Combustion Engine Development Utilizing Design for Six Sigma (DFSS)

ABSTRACT

Currently, the design of the internal combustion engine are highlighted by a rapid development time with increased demands for high levels of quality, NVH, specific power and lower weight, with reduced production costs. In order to achieve these results, implementation of a new and systemic design management system is required from the outset of the concept to Start of Production (SOP). The most promising way to achieve the demanded goals is through the Design for Six Sigma (DFSS) process. The DFSS approach includes both manufacturing and serial production issues in the initial development phase.

FEV's methodology for DFSS will be explained in single steps, using specific examples. The information contained in that explanation will include QFD, FMEA (product and process), scorecards, DOE and kneading process with its tolerance analysis and process capability investigations. In addition, a description of these different tools for each phase of the design process is provided.

INTRODUCTION

FEV Motorentechnik GmbH, (FEV) has created its process for combustion engine development founded on the well-known Design for Six Sigma (DFSS) strategy, based on vast experience acquired through the conduct of a multitude of engine R&D programs. The process is initiated with the definition of the requirement phase and continues through to SOP (start of production). Key elements of Six Sigma methodology were revised during the creation of the process by FEV, so that it could meet the special demands in supporting engine development. Supporting tools were also incorporated in the process to improve the quality and efficiency of the engine's development. The design process is highlighted here; however, other development procedures (analysis, simulation, testing and vehicle integration) are structured in a similar way.

Future quality requirements have been taken into account through an integrated quality and environmental management system that FEV has established. FEV's success is due to attention to quality, performance and customer satisfaction through process control. Designing quality into the product is a primary goal of the DFSS process. Achieving this goal is accomplished through the identification of customer-driven critical to quality features (CTQs) and employing quality management, including DFSS, throughout the development and design process. The design and quality tools used during the different phases of the design process are highlighted in Figure 1.

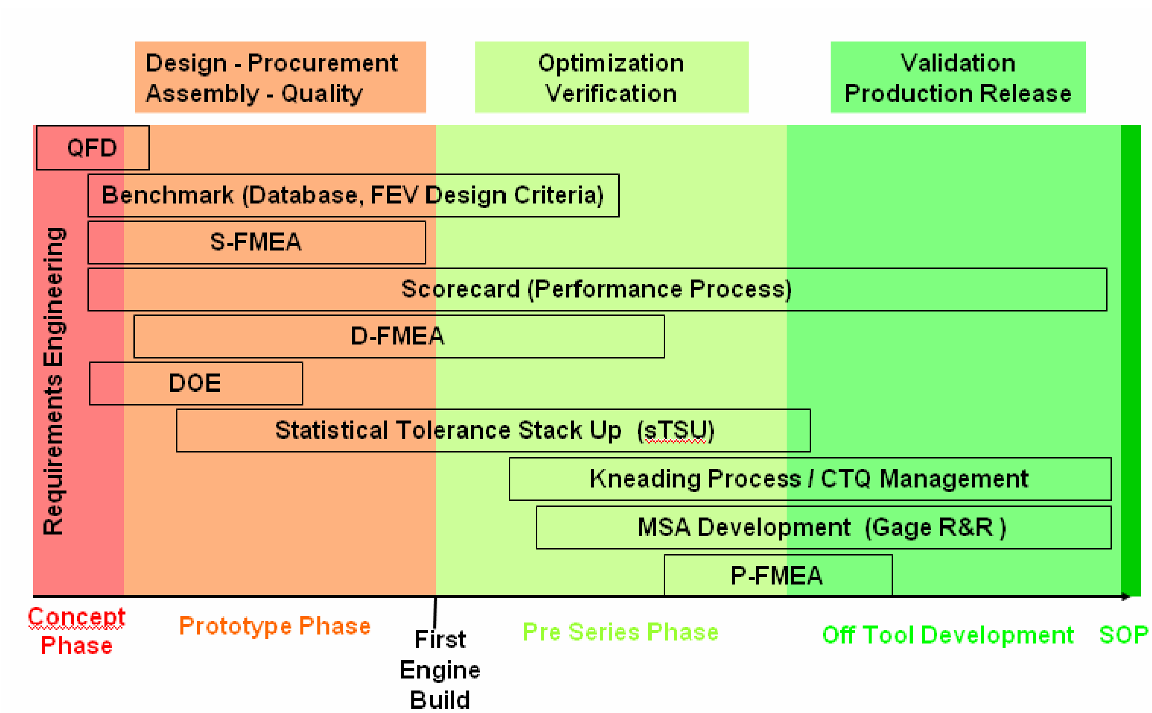

Figure 1. Design / Quality Management Tools

The whole process of designing and developing a combustion engine starts with the task of requirement engineering (RE). During the task of conducting RE, FEV employs the Quality Function Deployment (QFD) tool. The primary tools and processes deployed in the Prototype Phase are benchmarking, system-FMEA (S-FMEA), scorecards, design-FMEA (D-FMEA), design of experiments (DOE) and statistical tolerance stack up (sTSU).

During the Pre-Series Phase, the primary tools become the kneading process, measurement system analysis (MSA) and process-FMEA (P-FMEA). Documentation of all of the available information is made on the performance and process scorecards. These scorecards provide a complete summary of the development status. During the Off Tool Development final design phase all sTSU, kneading processes, MSA and P-FMEA are finalized and documented. The primary tool used during all of the design and development phases is the scorecard, which lists every CTQ and provides a comprehensive representation of the engine on one spreadsheet.

Utilization of specific tools during a development program depends upon the specific customer agreement. Customer support is in fact required for some of the processes. In addition, a number of the described processes and tools that are outlined here (e.g. scorecards, kneading process, DFMEA and sTSU) are always part of the design and development program within FEV.

CONCEPT PHASE

Before the Conceptual Phase of a development program can be started it is essential to fully understand the customer's requirements, which is referred to as the voice of the customer (VOC). QFD is one tool to create a systematic approach to transfer the customer's wants (WHATs) into technical features (HOWs). Another main aspect of a QFD is the improved communication that resulting from the use of a common language between all involved organizations. There are many different approaches how to use QFD and some of these will be described later. The final results of the Requirement Engineering Phase are summarized in a technical specification with a detailed description of all major subassemblies of the engine.

In general, a QFD matrix translates customer wants into product characteristics (engine performance, power, emissions, etc). Another approach is to start with the product requirements (weight, length, height, etc.) and then translate these into a QFD matrix of part characteristics. Figure 2. shows an example of a QFD. On the left side of the QFD, the WHATs are listed to identify the customer's requirements, needs and desires with their rated importance. On the top the vertical list is the HOWs. The QFD-team interprets these listings in different ways to get solutions plus define technical features to meet the requirements. The relationship between the customer wants and technical features indicates how the two lists (WHATs and HOWs) are working with each other (described as blue point, green ring and red triangle). Behind these signs are factors that are necessary to give a priority number for each requirement.

The tradeoffs, located in the roof of the House of Quality, indicate the synergistic or detrimental impacts of the design features. They are used to identify any critical compromises in the design.

Within the Concept Phase, the main focus is in the investigation of feasible solutions for the major engine components (cylinder head, crankcase, connecting rod, crankshaft, camshaft, bearings and accessories).

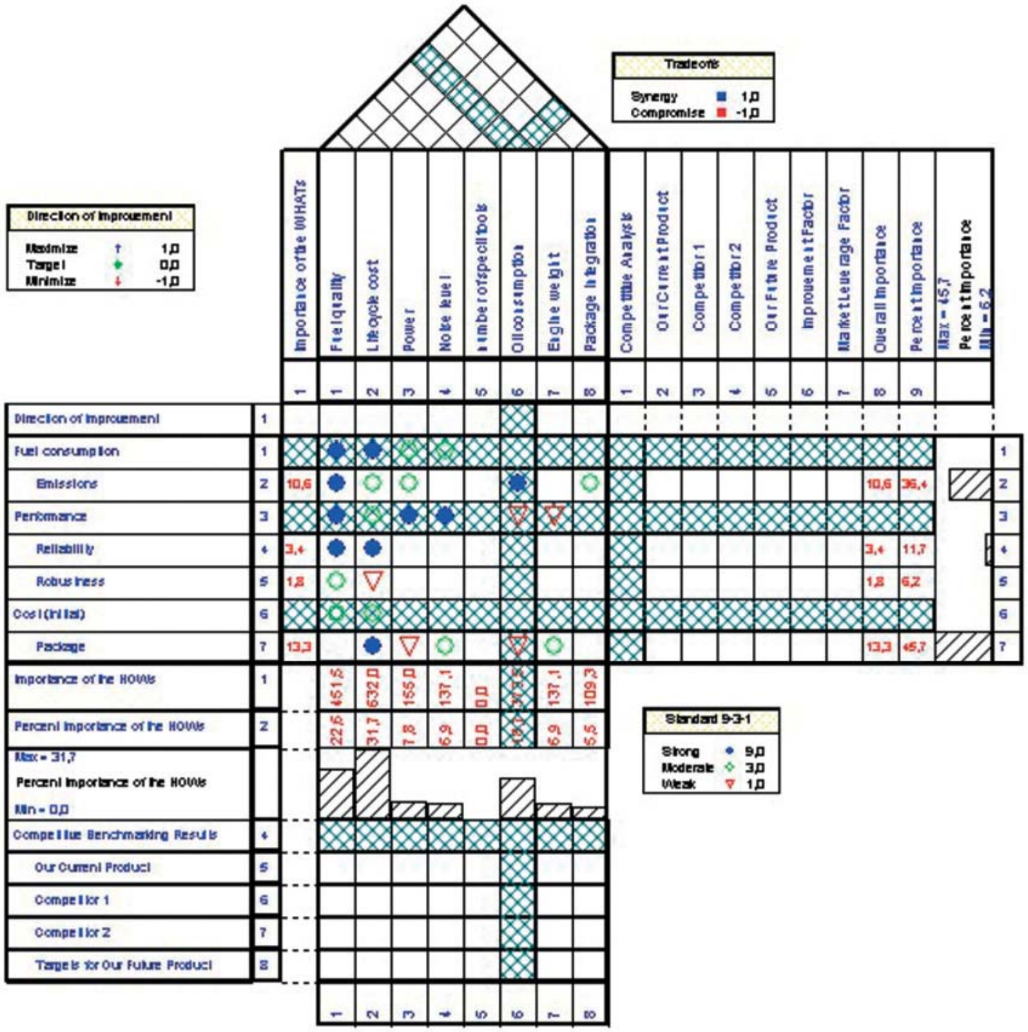

Figure 2. Quality Functional Deployment

One very important element, to support this phase of a development program is to also reference the extensive FEV benchmark database. This provides a well-founded estimation for major design criteria. Figure 3. shows an example with regard to expected engine weights of passenger car gasoline engines.

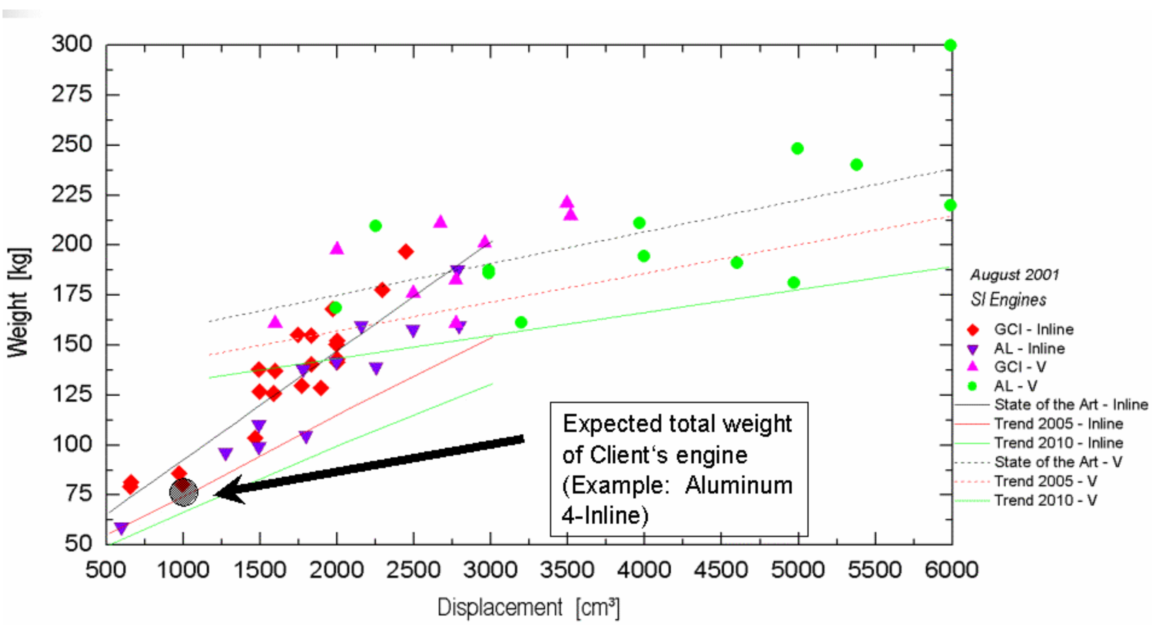

Figure 3. Benchmark Engine Weight

From its vast experience in combustion engine development, FEV has also established design criteria for major design features. These are also used as a guideline throughout the complete development process.

DOE, known as a tool to optimize testing effort, is also used sometimes to effectively investigate design parameters that might have a major impact on the overall engine layout. Figure 4. shows an example for determining crankshaft stresses considering main and connecting rod bearing dimensions. In order to eliminate investigation of too numerous possible configurations, a reasonable range for the influencing factors is defined. Based on pre selected combinations of these factors, the major design criteria, such as, torsional and equivalent crankshaft stress, are calculated.

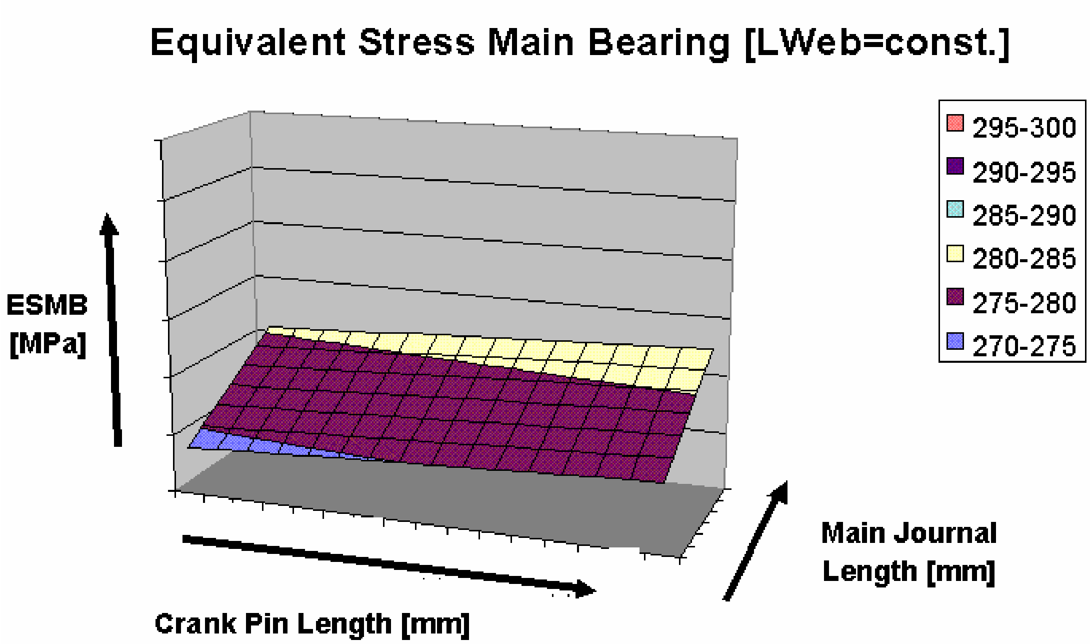

Figure 4. Crankshaft Stress DOE

Before going into the details of each component, a system-FMEA (S-FMEA) for the complete engine is set up to get a first risk assessment for the concept. The function and features could be derived from a previous QFD. During the FMEA meetings a system structure is created, functions are determined and a failure-net is created as shown in Figure 5.

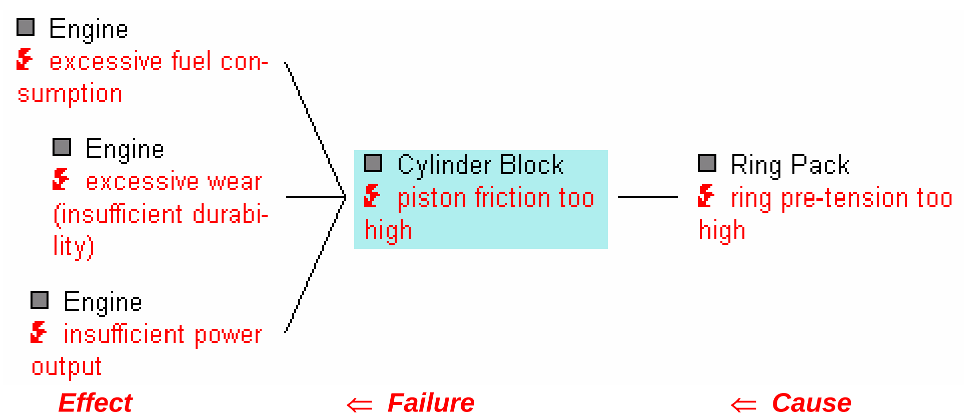

Figure 5: FMEA Structure with FAILURE-NET

In parallel, the main targets and parameters (CTQs), as derived from QFD and FMEA, will be listed on the scorecard. The scorecard will then be monitored throughout the complete design development process. The scorecard is the main and mostly used living document during the design process.

PROTOTYPE AND PRE-SERIES PHASE

DESIGN / OPTIMIZATION / VERIFICATION - In this phase, the first prototype engine will be designed, procured, assembled and tested. The goal is to start the first engine run in the test cell nine months after concept freeze. Based on the S-FMEA, as established during the Concept Phase, other S-FMEA and D-FMEA for the subassemblies and major engine components will be completed. This is done in order to define functional features and identify potential failure mechanism and risks associated with the chosen design.

Every critical output of the QFD, FMEA, customer requirements, etc. will be documented in a component level scorecard as shown in Figure 6. The scorecard is the major document for tracking all critical performance and process features of the major engine components. It is a very effective management tool for keeping the whole development team up to date about the current status in achieving the design targets.

The performance scorecard of a component contains physical requirements such as torque transmission capability, stress or temperature limits etc. as well as cost and weight targets. In order to predict expected failure rates during engine operation, transfer functions will be developed for those physical requirements. These are then documented on the performance scorecard.

All critical component tolerances are additionally documented on the process scorecard. This allows a very effective assessment of the required process capabilities for the different suppliers, including internal, by the customer. If new manufacturing lines have to be set up, it is essential to clearly identify required process capabilities at the earliest point possible.

Scorecard for: put name here (System / Assembly / Part)

$Z_{target (ST)}$: 4,0
n SDEV [LSL;USL]: 8,322

Design Responsible: put name here

No.	Description	Nominal Value	Dim.	LSL	USL	MEAN	SDEV	COV	T		Z_{ST}	Z_B		LSL/USL source	stat. data source	last change date	upper-level CTQ
Performance																	
– Reliability																	
1										2				Z_target estimation	Z_target estimation		
2										2				Z_target estimation	Z_target estimation		
– Maintainability																	
3										2				Z_target estimation	Z_target estimation		
4										2				Z_target estimation	Z_target estimation		
– Cost																	
5										2				Z_target estimation	Z_target estimation		
6										2				Z_target estimation	Z_target estimation		
– Weight																	
7	Piston weight	25,000	kg	24,750	25,250	25,000	0,1	0,40%		2	3,74	2,24	!	Z_target estimation	Z_target estimation		
8										2				Z_target estimation	Z_target estimation		
Process																	
9	characteristic 1	55,000	mm	55,200	55,400	55,300	0,03	0,05%		2	4,64	3,14		design	Z_target estimation		
10	characteristic 2	25,000	mm	24,800	25,200	25,000	0,08	0,32%		2	3,74	2,24	!	design	supplier data		
11	characteristic 3	156,000	mm	155,800	156,000	155,900	0,08	0,05%		2	2,30	0,80	!	design	Z_target estimation		
12	characteristic 4	225,000	mm	225,300	225,500	225,400	0,035	0,02%		2	4,13	2,63		design	supplier data		
13	characteristic 5	15,000	mm	14,500	15,100	14,800	0,11	0,74%		2	3,99	2,49	!	design	Z_target estimation		

Figure 6. FEV Scorecard

The scorecard gives an overview and control based on;

- Listing all critical elements for design, performance and process,
- Having measurable characteristics (part specifications, manufacturing information),
- A design evaluation process (benchmark, Z value)

The scorecard also provides the project management with;

- A system structure (connection between different scorecard levels),
- A documentation process over the complete development project,

- Lessons learned,
- A common language and communication system.

As all manufacturing processes lead to statistical distributed tolerances, it is also reasonable to consider these statistical distributions for tolerance studies during the design phase. FEV has developed an Excel based spread sheet to determine required tolerences, as well as to identify the most important influencing design parameters in a certain dimension chain. Figure 7, shows the statistical tolerance stack up sheet. (sTSU).

FEV Tolerance Stack-up — Enter Description of Tolerance Stack-up here!

1st Chain of Dimensions ("Chain 1"): Enter Description of 1st Chain of Dimensions here!

#	description	dim.	dir.	LSL	USL	T	MEAN	SDEV	COV	source stat. data	contrib. MEAN	contrib. VAR
1	characteristic 1	mm		100,200	100,400	0,200	100,300	0,010	0,0%	design estimate	18,7%	0,7%
2	characteristic 2	mm		99,800	100,200	0,400	100,000	0,050	0,1%	design estimate	18,6%	18,7%
3	characteristic 3	mm		-99,800	-100,000	0,200	-99,900	0,020	0,0%	design estimate	18,6%	3,0%
4	characteristic 4	mm		187,300	187,500	0,200	187,400	0,072	0,0%	FAI	34,9%	38,8%
5	characteristic 5	mm		49,500	50,100	0,600	49,800	0,072	0,1%	FAI	9,3%	38,8%
										p(<)	0,00000	0,99973

Please note: "Chain 1" should be the larger one of both (comp

	MEAN	SDEV	COV	Term	LSL	USL
Distribution of Chain 1	337,600	0,116	0,0%	S	337,000	338,000

MEAN ± 3 SDEV (99.7%)				
	Z Short	3,46	z	5,19 / 3,46
337,253	Z Bench	1,96	p	0,00000 / 0,00027
337,947	DPMO	25.160	p total	0,00027

2nd Chain of Dimensions ("Chain 2"): Enter Description of 2nd Chain of Dimensions here!

#	description	dim.	dir.	LSL	USL	T	MEAN	SDEV	COV	source stat. data	contrib. MEAN	contrib. VAR
1	characteristic 6	mm		-55,000	-55,200	0,200	-55,100	0,050	0,1%	OI	11,6%	27,6%
2	characteristic 7	mm		25,300	25,400	0,100	25,350	0,030	0,1%	OI	5,4%	9,9%
3	characteristic 8	mm		150,000	156,500	6,500	153,250	0,012	0,0%	OI	32,4%	1,6%
4	characteristic 9	mm		225,200	225,500	0,300	225,350	0,018	0,0%	OI	47,6%	3,6%
5	characteristic 10	mm		-14,200	-14,500	0,300	-14,350	0,072	0,5%	OI	3,0%	57,3%
										p(<)	0,00000	1,00000

Please note: "Chain 2" should be the smaller one of both (comp

	MEAN	SDEV	COV	Term	LSL	USL
Distribution of Chain 2	334,500	0,095	0,0%	S	334,000	335,000

MEAN ± 3 SDEV (99.7%)				
	Z Short	5,11	z	5,25 / 5,25
334,214	Z Bench	3,61	p	0,00000 / 0,00000
334,786	DPMO	154	p total	0,00000

p(<) 0,00003

	MEAN	SDEV	COV	Term	LSL	USL
Diff.-Distribution (Chain 1 - Chain 2)	3,100	0,150	4,8%	S	2,500	

MEAN ± 3 SDEV (99.7%)				
	Z Short	4,00	z	4,00
2,65052	Z Bench	2,50	p	0,00003
3,54948	DPMO	6.144	p total	0,00003

Figure 7. Statistical Tolerance Stack-up Form Sheet

This tool also correlates with the FMEA or scorecard and will be virtually completed during the Pre-Series Phase.

OFF TOOL DEVELOPMENT / SOP

VALIDATION PRODUCTION RELEASE - The Off Tool Development Phase primarily focuses on final adjustment for serial production related issues. During the previous design stages all design features were developed, documented and verified. Within this development phase, the main task will be the final tolerance assessment considering the serial production process capabilities. Therefore, the predefined manufacturing process data documented on the process scorecard will be discussed and if necessary adjusted. This adjustment is in close co-operation with the serial production suppliers or the manufacturing departments of the customer.

This process is called the kneading process. In a first step all design characteristics with a Z-score below the target are automatically highlighted on the process scorecard. This ensures a quick overview about design features that would need either additional design investigations to check for the ability to open up tolerances or manufacturing investigations to improve process capabilities (see Figure 8.). Within this kneading process, the scorecard is used to calculate either reachable tolerance ranges (upper and lower specification limit) for a given process capability or a required process capability (mean and standard deviation). This is required if functional requirements would not allow to open up tolerances.

Scorecard for:	put name here	$Z_{target (ST)}$	4,0
	● System ○ Assembly ○ Part	n SDEV [LSL;USL]	8,322
Design Responsible:	put name here		

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Figure 8. FEV Scorecard with Manufacturing Data

The kneading process documents and assesses quantitatively the project progress plus supports the communication within the development-team. In parallel, manufacturing processes are analyzed and rated by use of the P-FMEA. Sometimes it will be necessary to change manufacturing or create new processes (Design for Six Sigma). In both cases a mechanism to control or to measure the results is needed. FEV assists to develop a measurement system for the new features in new or changed processes and shows a capability study for a measurement device as indicated in Figure 9.

FEV

Meßsystemanalyse
Measurement System Aanalysis
Verfahren 1/Type 1: Cg / Cgk - Studie/Study

1/1

Date:		Operator/OU:		Location:	Aachen, Meßlabor	Temperature:	
Cost account:		Customer:				Air humidity:	

Gage		Normal/Master		Charachteristic			
Description		Description		Description	Type 1-Study		
Number		Number		Number			
Resolution	0,00010 mm	Actual value	56,8300	Nominal value	56,8300	USL	56,8400
Test reason	Abnahme/Acceptance	Unit	mm	Unit	mm	LSL	56,8200

Remarks Berechnungsgrundlage Automobilindustrie -

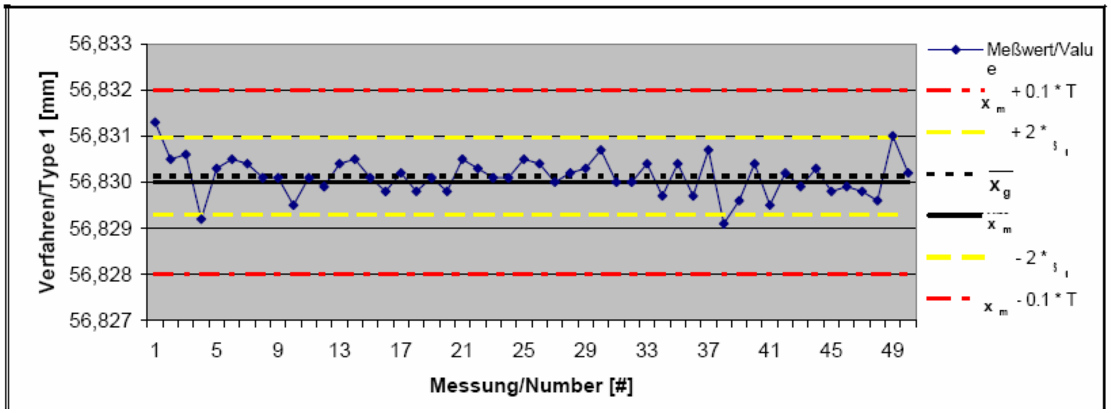

Figure 9. Measurement System Analysis – Capability Study

Another measurement System Analysis (MSA) is the Gage R&R. This is performed to check if there is a failure in a measurement process. In that instance, it is necessary to isolate the failure and redesign the measurement process or look for new measurement devices or train the operator. The MSA information is normally also listed in the scorecard and will be monitored as a CTQ related feature.

CONCLUSION

FEV's systemic approach to the design process allows managing highly complex projects. The subsequent result of the processes and tools presented is an optimized and validated high-quality product. In addition, a secondary benefit is the simultaneously verified manufacturing processes. This method provides a proven and optimum means of achieving satisfied customers.

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