of processes, it is more or less impossible to find proof of what directly influences a given outcome. There are so many variables involved, and the correlations and interactions between different elements are hard to single out. Therefore a decision was made to use the scientific method of creating hypotheses and theories, and try to disprove or verify these. The history of scientific research has shown that a theory can seldom be verified, so the aim has been to try to disprove the theory in order to either create the basis to refute it, or provide data to be able to establish confidence in the probability of the theory being correct. Even though this thesis is not based on a research project performed in a laboratory, this scientific method was thought to create the most valid premise for uncovering the most well-founded and valuable answers to the question in this thesis.

When the question of the thesis had been established ("What can inhibit the successful implementation of set-based design in Kongsberg Automotive"), theories to what could answer this question were composed. Through literature research, observations, discussions with and feedback from employees, interviews and surveys, an attempt was made to disprove the theories. With the limited time available it became increasingly clear that there was not sufficient time to gather enough data to adequately disprove or support all the theories. Therefore, since the implementation depends to a great extent on the people who are going to use these processes, the main focus has been on the following three theories as to what can inhibit the implementation:

- People's lack of knowledge on how to work set-based
- People's lack of understanding of the goals of set-based design
- People's lack of motivation to work set-based

Results and evaluations

This chapter presents results from the research related to the three main theories investigated, and evaluations of these results.

Elements of set-based design in the pilot projects

The three projects all had some elements of set-based design, but not necessarily the same or to the same extent. Table 1 shows varying set-based elements in the projects. It should be noted that project A is the "youngest" project, still early in the development process.

Project A **Set-based design introduced in concept phase**	**Project B** **Set-based design introduced in early engineering phase**	**Project C** **Set-based design introduced in detail engineering phase**
Early simulation and analysis to eliminate inferior designs and saving knowledge in a knowledge base	Component and system testing to eliminate inferior designs and gather knowledge	Component and system testing to eliminate inferior designs and gather knowledge
Decomposition of system into sub-systems , and combining different sub-systems	Working on sets of components (varying through for example different materials) , and working on several segments at the same time (*concurrent* set-based design)	Development of sets of concepts on system and component level, and dividing the system into clearly defined sub-systems
Having a mentor available who is knowledgeable on set-based design (and lean in general)	Having a mentor available who is knowledgeable on set-based design (and lean in general)	Having a mentor available who is knowledgeable on set-based design (and lean in general)
Selection matrix/comparison matrix on both system and sub-system level	Mentoring with focus on designing product elements that are robust with regard to design changes in other product elements	Comparison matrices on both system and sub-system level
Creating checklists based on knowledge, and getting input from several functions simultaneously in the design process	Using checklists and getting input from several functions simultaneously in the design process	Input from several functions simultaneously in the design process
	Identification of knowledge gaps before committing to a design. Effort to avoid jumping to a solution and rather find root-cause of problem before finding several ways to solve it	Establishing baselines for constituent parts of the system and then exploring alternatives
	Using target pricing in design	Start of development before receiving a customer enquiry

Project A	Project B	Project C
		Working with sets of suppliers and reusing suppliers KA has worked with before (Baseline in supplier management since knowledge exists from previous cooperation. Then exploring alternative suppliers)
		Establishing supplier involvement early, not waiting for final design to be finished before investigating possible suppliers (early learning about limitations at the supplier can be used in the design)
		Focus on designs which are robust with regard to changes in customer and application, and mapping of flexibility required in design in order to supply the complete market for this product

Table 1 Showing elements of set-based design in the three pilot projects

It is interesting that the project that shows most signs of set-based design is also led by one of the early advocates of lean (and set-based design) in the company. However, the observations shown in Table 1 that show evidence of attempts to implement set-based design do not provide enough data to support or refute the three theories above. Therefore a more thorough investigation was carried out in order to get results which could be specifically related to the theories.

Research results related to the theories

The three theories outlined earlier are three possible explanations as to what could inhibit the successful implementation of set-based design in Kongsberg Automotive. They have been investigated in order to either refute them or create a basis for asserting the probability that they are actually contributing to adversity in the implementation of set-based design.

What could inhibit implementation of set-based design?

Hypothesis no.1: People's lack of knowledge on how to work set-based

This theory developed after discussions with employees about set-based design. The discussions revealed that the employees had different ways of explaining set-based design, and therefore a relevant question emerged: "Do the employees have different views of set-based design?"

If that was the case it would most likely make the implementation more difficult, if not impossible. If the employees of Kongsberg Automotive have different understandings of how to work set-based, then there is a chance that they will pull the work in different directions, not be able to coordinate their efforts, or possibly not be able to use set-based design at all.

Data collected show that in some areas there is clear agreement on what is or is not part of set-based design. In other areas however, the opinions are clearly divided. This indicates that some parts of set-based design are not evident to the employees. The following two figures show the results from a multiple-choice survey distributed amongst the employees. The results, as they are shown here, do not distinguish between the employees (whether they are design engineers, test engineers, project leaders, or program managers). They show agreement to statements on what set-based design entails, and potential effects of set-based design respectively.

Figure 7 shows that there is some ambiguity among employees as to exactly what set-based design entails. The results explicitly show that some elements are clear, while others are fuzzier. Level of agreement was set to 25% or less and 75% or more of the employees giving the same answer. Green text frames indicate statements gathered from literature (i.e. "correct" statements with regard to set-based design).

When the numbers were studies, it turned out that the ambiguity in the answers was on a general basis, regardless of what position the employee had. The figure shows that the employees disagree on one third of the statements. What is also worth noting is that five of the statements they disagreed upon (25%-75%) and one statement thought *not* to be correct (25% or less) where actually taken from literature describing set-based design, namely *statements marked in red and italic* in Figure 7. These findings support the probability that people's lack of understanding of set-based design might in some way inhibit the implementation.

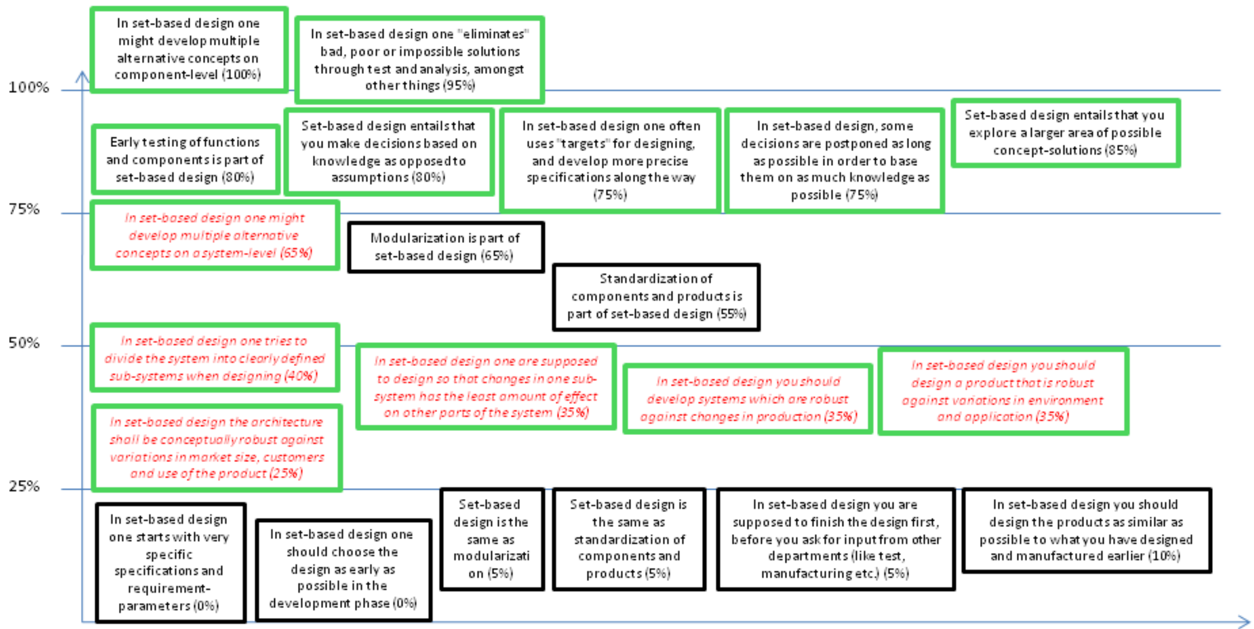

Figure 7 Showing percentage of employees agreeing to the given statements about what set-based design entails

Hypothesis no. 2: Peoples lack of understanding of the goals of set-based design

When doing the same with the statements on what potential effects set-based design might have (Figure 8), the picture is somewhat different (same color code as in Figure 7). Here, only two of the nine statements fall into the category of ambiguity (between 25% and 75%). Otherwise the employees chose the "correct" statements here compared to what can be found in literature on potential effects of set-based design. These results show that the goals seem to be clear to most employees, but the means of getting there are not very clear. In other words, this suggests that lack of visible goals should not be an obstacle in the implementation of set-based design.

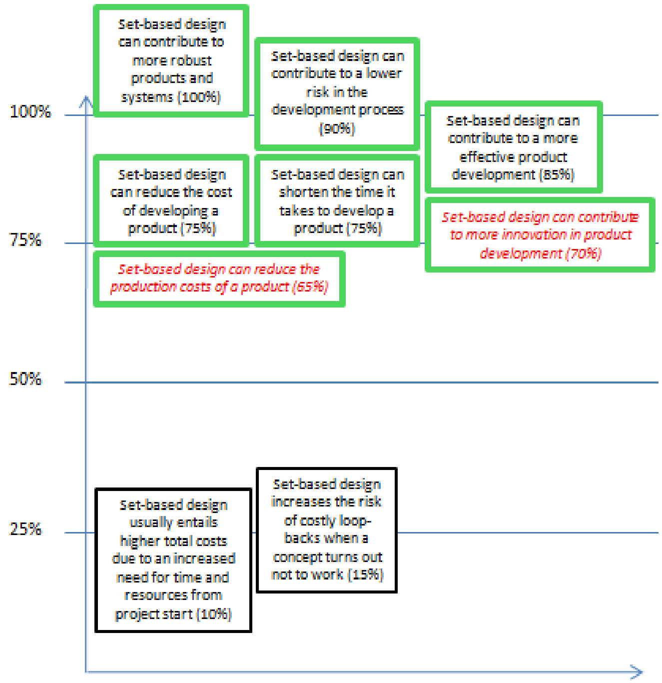

Figure 8 Showing percentages of employees agreeing to the given statement about potential effects of set-based design

Hypothesis no. 3: People's lack of motivation to work set-based

The results from the multiple-choice alone do not reveal any data that could support or refute this theory. However motivation to work set-based was one of the subjects in a series of interviews that were performed. The interviewees were engineers working in one of the three pilot projects. The answers revealed what employees thought could be motivational factors to working set-based. A clear majority expressed that being able to see the results of working set-based (hence, achieving the alleged benefits of set-based design) were believed to have the potential for being a strong motivational factor. Actually, 87.5% of the interviewees mentioned one or several potential gains of working set-based as the main motivational factor.

Working set-based is by many considered very resource- and time demanding, with good reason. Front-loading projects might require a fair amount of effort in the beginning of projects. Through interviews it became clear that this was the view of several employees, but it was also mentioned that when our knowledge base becomes bigger, the job will become easier since the employees don't have to ”reinvent the wheel” in every project. The time- and resource issue related to increased exploration of alternatives and more learning early in projects is therefore expected to become less of an issue in the future, and it is believed that the phase the company is in now (trying to work set-based, but without a well developed knowledge base), is the most difficult one.

Several employees also raised issues with regard to the capturing and maintenance of knowledge. The knowledge that is gained from working set-based must be readily available and easy to retrieve in order to be used in future set-based work. Several expressed that it was not clear to them how this was to be achieved. It should be noted that this is under development in the company. Right now however, the company seems to be at an intermediate stage, trying to work set-based but without all the necessary tools. In other words, the answers from the interviews combined with the employees' clear understanding of potential effects of set-based design (shown in the multiple-choice results), show that there might be a lack of motivation to work set-based. A likely cause could be that the potential benefits are clear, but the actual gains are not visible yet.

Recommendations

The data showing ambiguity with regard to what set-based design really entails reveal a potential pit-fall and indicate that a clear picture of set-based design should be conveyed to the employees. In this respect, linking the elements of the method to their potential benefits seems important in order to increase understanding and motivation.

With regard to the implementation of set-based design (and knowledge based development in general), it implies that the employees have to learn the processes. It could therefore be beneficial to take a closer look at *how* the employees learn. The book "Developing management skills" by David A. Whetten and Kim S. Cameron describes four preferred learning styles called diverging, assimilating, converging, and accommodating. Knowing a person's preferred learning style enable teaching and training to be oriented accordingly. Efforts have been made to encourage employees to read books on the relevant subjects, informational meetings have been held, and now the new processes are being implemented in three pilot projects. In addition, more thorough training sessions are planned in the near future. However, these means of learning might miss some preferred learning styles in employees. Adapting for the learning styles might be more beneficial in increasing the efficiency of learning the new processes.

It is a good sign that people want to work set-based because of the potential benefits. However, that makes it even more important to focus on *how* to do it. If the benefits of working set-based are the main motivational factor, failing to make the benefits visible to all employees could be another potentially devastating pit-fall. As long as the benefits are not visible yet, it seems to be the employees' *belief* in them that fuel the motivation for making this change. Hence, the sooner one starts seeing the benefits, the better.

With regard to the issue of collecting knowledge, several of the employees have expressed a desire for clear guidance on how to save the knowledge gathered in order to prepare for its reuse. Some also had some suggestions on how to do this. One way, therefore, to expedite this could be to have a discussion with the employees or perhaps a workshop where they could express their opinions. Given that it is the employees who are going to use this system of knowledge gathering, they might have some relevant and clever ideas on how to do this in an efficient manner.

It is believed that the checklists at Toyota are an essential part of their set-based design. Given that Kongsberg Automotive has already started the work with creating such checklists, it is believed that they could benefit from using more effort in this area in order to speed up the mapping of the design space. This does not entail any complicated computer programs, so this might be a good start with regard to making the benefits of set-based design visible. The importance here is the use of an efficient way of communicating for example manufacturing limitations to design engineers so it can be used as a basis for the design.

Since the projects are in different phases of development, you would not necessarily expect them to be learning the same lessons from trying to implement the new processes. What this suggests then is that the different projects are most probably learning different lessons, both with regard to set-based design and the new processes in general. This means that it could be valuable to adapt for sharing this learning about the processes across the projects to benefit from the projects but also to prepare for the implementation of set-based design in future projects.

To sum up the most important issues, based on the data in this paper, it is the following:

- Focus on correct understanding of set-based design and the goals
- During training, link the elements of the method to potential benefits to increase understanding and motivation
- When some of the benefits are actually achieved, make them visible to all employees as soon as possible in order to fuel continued motivation
- Adapt for saving knowledge in an efficient way, or else the current gathering of knowledge might turn out to be less valuable and more wasteful than necessary
- Give clear guidance on changes in responsibilities and roles in the new processes (particularly now in the “early days” of the implementation) to avoid misunderstandings
- Make implementation issues visible in all pilot projects so that they can all learn from the different challenges the other projects face in the implementation of the new processes

Conclusion

There was clear evidence of efforts to work set-based in the three pilot projects, but the efforts were not consistent across the projects. This seems to be at least partly due to misunderstandings with regard to the elements of set-based design and the fact that the projects are in different phases of development.

In addition, achieving the gains of set-based design was pointed out as the main motivational factor for working set-based. Hence, the data show that failure to achieve any benefits could potentially be one of the main pit-falls in the implementation of set-based design. Therefore, more effort should be put into the *means* of reaching these goals and potential benefits.

Hopefully the data presented in this thesis will help shed some light on the most important and urgent challenges of the implementation of set-based design. It seems clear that a majority of the employees are positive with regard to the implementation. They seemingly need clearer guidance, and ask for access to and knowledge about appropriate tools to use in the implementation. There seems to be a great potential for successful implementation provided the employees gain a better understanding of the method.

It can be hard to resist the temptation of trying to implement set-based design, given the potential gains. Hopes are that not only Kongsberg Automotive can benefit from these findings, but also other companies could see the benefits of elements like

- gathering and making knowledge available for all employees
- exploring more alternatives and basing decisions on knowledge
- avoiding costly loop-backs late in the design process
- a more efficient and less risky development process

This can only be achieved if the set-based roadmap is clear and everyone is pulling in the same direction. In addition one has to truly understand set-based design i.e. being able to relate the tools to the benefits in order to gain support among employees. Since one of the main motivational factors is actually *seeing* the benefits, the employees have to be willing to make an effort, and aware of that the benefits will not necessarily be visible immediately. This is a requisite for getting through the initial phases of implementing set-based design, and given successful implementation, it can subsequently continue to build and fuel the motivation of the employees.

Subjects for further study

As mentioned in the recommendations, the means for an efficient collection of knowledge should be put in place in order to obtain the full benefits of set-based design. There is however a possibility that the methods of Toyota in this respect are not the most appropriate. One should take into account that set-based design was developed by Toyota several decades ago, and given the development in information technology, there might be better ways than checklists for the gathering of knowledge and mapping out the design space.

In addition, given the short span of this research project, it could be beneficial to carry out larger scale research projects. Then there would be time to investigate how well set-based design works under different sets of condition. This is something that is difficult to investigate in a short research project since it takes time to see the actual results.

This research was more comprehensive than what comes across in this paper, and some of the findings had to be omitted. Also, as mentioned earlier, due to time limitations not all of the theories were satisfactorily investigated. These theories could therefore be potential subjects for further study. Implementation of set-based design can be inhibited by:

- OEMs not working set-based, and therefore providing blueprints and clear specifications which inhibit set-based design
- Working under pressure can lead people to jump to the seemingly best solution without exploring other alternatives
- Problem-A3s (which encourage set-based thinking in problem solving) are becoming just another form to fill in
- Cultural differences (in particular individualistic versus collectivistic)
- Customers that do not understand the usefulness of set-based design, and therefore do not adapt for working set-based
- Differences in working set-based depending on if you deliver total systems or sub-systems/components (hence, a typical component supplier company will not benefit from implementing Toyotas methods)
- A lot of new knowledge needed on new products and products with several new functions (so working set-based becomes too resource- and time demanding)
- New suppliers/customers that inhibit set-based work, in that the company trying to work set-based need to acquire a lot of new knowledge about the new suppliers/customers (Related to the assumption that western companies change suppliers more often than eastern companies, where most of the study on set-based has been performed)

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