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Rapid product development methods in practice – case studies from industrial production and technology development

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Abstract: The classical way of developing products in industrial R&D is the so-called point-based or sequential method, where the design concepts for the project and all its constituent elements are decided up front and only these concepts are matured in the product development. In contrast to this traditional approach, in set-based concurrent engineering approach, several alternative solutions are being developed simultaneously. If the requirements change during the R&D process, there is still a possibility than one of the several possible solutions can meet the new requirements. In the set-based approach the requirements can also be adjusted during the later phases of the R&D process, when there is enough information to do so. In this manner, the set-based R&D differs significantly from classical sequential R&D that is typically time-consuming, and does not allow major changes during the process. The goal of this paper is to make a practically oriented presentation of set-based rapid concept development methods. The presentation in the paper is illustrated by industrial production and technology case examples from United States and Finland.

Keywords: Research and development, product development, set-based design, concurrent engineering, rapid concept development.

1 Introduction

Research and development (R&D) is a key source of competitive advantage for high-technology organizations (Artz *et al.*, 2010). Working under pressure in highly competitive environments is characterized by rapid and unpredictable technological changes and short product life cycles, hence, technology organizations have to decide how to use their limited R&D capabilities in the best possible manner (Teece, 2007). However, investments in R&D and innovation development can be risky and costly; research has shown that only one of four R&D projects is successful (Evanschitzky *et al.*, 2012). One essential reason for this is the lack of flexibility in the traditional R&D approaches, which are typically based on waterfall development processes. In these sequential processes, the contribution of each functional department (e.g., mechanical, electrical, packaging, manufacturing, quality control, etc.) is done one after the other. What is even more important, the starting point of the product development is usually one particular idea or concept that is developed towards a product in a milestone-driven process. At the end of the product development cycle, the obtained result does not necessarily answer the market needs or user expectations, and the R&D process does not enable adjustments to the product at the final stages. Because the contributions of functional departments are integrated in the final product, changes to the design by one functional department to meet its requirements late in the design cycle may cause the other functions to fail meeting their requirements. Typically a single design is usually down-selected too early in the design cycle with considerable "knowledge-gaps" (Kgaps) and associated risks which cause "loop-backs" (i.e., the design returns to an earlier stage in the sequential design process, necessitating repeating all the subsequent stages) late in the product development life cycle causing exponential increases in cost and delays in schedule (Cloft, Kennedy and Kennedy, 2018). This kind of product development based on one particular idea is referred as *point-based R&D*.

During the last few decades, the traditional point-based R&D procedure has been challenged by a new type of thinking that is based on the development of several alternative technological functional solutions in a parallel process. In this new R&D process, called *set-based design* (Sobek, Ward and Liker, 1999; Sobieszczanski-Sobieski, Morris and VanTooren, 2015) it is possible to make adjustments and changes between the alternative solutions to the very end of the product development cycle with few, if any, loop-backs needed. The set-based concurrent engineering (SBCE) approach enables the R&D of a product to adapt to the changes in the market or user requirements during the whole R&D process, which, in turn, minimizes the risks of total failure in the R&D effort. SBCE represents an example of new methods of rapid R&D, in which the key idea is to perform the development work as a parallel process instead of traditional serial process (Flanigan, Schneider and Wolfrom, 2013). Toyota was probably the first car manufacturer who applied SBCE in its car development (Sobek, Ward and Liker, 1999). (Ford and Sobek, 2004) suggest that Toyota has the fastest development time in the whole automotive industry due to applying the set-based methodology.

In this paper, our purpose is to make a practically oriented presentation of rapid concept development methods, including the principles of set-based design and rapid prototyping. We illustrate the presentation with practical example cases on the use of these new methods in industrial production, quality control as well as technology development in United States (NASA) and Finland.

2 Background

An ability to develop and launch successful new products and services is critical for technology firms to achieve and maintain their competitiveness in global markets (Marsh and Stock, 2003). This is particularly important for the companies operating on the business areas with strong consumer focus (business to consumers, B2C). This is because the prediction of customer and user preferences, trends and expectations is difficult, and thus the business environments change rapidly. However, strong global competition in terms of new product development time and cost also influences the businesses focusing on business-to-business (B2B) markets, in which pressure is increasing on R&D organizations to rapidly develop new, innovative and high-quality products (Cooper and Dreher, 2010). In the light of this kind of development, the industrial R&D units have to constantly sustain their competitiveness by developing dynamic capabilities (Teece, Pisano and Shuen, 1997; Eisenhardt and Martin, 2000) that enable them to draw on, to extend and redirect their technological and functional capabilities, and R&D resources (Marsh and Stock, 2003; Kunttu, 2017). Besides innovativeness, the R&D units have to demonstrate project performance by meeting and exceeding the strategic goals and targets set by the current competitive environment and customer expectations. This means that the industrial R&D have to continuously build new capabilities for the future through learning, renewal and innovation (Kunttu and Kohtamäki, 2018). It is also important to note that the industrial product development process has a direct connection to product portfolio management. This is because the purpose of the product portfolio management is to determine and optimize the products to be created, sold, delivered and maintained (Verrollot *et al.*, 2018). In this manner, the role of R&D function is essential in creating new products that are able to meet the users' or customers' needs as well as the strategic targets of the company. In addition, R&D is responsible for rapidly maturing new technologies, minimizing critical knowledge gaps (Kgaps) and developing modelling and simulation methods, verified by experiment, which can predict root cause failure mechanisms.

2.1. Towards adaptive and flexible rapid R&D

As described in the previous section, the technology organizations that are slow in developing new products and services are often unable to adapt to the rapidly evolving customer needs or changes in their business environments. In this manner, organizations with slow response to these kinds of external changes or sudden demands often lose to those with more agile R&D process (Stock, Greis and Fischer, 2001; Verrollot *et al.*, 2018). Thus, shorter lead times and an ability to make rapid changes according to customer demands as well as environmental changes are seen as key elements influencing the firm's success and R&D performance (Sousa, Ruzo and Losada, 2010). Industrial R&D processes have traditionally been designed to be repeatable to reduce risks, costs, and issues caused by low quality. However, these kinds of milestone-driven R&D projects have often been criticized to be too linear, too rigid, and too planned for dynamic environments caused by environmental changes or sudden market demands (Cooper, 2014). In addition to the limited ability to answer to the sudden demands, the R&D projects based on milestones, gates, or phases also typically focus on one particular design. However, one single development concept may not be adaptable to satisfy changes in requirements and all the various ranges of development needs in terms of cost, time, or risk (Cooper, 2014; Verrollot *et al.*, 2018).

Cooper (2014) presents three main principles for a rapid and adaptive R&D system, called "Triple A system". The main characteristics of the system are the following. First, the system is *Adaptive and Flexible*, which means that the R&D process is evolving and adapting as it moves through a series of build-test-revise iterations. In this manner, the product may be less than 50 percent defined when it enters development, but it evolves and adapts to new information and requirements, and involves the customers as early development phases as possible. However, prior to down selection to a single concept for development, it is highly recommended to close all Kgaps and have an in-depth understanding of all critical failure modes validated by test and/or analysis. Second, the system is *Agile*, since it adopts the principles of agile development systems, originally developed in the software industry. Thus, the R&D process may use sprints and scrums, short time-boxed increments with concrete deliverables. Third, system is also *Accelerated*, since the system is designed to maximize the speed to market. This is enabled by proper resourcing and the use of dedicated cross-functional teams, as well as clear scoping of the project with proper identification of risks, unknowns, and uncertainties.

2.2. Set-based design as a tool for rapid R&D

As explained in Introduction, traditional R&D typically relies on point-based design approach, in which the end product is defined based on one particular idea, called the product "baseline", in the beginning of the product development project. The project typically follows a series of functions, each affecting the final design of the baseline (Sobek, Ward and Liker, 1999). In this kind of serial engineering approach, each function adds their own development part, after which the project is transferred to the next function for them to add their contribution. Indeed, there exist feedback loops between the functions, but it is typical that the feedback from the downstream functions are available too late, often after the upstream functions have committed to a particular solution for their function. In addition, the feedback that is acceptable without major repercussions typically addresses specific issues and details requiring only minor changes to the baseline design. There are obvious problems with the point-based design (Sobek, Ward and Liker, 1999; Ford and Sobek, 2004). First, as the design passes from team to team, every change causes further changes and requires analyses by several functions, results in re-work and increases communication demands. The cascading effect makes changes time-consuming and costly. Second, as the design is typically carried out in separate functional teams, each having their own focus area and expertise, the whole picture of the design and its possibilities may be unclear to the project participants, which in turn can yield to sub-optimal results in the end product. Third, as a result of the two problems mentioned, the ability of the design to respond to the market demands or customer requirements is very limited.

Set-based design provides an alternative to the traditional point-based design (Singer, Doerry and Buckley, 2009). Whereas the traditional point-based design practice aims at converging into one solution, and then modifying the solution until it meets the design objectives, the set-based design starts from a broad set of possible solutions. These sets are most commonly sets of functional solutions, each having a range of capabilities, that can be used in the product, but there could also be sets of "baselines" for the product. During the set-based design, the set of possible solutions is gradually narrowed, after which the final solution is selected. In this manner, the design starts with a wide net of alternative solutions whose capabilities may be somewhat overlapping, and gradual elimination of weaker (i.e., less capable) solutions makes the finding of best or better solutions more likely (Sobek, Ward and Liker, 1999). In some cases, finding any solutions with capabilities that can meet the design requirements may be a challenge. In SBD having alternatives with a broad range of capabilities increases the likelihood of coming up with a design that meets the requirements. What is even more important, the set-based approach allows the design effort to move concurrently and to defer detailed specifications until the trade-offs and unknowns are more fully understood. It also allows the designers to move between multiple alternative solutions, and find the best possible solution to the end product. In this manner, the design approach follows the principles of Triple A system (Cooper, 2014): it is *adaptive and flexible* due to possibilities to move between alternative designs, and iteratively finding the optimal final design. The set-based design also fits particularly well to the principles of *agile* development, since it allows short-term development periods with cross-functional teams, concrete outcomes, and customer involvement. It also inevitably accelerates the R&D development cycles, given that the fact that set-based design cycle moves more quickly towards convergence and ultimately to production than its point-based counterparts. However, set-based design may take more time in the beginning of the process, where a variety of parallel solution candidates are identified.

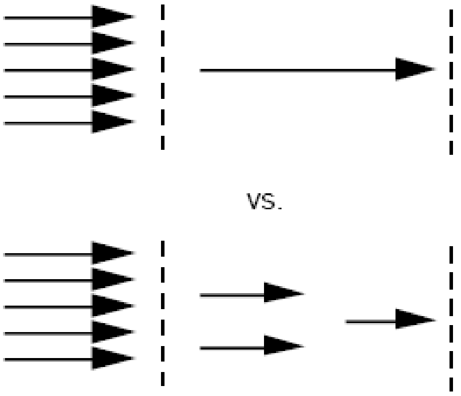


Figure 1. The traditional point-based design and the set-based design approaches.

Figure 1 compares the traditional point-based product development approach with the set-based SBCE approach (Sobek, Ward and Liker, 1999). The five arrows on the left represent the possible development solutions for the product. In the point-based approach (upper part of the figure), the best possible development line is selected in the beginning of the process, and it is developed as the only option for the final product. In contrast to this, the lower part of the picture illustrates the basic idea of the set-based design (SBCE), in which the several possible alternatives (two arrows) are developed further, and the final design is selected later in the process, when there is enough information to make the final decision. In this manner, more than one alternative has gone through the process, as far as it is possible to decide the final design. The SBCE-based R&D processes widely used by e.g. Toyota are based on five main principles (Ward *et al.*, 1995):

1. To define a set of solutions at the system level, rather than a single solution,
2. To define sets of possible solutions for various sub-system tasks,
3. To explore these possible sub-systems in parallel, using analysis, design rules and experiments to characterize a set of possible solutions,

4. To gradually narrow the set of solutions, converging slowly towards a single solution and,
5. Once the development team establishes the single solution for any part of the design, it will not change it unless absolutely necessary

2.3. Just-in-time decision making

As described earlier, milestone-driven R&D approaches have typically limited ability to answer to the sudden demands, and the fixed milestones or gates can also cause unnecessary delays to the process (Verrollot *et al.*, 2018). This is true due to the fact that the each decision can be made only at the time when each milestone has been reached. Because the times for milestones are fixed beforehand, there is a possibility that the necessary information, which enables knowledge, is ready before the scheduled milestone and thus time is wasted in waiting. On the other hand, there is a risk to make the milestone acceptance without having enough information and knowledge (i.e. large information gaps or knowledge gaps, Kgaps), which might lead to the need to rework later in the design process, or cause increasing quality and reliability problems in the field use, resulting in exponential increases in cost, and schedule delays. Left part of Figure 2 illustrates process-based decision-making.

In contrast to this, information-driven approach, adopted by e.g. Toyota as a part of its SBCE-based product development, does not use any pre-defined milestones in the decision making. On the contrary, the decisions are made frequently during the development process. According to (Holman, Kaas and Keeling, 2003), this kind of set-based development of Toyota is based on a better utilization of information in decision-making compared to the competitors. Instead of making decisions according to pre-defined milestones whose dates are fixed, the information-based teams solve problems continuously and combine their findings frequently. The principle of this kind of "just-in-time" decision making approach is described in Figure 2 (right side).

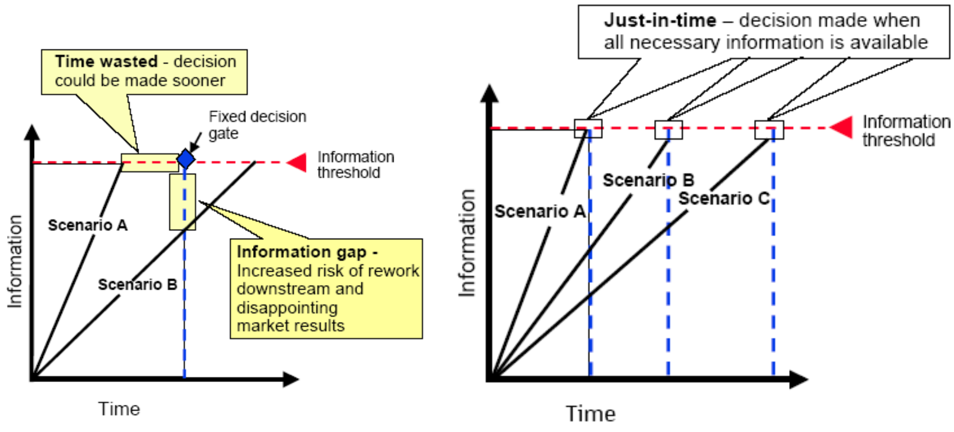
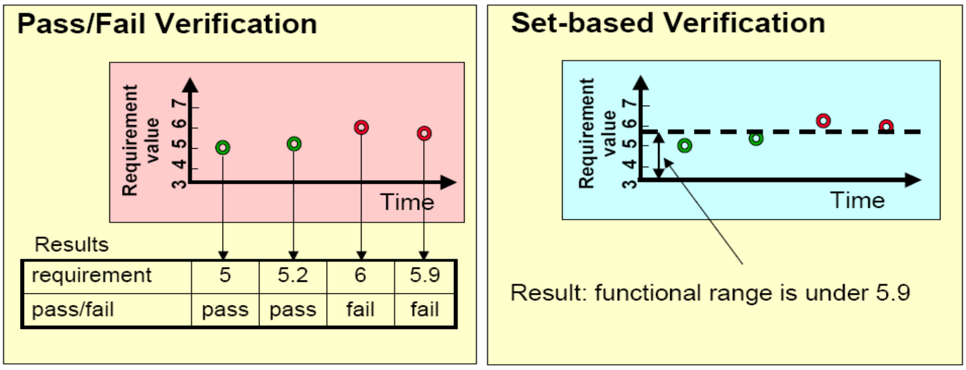


Figure 2. The process-based decision-making (left) compared to just-in-time decision making in the information-driven approach (right) (Holman, Kaas and Keeling, 2003)**.**

3 Practical cases from industrial R&D and education

3.1. Case study: set-based verification and control in industrial mass production

The application of the set-based philosophy has been found beneficial in developing the product verification processes (Perttula, 2005). The traditional point-based verification approach required a set of exact requirements, and the purpose of the verification process was to answer the question: “Are we meeting the requirements or not?” Obviously the only possible answers were “yes” or “no” (i.e.,“pass” or “fail”). One of the main benefits of the set-based approach is that it more readily accommodates the fact that the requirements do not remain stable from the beginning to the end of the development, but instead, they are changing. For this reason, it may be necessary to carry out repetitive verifications by comparing the design with the altered requirements. Sometimes we have to repeat this comparison several times during the development. The left hand side of Figure 3 displays the traditional, point-based way of carrying out the pass/fail verification. The design meets the requirement with values of 5 and 5.2 but fails when the requirement is 6 or 5.9. It is not known whether the design is working between 5.2 and 5.9. By utilizing the set-based approach in the verification, it is possible to remarkably improve the product development in certain circumstances. In this approach the verification is close to the normal design work and it rather tells the designer about the opportunities that the object has than answers whether a single requirement is met or not. In the set-based verification, all the necessary information is collected from the design by using measurements and analysis. It is also possible to return to this data whenever needed to check whether the design still meets the changed requirement or not, without repeating again the physical measuring or testing. In a set-based design (on the right hand side in Figure 4), there are several alternate solutions and at each time point, we know the range of values (i.e., interval along the Y-axis) for their functional capabilities that is possible. Some alternatives will have ranges of values that meet the requirement and some may have a range of values where none meet the requirement. SBD will eliminate the alternatives that can’t meet the requirement, but will carry forward those which are still feasible and are not dominated by other feasible alternatives.



requirement	5	5.2	6	5.9
pass/fail	pass	pass	fail	fail

Result: functional range is under 5.9

Figure 3. the Y-axis is a functional value, and the horizontal, dashed line is the maximum of this functional value that meets the requirement. In the normal Point-based developing process Pass/Fail verification answers the question: “Is the requirement met or not?” However, the Set-Based verification estimates the design possibilities (Perttula, 2005)**.**

The set-based verification can be particularly useful in the modular or platform-based development. The products to be developed may have different requirements. The usage of the Set-Based verification can minimize the amount of re-testing. In the case study example, set-based methodology is applied to a mass production process to indicate how stable the production process is and to predict when the process is most likely to produce failing products. Based on this information, the process can be adjusted before production starts so that it will yield products with an acceptable failure rate. Figure 4 illustrates some real test data from mechanical tests of samples in mass production. The left hand side shows the data from Point-Based verification and the right hand side Set-Based verification.

The set-based methodology can also be applied in the analysis, monitoring and controlling industrial mass-production. The set-based approach may be used to indicate how stable the production process is, and to predict when the process is most likely to produce failing products. Based on this information, the process can be adjusted prior to any failures. In addition, the set-based approach gives valuable information on the impact of new requirements, for instance. The same analogy applies to the verification of modules on which new products are being built. The set-based verification can give information on which kind of products it is possible to integrate new modules without re-testing. In this case study example, a re-qualification process of a mass production line has been modified in a way that 50% of the samples were tested until failure or maximum of 300 cycles. Normal pass/fail criteria was 100 cycles. One sample was taken per day and per shift for this testing. The test data resulted from these measurements are displayed in Figure 4. The left hand side shows the data from the point-based verification and the right hand side set-based verification. In the case of point-based approach (left side), the only available information is that during weeks 31 and 37 some test samples failed in production testing. They did not meet the pass/fail criteria of 100 cycles. The set-based method displayed on the right contains much more information. For example, it shows that the beginning the process was not very stable and from week 45 onwards, any major failures are not expected.

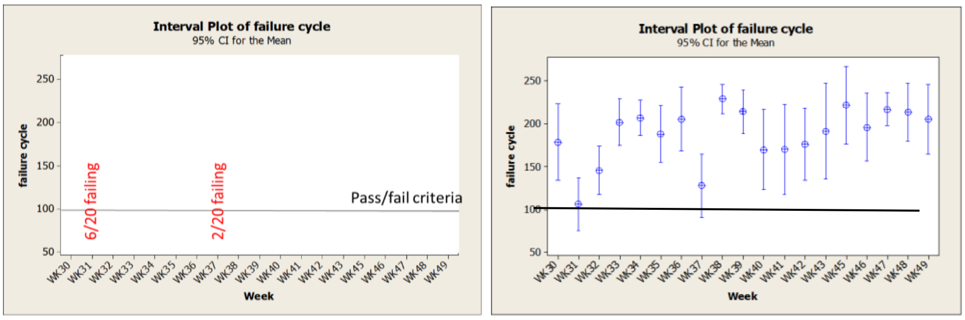


Figure 4. Information received from point-based (left) and set-based verification (right).

3.2. NASA Case Study: Space Shuttle Design and Lessons Learned

The Space Shuttle was an amazing and unique spacecraft that transported crewmembers, supplies, equipment, experiments, and large payloads to and from low Earth orbit (LEO). The history of the Space Shuttle Program (SSP) clearly demonstrates the drawbacks of a serial, point-based design approach to design a complex technical product. The technical, scientific, political, and programmatic challenges during its development were fraught with ambiguous and ever changing design requirements; multiple stakeholders (NASA, military, industry, civilian, and scientific communities) to secure sufficient funding and support; and severe budget constraints and schedule pressures. It was hoped that this very complex, highly sophisticated space vehicle could usher in a new era of safe, low-cost access to space which would enable effective commercial and private utilization of space for everyone.

The engineers, scientists, and program managers that helped develop the thousands of components, sub-systems, and systems which comprised the Space Shuttle used a reductionist approach to functionally decompose the problem, and systems engineering principles to relate the elements and to predict the integrated behavior as if it was a “complicated”, deterministic problem as opposed to a “complex” problem (Mitchell, 2009). The construction of knowledge and subsequent reduction of knowledge gaps of each complex, multidisciplinary subsystem, such as its thermal protection system (TPS) or cryogenic tanks, followed a rigorous analysis-experiment-design process and “building-block” approach to validate understanding, and to predict performance and failure as shown in Figure 5. This building-block approach allows a system to be studied at increasing levels of complexity as the system is built up to understand the interactions that occur among the constituent parts, and to more closely represent a realistic embodiment of the technology. Failure, testing to failure, and learning from failure were a fundamental part of the “research engineering” culture at NASA and are critical elements in the construction-of-knowledge process. The skills required to identify critical failure mechanisms, to construct a building-block experiment/analysis approach to understand fundamental, physics-based behaviors, and to predict complex, system-level performance up to and including failure were carefully nurtured and mentored.

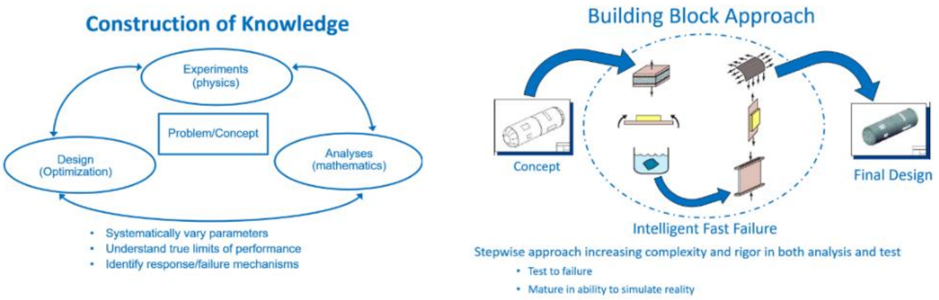
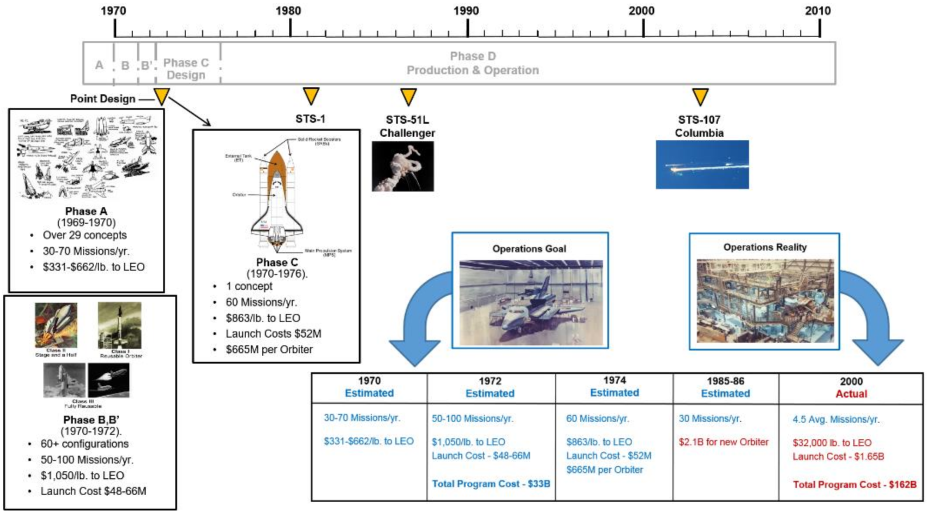


Figure 5. Information received from point-based (left) and set-based verification (right).



1970 Estimated	1972 Estimated	1974 Estimated	1985-86 Estimated	2000 Actual
30-70 Missions/yr. $331-$662/lb. to LEO	50-100 Missions/yr. $1,050/lb. to LEO Launch Cost - $48-66M Total Program Cost - $33B	60 Missions/yr. $863/lb. to LEO Launch Cost - $52M $665M per Orbiter	30 Missions/yr. $2.1B for new Orbiter	4.5 Avg. Missions/yr. $32,000 lb. to LEO Launch Cost - $1.65B Total Program Cost - $162B

Figure 6. – The effect of point-based design and making an early design decision in a program with ambiguous and changing requirements and large knowledge gaps in critical systems technologies.

Figure 6 illustrates schematically what is described in (Camarda, 2014a) how the ever-changing design requirements and funding issues in phases A through C of the Shuttle Phased-Gated product development cycle resulted in the selection of the partially reusable Shuttle configuration shown in Phase C. The Shuttle was originally required to fly somewhere between 50 to 100 missions per year, turnaround from landing to launch to be less than 2 weeks, launch costs on the order of $1,000 per pound of payload, and airline-like operations while on the ground and being readied for flight. By far, the most significant objectives of the program were to demonstrate a significant reduction in the cost of travel to low Earth orbit (LEO) and routine access to space. As shown in figure 6, it is clear that the Shuttle program was a dismal failure on both counts: the system had an average flight rate of 4.5 missions per year with a recurring cost of approximately $4B per year and 18,000 ground personnel to operate resulting in a launch cost of $32,000 per pound to LEO. In addition, the safety record was poor, with 2 tragic events which lost 14 crew members and two vehicles in a total of 135 missions.

Part of the reason for the failure of the program to realize its objectives can be traced to the decision to lock into a point design early in the program life cycle as shown in figures 6 and 7 with vary large Kgaps in major critical subsystems such as the TPS, Space Shuttle Main Engines (SSME's), solid rocket boosters (SRB's) and cryogenic tanks. The selection of a fragile, low-density, fibrous ceramic thermal tile system to protect the low-temperature aluminum structure necessitated over 30,000 individual, unique tiles to be bonded to the belly of the Shuttle Orbiter. The selection of this subsystem without adequate knowledge of its real-world, operational characteristics and its refurbishment overhead (large Kgaps) was one of the critical factors which led to significant cost per flight, slow turnaround, and thus, failure to meet key goals of the program.

Prior to the launch of Space Transportation System-1 (STS-1) on April 12, 1981, after flight profiles and air loads were refined, it became apparent that while the TPS material satisfied loading requirements, the TPS as a "system" had inadequate tensile strength. This meant that many of the Shuttle tiles would exceed structural limits and fail. At the time, Rockwell had already installed over 24,000 tiles on the vehicle before the root cause of problem was finally discovered and a solution was in hand. In fact, on the Shuttle ferry flight from Palmdale, California where the Shuttle was built to its launch site in Florida at Kennedy Space Center (KSC), a large number of tiles fell off. In an actual mission, loss of even one TPS tile in a critical location could cause a burn through of the aluminum structure leading to loss of the vehicle during the high heating phase of entry. This Shuttle TPS anomaly was discovered late in the program and is notionally shown by the lapse in knowledge (Kgap rise of dashed grey line in figure 7 and the large magnification in cost (blue loop-back denoted by 1000 x)). NASA created a “Tiger Team” led by Dr. Paul Cooper at LaRC, which included scientists and engineers from multiple NASA Centers to determine the root cause of this very serious problem and recommend a solution (Cooper and Holloway, 1981). It is very important to emphasize that it required a small team of key subject matter experts (SME’s) in distinct areas of materials science, structural mechanics, structural dynamics, material and geometric nonlinear behavior, and advanced experimental techniques (in this case photoelasticity) to identify the elevated stress concentrations caused by the transverse fiber bundles of the strain isolator pad (SIP) material (Figure 7) which was the root cause of the reduction in transverse ultimate load of the bonded system. Only then was it possible to conceive a solution (in this case the densification of a thin layer of the tile adjacent to SIP) and conduct the necessary validation and verification testing.

The case study above serves to highlight the drawbacks of a point-based design, phased-gated approach to product development with a NASA Space Shuttle design problem. The case study which follows, also taken from NASA experiences, provides some additional examples of using principles of a SBCE/rapid concept development approach by experienced NASA research engineers raised in an R&D culture.

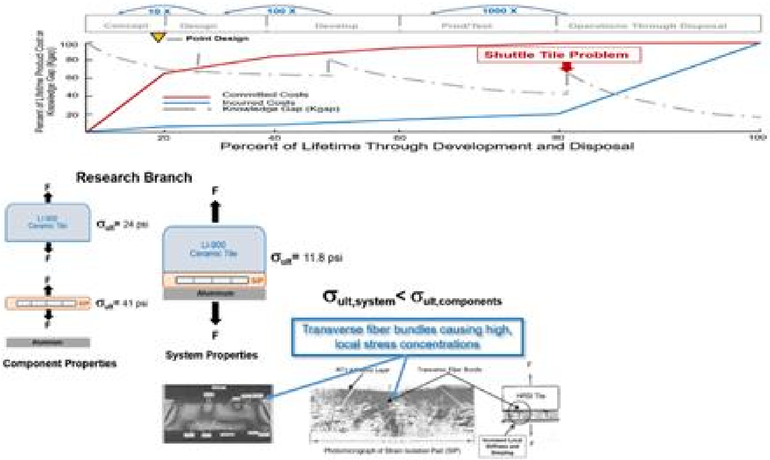


Figure 7. Space Shuttle TPS bonding issue identified late in the product development life cycle (just prior to the first launch which caused major “loopbacks” and rework which cost excessive delays and cost overruns.

3.3. NASA Case Study: Reinforced Carbon-Carbon (RCC) R&D Repair Effort Post Space Shuttle Columbia Disaster

After the loss of the Space Shuttle Columbia, one of the Columbia Accident Investigation Board (CAIB) recommendations for future flights was for NASA to develop methods to repair on-orbit damage similar to that which led to tragedy (Gehman, 2003). A large hole in the reinforced carbon-carbon (RCC) wing leading edge (WLE) resulting from impact of insulation foam on ascent was believed to be the damage that led to the loss of the vehicle and crew during Earth entry on February 1, 2003 (Gehman, 2003; Camarda, 2014b).

A Technical Exchange Forum (TEF) was held at NASA Johnson Space Center (JSC) June 3-4, 2003 to investigate ideas for on-orbit repair of the Shuttle WLE. Numerous repair concepts were suggested in multiple categories related to the size and type of damage and the suggested repair method. The SSP was interested in repair ideas that spanned the smallest possible critical damage (e.g., small cracks, holes, and/or SiC coating losses) to very large holes typical of the tests reported in (Camarda, 2014b) (approximately 16 in. (41 cm) square). For small damage, a spreadable pre-ceramic polymer was developed that could be applied over a damage site by astronauts during a spacewalk (more correctly called an Extra-Vehicular Activity or EVA). The polymer would adhere to the damaged surface and cure on orbit and then convert to a high-temperature ceramic barrier which would protect the surface during entry heating. For larger damage (small to medium size holes or cracks), a "patch" which could be bonded to the outer surface or a "plug" which would be mechanically attached to the surface of the RCC WLE and secured tightly and conform to the WLE outer moldline were developed (Camarda, 2007). These on-orbit, RCC WLE repair concepts are shown in figure 8.

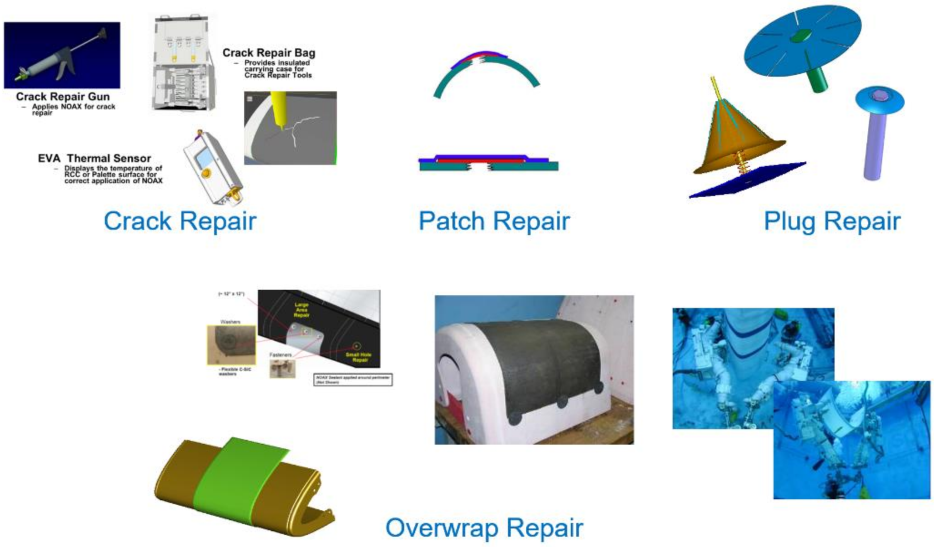


Figure 8. – Categories of types of reinforced carbon-carbon (RCC) wing leading edge on-orbit repair concepts.

Most of NASA’s resources were focused on small cracks and holes in the leading edge because the crew could use the International Space Station (ISS) as a “safe haven” if damage occurred and was deemed unrepairable and await a hurried Shuttle rescue mission. However, there was one mission to the repair the Hubble telescope that did not dock with the ISS, so the Shuttle program sponsored a “large-area repair” team to find a way to repair large holes in the leading edge for that mission.

The large-area repair effort followed a free-flowing approach similar to the innovative conceptual engineering design (ICED) methodology described in (Camarda, 2014a). It began with a meeting of experts in high-temperature materials and structures, in the re-entry environments, and in on-orbit operations (e.g., EVA-qualified astronauts), as well as a number of “free thinkers” who had technical backgrounds. Inviting actual astronauts who were trained in EVA would force the team to consider “downstream”, operational design considerations early in the conceptual design phase and minimize potential loopbacks and rework. The goal of the meeting was to exchange knowledge – each participant sharing essential information from their perspective – and to define a broad design space by brainstorming concepts that could be used in a repair. Because of the varied backgrounds of the attendees, a good “cross-pollination” of ideas occurred. Over 70 individual repair concepts were generated in real time with another 30 added the following week. These concepts were later categorized into classes having specific salient features in common.

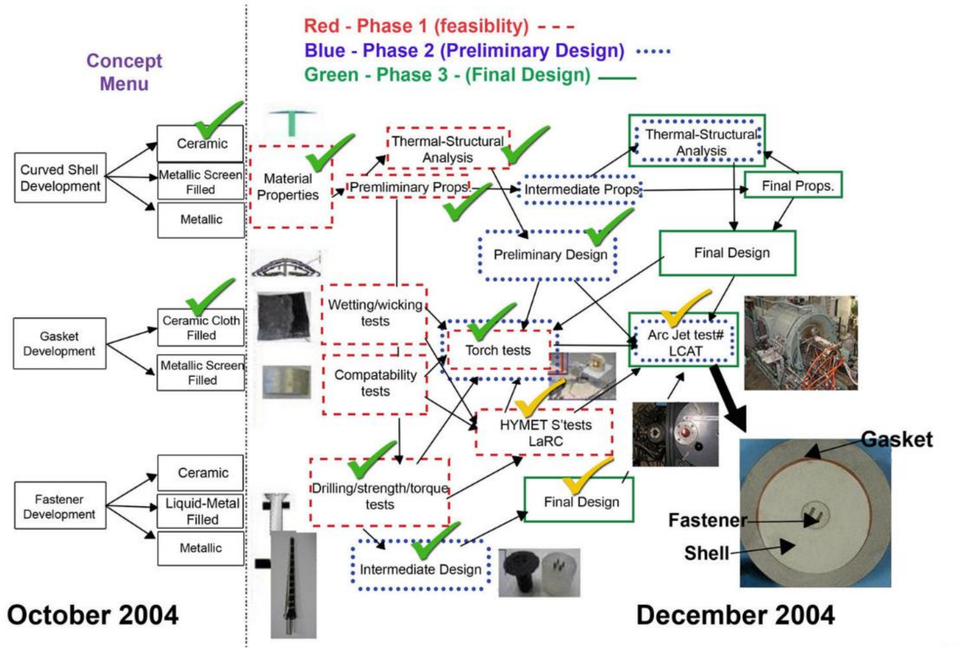


Figure 9. – Rapid concept development test plan for Space Shuttle on-orbit wing leading edge repair

Categories of repair concepts included metallic and ceramic shells that could deform to fit different surface curvatures, large flexible refractory metal and ceramic sheets that could cover the largest damage areas, soft gaskets and pastes to prevent hot-gas ingress though gaps, and many different types of fasteners and means to drill and tap holes in the leading edge. The critical knowledge gaps for each class were identified – both in the meeting and later on – and separate teams that "championed" a given class of repair concepts were formed to fill in the knowledge gaps. The most critical knowledge gaps dealt with: 1) how a repair concept could be installed by a space-walking astronaut, 2) whether the concept withstand the temperatures and pressures during reentry, and 3) whether the concept could prevent the hot plasma formed during reentry from entering the interior of the leading edge. Concept "gates" – simple tests and analyses that establish concept feasibility - were established for each repair concept that provided goals for each team's efforts. Within each concept class, the set-based design philosophy of concept elimination of the "weaker" solutions was performed within the team championing the concept. Weaker was determined in several ways – it could be inferior performance demonstrated in a quantitative metric such as maximum operating temperature, it could be having a larger number of knowledge gaps that cannot be easily addressed, or it could be that there alternatives within the class that had greater applicability to the different damage scenarios. However, there were solutions that were applicable to teams outside their development team – such as a high temperature fastener that could be used with several repair concepts – which were not eliminated. Each repair class team was allowed to continue their development in parallel as long as possible because the teams didn't all proceed at the same pace and a "show-stopper" in one class could be revealed late in the development. A rapid development plan for one of the concepts is shown in figure 9.

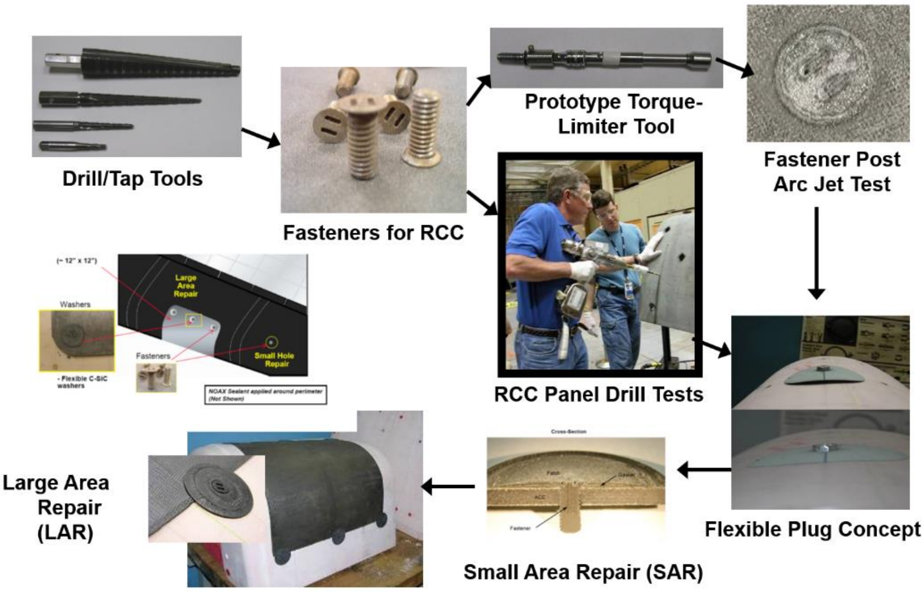


Figure 10. – Assortment of technologies and concepts developed by the R&D Space Shuttle Wing Leading Edge Repair Team to repair small to large on-orbit damage to the reinforced carbon-carbon (RCC) wing leading edge.

However, pressure from the Shuttle program forced a selection of the most promising concepts for the Hubble repair mission which ended the efforts of those teams that were not as mature. The concepts that were carried forward to be developed into repair kits for the Hubble repair mission were a low-force drill to install fasteners in the carbon-carbon leading edge, ceramic-composite fasteners and washers, and a flexible ceramic composite sheet that could cover a hole as large as 12 inches wide (Figure 10). Most of these concepts were rapidly validated and certified to fly in time for the first return to flight mission following the Columbia tragedy, STS-114 in July of 2005!

4 Discussion and conclusions

In this paper, we have presented how set-based methods in product development may significantly improve the product development, production, quality assurance as well as sophisticated problem solving in challenging environments. This paper relies on practical case studies from industrial production as well as from design challenges from NASA.

The case studies illustrating the set-based approach in industrial production revealed that the set-based approach is advantageous in the circumstances where the requirements are really changing or they are not known in advance. However, if the requirements are stable from the beginning to the end of the development, then the normal pass/fail testing is probably the best approach, because it is usually easier and faster to carry out. In addition, the pass/fail type verification can be outsourced more easily, because it can be carried out without knowing the design thoroughly. Additionally, the communication between the designers and the verification persons do not need to be very close. Besides, the automated testing methods can be implemented easier in the pass/fail verification. However, when the pass/fail method is selected it is usually advantageous to find out the failure point, which provides useful information on the design margins.

The two case studies from NASA real-world design activities highlighted several lessons learned that show the value of a set-based design philosophy for challenging and complex problems. In particular, they illustrated the value of starting with a broad design space, understanding the knowledge gaps (Kgaps) that characterize each potential design solution, the use of a systematic approach to closing the Kgaps (e.g., the building block approach), and the pitfalls of selecting a point-design before the Kgaps are closed (e.g., Space Shuttle Design). Also, it was shown that a significant Kgap present in many of these case studies is understanding the root cause of failures so that the design can be tailored or modified to avoid them.

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