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A HOLISTIC DESIGN FOR EXCELLENCE MODEL BASED ON LIFE CYCLE COSTING AND DESIGN SCORECARDS

Matthias M. GATZEN, Robert W. PEMBERTON, Volker PETERS, Sven KRUEGER
Baker Hughes Inc., Germany

ABSTRACT
Demand for shortened design cycles, higher quality and reliability, reduced production costs and at the same time maintaining predictable, on-time delivery of new products and services, has forced companies to re-examine their product design and development processes. This paper presents a DfX model developed and implemented at Baker Hughes Incorporated. The DfX model is aimed at developing products and services that meet or exceed the business case by horizontally integrating experts from all relevant enterprise disciplines and holistically focusing on reducing life cycle costs early in development. It allows effective reaction to customer demands by focusing on rules and data based decisions throughout the entire product lifecycle.

Keywords: design for excellence, DfX, life cycle cost, design methodology, conceptual design selection

Contact:
Dr. Ing. Matthias M. Gatzen
Baker Hughes Inc.
Engineering
Celle
29221
Germany
matthias.gatzen@bakerhughes.com

1 INTRODUCTION

Design for Excellence (DfX) is a methodology in which all aspects of the product life cycle and their interactions are considered early in the product definition and design stages, and reviewed regularly as the product is developed. The ultimate goal of DfX is to develop products and services that meet or exceed the business case by horizontally integrating experts from all relevant enterprise disciplines and holistically focusing on reducing life cycle costs (LCC). The X in DfX represents each discipline involved in the life cycle of the product, such as Safety (DfS), Compliance (DfC), Test (DfT), Manufacturing (DfM), Assembly (DfA), Reliability (DfR), Maintenance (DfMt), and more (Holt, Barnes, 2010).

An overview of DfX definitions is given by Stoeber et al. (2010). Typical characteristics of DfX are:

- Knowledge and tools are utilized in development decisions relating to the specific X discipline
- Decisions made aim at improving properties of technical systems

DfX reviews the developing product design from multiple perspectives, each seeking to maximize product design per that angle (Holt, Barnes, 2010). For example, a Design for Test (DfT) perspective would maximize test coverage of a product while Design for Maintainability (DfMt) would address issues that affect future repair and maintenance of said product. The DfX approach utilizes Life Cycle Cost Models for selecting alternatives showing the lowest life cycle cost potential.

Up to 75% of the life cycle cost decisions are made in the conceptual design phase, while only a minimal percentage of the actual life cycle cost has been incurred (Farr, 2011). Decisions that seem good for one life cycle requirement can conflict with other life cycle phases (Hubka, Eder, 1988), so tools must be developed for assessing decisions across the entire life of the product and for capturing and presenting recommendations based upon lessons learned from previous projects.

This paper presents a DfX model developed and implemented at Baker Hughes Incorporated that consolidates numerous separate design related processes. Baker Hughes is a 55,000-plus employee oil and gas service provider that is an industry leader in advanced technology development. This methodology was developed, introduced and iteratively refined to further improve efficiency in product development. Efficiency becomes imperative as additional focus is laid on further increasing the speed of delivery on nearly all development projects.

2 BUSINESS PROCESS FOR MANAGING PRODUCT DEVELOPMENT

Most product design organizations employ some form of a Product Development Management (PDM) system. A typical PDM process, such as the one implemented at Baker Hughes (Crump, 2010), segments the product life cycle into stages and gates (Figure 1).

Figure 1: Product Development Management Process (Stage-Gate)

Each stage contains specific tasks that must be completed prior to progressing to the next stage. The tasks are tracked via extensive metric-based stage completion checklists that are reviewed, approved and signed off in gate review meetings at the conclusion of each stage. A typical definition of the five PDM stages is shown in **Table 1**.

Table 1: Stages of Product Development Management Process

Stage	Name	Description
Stage 1	Define	Product requirements and definition stage
Stage 2	Evaluate concept	Requirements refinement, concept formulation and selection
Stage 3	Design, Verify, Accept	Design and early prototyping, test and evaluation, verification builds, system configuration, field testing
Stage 4	Launch	Release activities to move the product to full production
Stage 5	Life Cycle Management	Post launch product tracking, verification of success

3 INTEGRATION OF THE DESIGN FOR EXCELLENCE MODEL INTO THE BUSINESS PROCESS

A prerequisite for the development of a holistic DfX design process is full integration into the business process for managing product development as described above. The goal is to maximize the benefit of early involvement of all stakeholders by capturing, presenting, tracking and scoring design recommendations from each discipline, while simultaneously characterizing the financial impact of decisions over the life of the product.

Figure 2 illustrates the holistic DfX process introduced at Baker Hughes, which naturally integrates into the existing PDM process and focuses on both design methodology and life cycle cost. The process was developed over several years. In the first phase, sub processes such as cost modeling and trade-off analysis were introduced separately. Once validated, the sub processes were then tied into a holistic approach, which was iteratively improved by a cross functional team comprised of subject matter experts from all DfX disciplines.

Key features of this DfX implementation are life cycle cost models and a formalized DfX-based concept selection process. The process is set up in overlapping sub processes that enable the appropriate subject matter experts (SMEs) to introduce their domain expert knowledge and historical offset data when they can have the greatest impact.

In addition to the generally applicable methodology for concept generation and evaluation such as DIN 2221, the main tools used in the model are the DfX scorecards, Technology Readiness Level Assessments and Life Cycle Cost Models. DfX should drive the existing development from additional perspectives and reduce the overall effort, as changes are identified and implemented earlier. The toolkit used in the development phases and the six process steps are described in detail in following sections.

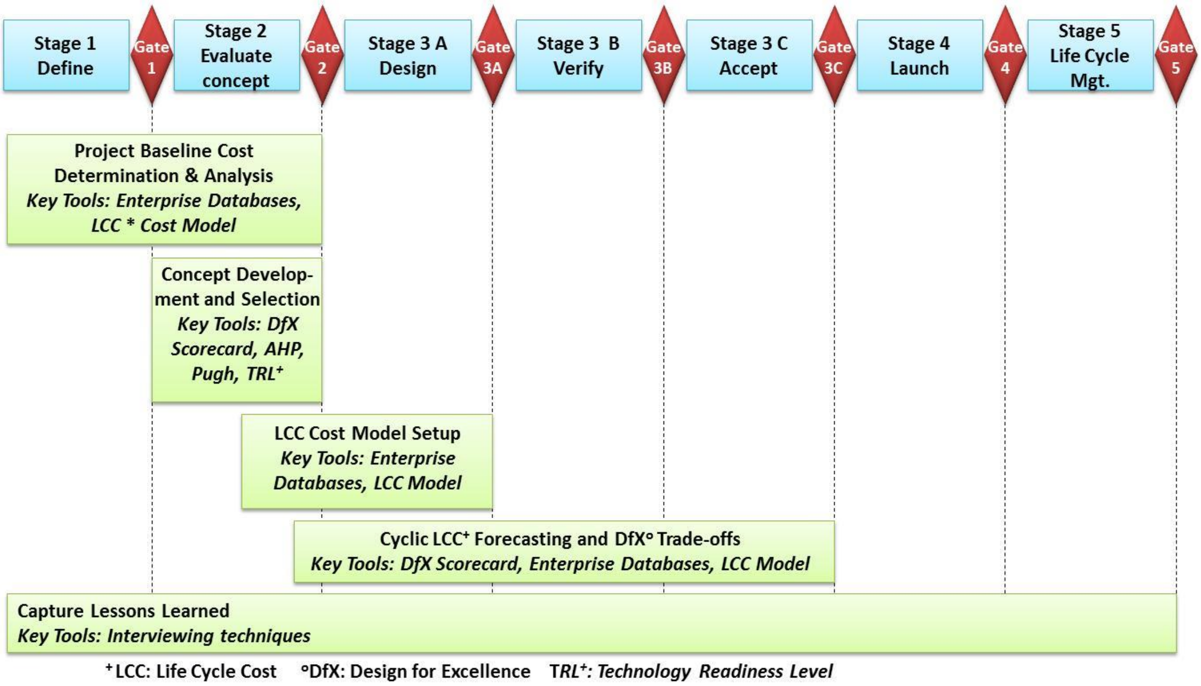

Figure 2: Baker Hughes DfX process fully integrates into Business Process for Product Development and Management

3.1 Toolkit

DfX Scorecards

A tool used throughout the DfX involvement is the scorecard. The DfX scorecard captures, presents, tracks and scores acceptance of design recommendations from each discipline. Created and maintained by the SME from each X discipline, the scorecards contain a combination of lessons learned and discipline-based recommendations that are presented to the design team and then used to track the acceptance or rejection of each recommendation throughout product development.

All DfX scorecards are composed of the following elements:

- Major categories of design-related criteria
- Criteria – individual design-related criteria within a major category.
- Unit of Measurement– unit of measure used to judge progress of a given criteria
- Applied Stage – defines the design stage in which the criterion is applicable
- Current Measurement versus Goal – current status versus target condition for a specific criteria desired by the X discipline

Master scorecards are maintained by each discipline and customized per project. During concept selection, the scorecards are used to review proposed concepts against the goals of each X discipline. During the detailed design phase they are used to introduce expert domain knowledge into the design. In both cases, the goal is to reduce life cycle cost by design improvements.

At Baker Hughes, the DfX scorecard is set up such that design criteria and the associated metrics can be filtered and displayed either by DfX discipline, project stage or based on metrics (enables the project teams to view DfX criteria that are relevant at a specific time). **Table 2** shows an example of data that is entered for a DfX criterion. To ensure that new criteria are adequately vetted before being made available to the project teams, they must pass through a stringent subject matter expert review. In the review, a board of cross-disciplinary experts review the new criteria before making a decision to release it to the database. Currently, more than 300 DfX criteria have been reviewed and are available for use by the project teams.

***Table 2**: Example of the scorecard criteria "maximum modularity with pre-tested sub-assemblies"*

Field	Content of Field	Description / Comment
Major category	Design for Assembly and Disassembly	Numerous criteria are categorized under this goal
Criteria	Maximum modularity with pre-tested sub-assemblies	Short description of criterion
Unit of Measurement	Number of major subassemblies that cannot be replaced directly/independently	Metric, in this case the goal is to reduce the overall value
Description/ Explanation/ Definition	A count of major replaceable components or subassemblies that require removal or disassembly of nonaffected parts or subassemblies to replace	Detailed description of criteria for further understanding
Applied During Stage	Conceptual Stage	This criteria is suited for the conceptual selection process
Current Measurement versus Goal	Number Field	The number of major subassemblies that currently cannot be replaced directly/ independently are measured and recorded (and are compared to the goal).
Baseline	Number of major subassemblies that cannot be replaced directly/ independently in the existing baseline product or service	Benchmark data gathered from similar designs

Technology Readiness Level

Technology Readiness Level (TRL) is a tool used to assess the maturity of a specific technology and enables a consistent comparison of different technologies' maturities within an application or system. The main purpose of TRL is to assist management in making decisions concerning the development or transition of technologies (Garnett, Rendon, 2006).

TRL typically comprises nine technology readiness levels. A business-specific set of definitions and criterion describes each readiness level, aiding the rating process. Technology readiness ranges from basic research through commercialized and mature (Garnett, Rendon, 2006; Harris, 2010).

Concept Selection Tools - AHP and Pugh

The **Analytical Hierarchy Process (AHP)** is a widely used theory for making decisions and setting priorities and was developed by Thomas Saaty (1980). AHP is predominantly utilized when both

quantitative and qualitative aspects of a decision need consideration. The methodology reduces difficult decisions to a sequence of simple one-on-one comparisons before synthesizing the results (Pillay, Wan, 2003).
The **Pugh Method,** named after Stuart Pugh (1991), is well suited for decision making in the concept selection stage where alternative concepts are quantitatively and qualitatively compared with a baseline. With the tool, decisions are documented in table format and the characteristics of each concept are rated as favorable or unfavorable. Outcome is a rating of each concept in comparison to the baseline concept (Sridhar 2005).

Baseline Analysis Tools - Enterprise Databases
Enterprise databases are essential for cost baseline determination and analysis and also for cost forecasting. At Baker Hughes, two primary systems are utilized for this task. The Enterprise Resource Planning (ERP) system is used to determine and analyze the capital expenditures (CAPEX) on existing tools and services. An operational database is used to monitor operational expenditures (OPEX) and to determine both the advantages and improvement opportunities on benchmark tools and services. By tying the data of both systems together, a detailed baseline analysis is possible.

Life Cycle Cost Model
Life cycle cost "includes the consideration of all future costs associated with research and development (i.e., design, construction and/or production, distribution, system operation, maintenance and support, retirement, and material disposal and/or recycling). It involves the costs of all technical and management activities throughout the system life cycle; that is, producer activities, contractor and supplier activities, and consumer or user activities" (Blanchard, 2008).
The goal of the Life Cycle Cost Model is to assess the life cycle cost of a product or service in a standardized way. The Life Cycle Cost Model is a collection of cost data from various databases along with the formulas necessary to calculate projected project costs. As new data or actual data on product costs becomes available throughout the product development, the Life Cycle Cost Model is updated and refined. When tradeoffs and design decisions are made, the Life Cycle Cost Model is used to assess the financial impact of those decisions allowing the least costly decision to obtain priority.

3.2 DfX in concept evaluation – PDM Stage 2
Selecting a design concept is a key milestone in product development. Performing design concept selection while considering the entire solution space makes this a decision-intensive process (Mistree, Smith, 1993; Starvey, 1992). Each decision made by a designer is associated with consequences (Rehman et. al, 2005; Andreasen, Olsen, 1990; Duffy, Andreasen, 1993; Swift, Raines, 1997) that can be intended /unintended and good/problematic (Borg, Yan, 1998). Hubka and Eder (1998) contend that every design decision influences later stages of the product life cycle in terms of measures such as cost and time. Therefore, it is necessary for the designers to be aware of the consequences of their decisions during the conceptual design stage on later life phases of the product – one method to accomplish this is DfX.

3.2.1 Concept Development and Selection Process
DfX SMEs are an integral part of the development team starting at the beginning of stage 2. In numerous projects, Baker Hughes is fully integrating DfX SMEs into the project teams. In such instances, all participants are co-located, which significantly drives cross-functional teamwork.
Though the SMEs are responsible for advising the technical manager and delivering technical and financial data, they do not perform actual design work but instead consult with designers to drive and clarify recommendations from the SME's area of expertise.
The goal of concept development is to review and consider input such as:

- Operational needs definitions, project requirements, life cycle strategies
- Historical data/lessons learned from similar projects
- Design ideas and proposals on how to meet project requirements
- Subject matter expertise from each "X" discipline and the project team
- Technology readiness level assessments
- Concept selection criteria (DfX scorecard-based)

to generate a series of concepts for selection.

Experience has shown that two to six final concepts are beneficial for review in three layers (Figure 3). In layer one, Engineering SMEs identify concept risks. In layer two, DfX discipline experts identify opportunities to lower the life cycle cost jointly with the project team. In layer three, engineering experts identify means to implement DfX discipline expert's recommendations. Should substantially more than six concepts exist, they are typically pre-assessed by the project team and reduced to around six.

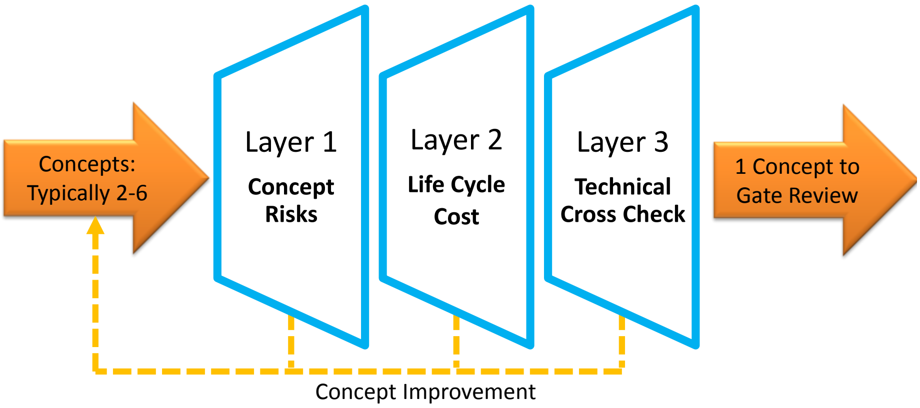

Figure 3: DfX Concept Review

In layer one, the Engineering SMEs utilize the Technology Readiness Level assessment tool. The goal is to mitigate risks associated with specific concepts and, where applicable, to further identify conceptual refinement opportunities.
The concepts are then jointly reviewed and ranked by all appropriate DfX SMEs and the development team in layer two. The goal is to give the Project Technical Manager a recommendation on preferred concepts that take the entire life cycle of the product or service and the respective discipline's domain expert knowledge into consideration.
The concepts are rated against the Concept Selection Criteria which are derived from the master scorecards maintained by each "X" discipline. Concept Selection Criteria must cover key design-related aspects considered by the development team and aim at reducing the product/service's life cycle cost. A suitable methodology for weighing such criteria is the Analytical Hierarchy Process. The ranking conducted always includes safety and compliance that can overrule economic decisions. Nonetheless, early reviews from the perspective help ensure product integrity for later use. A maximum of eight criteria are recommended per discipline be considered and then weigh those within, as well as in relation to, other discipline's criteria. Experience shows that more than eight criteria lead to a substantial increase in complexity when conducting the Analytical Hierarchy Process.
The group comprising all DfX SMEs and the development team reviews the designs from the vantage point of each of the DfX disciplines. The tool typically used for performing and documenting the process is the Pugh Matrix.
After the DfX concept selection review, the highest-ranked concepts are assessed by a group of Engineering SMEs in layer three. The goal is to validate the ranking and to identify further concept refinement opportunities, if required, by using synergies of positively rated aspects. Based on the recommendations of the DfX concept review and the SME review, the Project Technical Manager selects a concept that is detailed in Stage 3 of the PDM process.
A key challenge was developing design criteria which were equal in value or importance and avoiding duplicate entries in different categories. For example, the criterion "component count" may have been used in almost all major categories, but should only be used once for the evaluation. Based on industry experience, the "component count" criterion was sorted into the group where the major effect was expected. In this situation, the criteria went into the "Design for Assembly" category.

3.2.2 Cost/Project Baseline Determination and Analysis

To use the Life Cycle Cost Model as a tool during DfX implementation, a baseline cost analysis must be established to identify possible areas for improvement, allow for trade-off analysis, and provide cost estimates to ensure (at an early stage) that the product/service business situation is met. Since oil and gas service providers not only develop products and services, but also manufacture, operate, and maintain them, precise life cycle cost evaluation is extremely important. In this business model, OPEX have a much greater influence than in other industries and must therefore be considered early on - in many cases, for a product or service, OPEX can exceed the CAPEX many times over.

In the Life Cycle Cost Model, which is used to calculate the sum of CAPEX and discounted OPEX cash flows, CAPEX is assigned on the basis of standard cost for the component, sub-assembly, or final assembly. OPEX are discounted by the cost of capital to yield the present value of the cash flows; Net Present Value (NPV) calculations are used to convert future cash flows to current dollars.

Pareto analysis is used to analyze baseline data to determine areas for improvement. Also known as the 20/80 analysis, it is based on the observation that 20% of the causes produce 80% of the problems (Caplan, 2004). For CAPEX, it equates to 20% of components accounting for 80% of the cost. The purpose of the analysis is to focus attention on the largest cost drivers, because they represent the best opportunities for savings. Therefore, for OPEX, 20% of root causes generate 80% of expenditures.

The deliverable for the process step is a strategy which includes a cost control plan, all ground rules and assumptions used for developing the estimate, a list of the data sources and treatment of the data (e.g. normalization or filtering), a method of estimation and a summary of estimated cash flows and life cycle costs. At Baker Hughes, the cost strategy review is an integral part of design review.

3.2.3 Life Cycle Cost Model Setup

The Life Cycle Cost Model setup overlaps with the Cost/Project Baseline Determination and Analysis phase. Based on the project scope and available data, the model can vary significantly in detail. With respect to CAPEX, the model directly ties the current state of the bill of material (BOM) to the estimated CAPEX in the level of detail needed for each alternative. The OPEX model incorporates the maintenance strategy and other supply chain models and is updated as the concepts evolve.

3.3 DfX in Design, Verify, Accept – PDM Stage 3

3.3.1 Cyclic Life Cycle Cost Forecasting and Trade-offs

Upon passing the PDM Stage 2 gate, the DfX discipline SMEs review the product concept, product requirements, and baseline costs/targets to customize the discipline master scorecards for the development project. Continued “X” discipline SME involvement is imperative because product specifics around functionality, look/feel, materials, manufacturing processes and usability features are further specified. Regular communication between the DfX SMEs enables conflicts to be resolved in a timely manner to create the greatest value for the company.

Throughout this stage, regular updates to the Life Cycle Cost Model and DfX scorecards enable the design team to better monitor for project risks with regard to cost targets and other potentially hidden risks such as safety and compliance. When conflicts between recommendations occur, a trade-off analysis using the Life Cycle Cost Model and a technical applicability analysis is necessary. A typical example would be conflicts between design for manufacturability and design for assembly.

Guiding the decision is the ultimate goal of developing variants that have the lowest life cycle cost. As design change decisions are made throughout the product life cycle (Stages 2 through 5 of the PDM), those decisions are reviewed by the DfX SMEs against the agreed-upon design targets. The review assures the final design still meets the same goals as the initial design.

The more experience gained with the DfX methodology, the earlier the detailed design decision can be made and the greater the impact on overall life cycle cost. Nevertheless, DfX review/analysis should not be looked upon as a one-time event, but a progression that continues throughout the product development process.

In the later design phases of Stage 3, the Life Cycle Cost Model assumptions and preliminary cost estimates are replaced by current, actual costs gathered from prototype builds and field experience. The up-to-date data enables the engineers to quickly react should the project diverge from the specified cost target.

3.3.2 After Action Review

In many cases, after action reviews (AAR) are only held after a product is launched and, depending upon the length of the development schedule, lessons from early in the process are often forgotten. Depending on the scope of the development project, AARs at Baker Hughes can range from one-on-

one interviews in which checklists and interviewing techniques are used to facilitated workshops involving all DfX stakeholders.
The knowledge gained can flow among others into improved:

- Assumptions for financial calculation
- Engineering standards and processes
- DfX scorecard criteria

Moving forward, the goal is to further integrate the gathering of lessons learned into the ongoing development process. By integrating lessons learned concurrently within development, the effort of gathering lessons learned after the project has finished is significantly reduced. In recent projects, particular attention has gone into reviewing the design recommendations that were accepted or declined by the design team and identifying the reason for the decision.

4 CASE STUDY

This case study encompasses the goal of devising a product with similar functionality to an existing one, but with reduced OPEX. A cost model was utilized to forecast and track both CAPEX and OPEX. Among others, subject matter experts from product line, finance, reliability, manufacturing, assembly, testing, maintenance and overhaul, and operations participated (Figure 4).

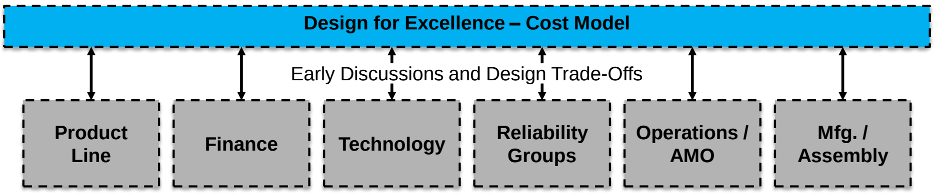

Figure 4: DfX SMEs focusing on trade-off discussions

Early on, emphasis was placed on identifying the key cost and reliability drivers. Both manufacturing cost estimates and the maintenance strategy were utilized and crucial issues identified by conducting Pareto Analysis. The analysis was conducted on a components, assembly, and systems level. Where applicable, trade-off decisions between CAPEX and OPEX were completed.
A typical trade-off example when modeling the cost of a sub-assembly was to determine if, over the entire life cycle of the product, it would be more cost effective to increase the manufacturing expenditure, and reduce the maintenance cost, or not. In instances where the module is disassembled several times during its life cycle, the increased manufacturing is justified.
As issues were identified and a plan was put in place to address those issues, the cross functional team actively engaged in performing refinements. These steps are continuously conducted throughout the development, iteratively improving the design, always based on data driven decisions.
The overall approach emphasizes the need to develop accurate life cycle cost models, and over time, improve those. Therefore, monitoring the actual product manufacturing and operational costs is essential. The chart in Figure 5 depicts the relative OPEX as well as the benchmark and target, monitoring the first year after the initial prototype is built. Initially, as expected, expenditures increase significantly and surpass the target during the first months (which can be attributed to the higher operational costs of a small fleet of prototypes). As the fleet size increases and all parties involved are more proficient in maintaining the new product, OPEX are reduced. Ultimately, to ensure the target is met and maintained, the key cost drivers, as identified via the cost model, are continuously monitored by the project team and corrective measures taken where applicable. Monitoring ensures that cost increases are addressed nearly in real-time, such as is the case mid- year, as costs first increase and then decrease.
By focusing on continuously integrating stakeholders during product development utilizing the Life Cycle Cost Model and visualizing the respective trade-offs early on, the project team was able to accurately forecast and reach the target cost, while at the same time delivering a successful new product in record time.

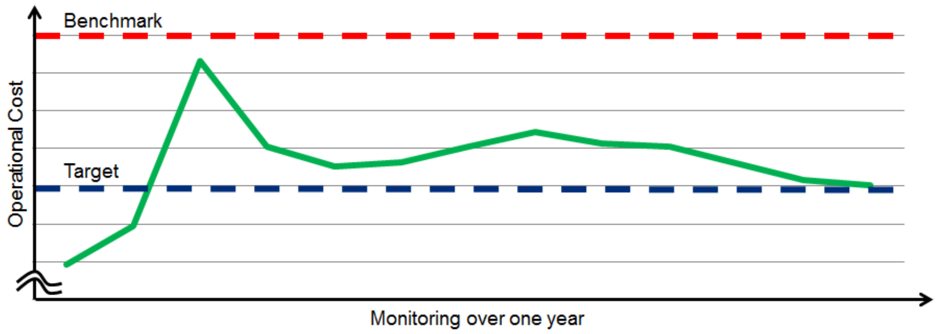

Figure5: Monitoring OPEX on newly developed product

5 SUMMARY

A holistic design for excellence model based on life cycle cost and scorecards ensures the integration of discipline experts and an auditable process of data-driven decision making. Costs are used to weigh alternative design decisions with the goal of life cycle cost reduction. The weighing of the financial impact of all design decisions and a concurrent Life Cycle Cost Model update provides a methodology that assists design teams in making decisions that are best for the product.

Scorecards provide a means, standard across all DfX disciplines, for presenting, tracking and even scoring whether to accept or decline discipline-based design recommendations. A formalized DfX-based concept selection process is also defined. As with other DfX approaches, early and continued involvement between the DfX team, the “X” discipline SMEs and the design team is required. After-action reviews enable active updates to be posted to the scorecards and to capture lessons learned before they are forgotten.

The presented Design for Excellence model enables Baker Hughes to respond more effectively to customer demands by focusing on rules and data-based decisions throughout the entire product lifecycle. Thus, valuable decisions are made and implemented earlier in the development, enabling quicker time to market and the development of more economic products and services.

The key deliverable for ongoing work is further integration of the DfX process into daily design work and to support key stakeholders with automation. Focus is laid on tying the DfX criterion into the product lifecycle management system. Furthermore, the cost models for CAPEX and OPEX are also tied into the product lifecycle system, driving automation.

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