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A NEW INTEGRATED APPROACH TO THE DESIGN OF A RACE CAR SUSPENSION

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ABSTRACT
An innovative approach has been used to design the front suspension of the Formula SAE race car of the Università degli Studi di Firenze. The critical review of the 2005 car showed that it's necessary to improve suspension reliability, reduce Time to Market and costs. DFSS is the only design methodology that allows to resolve these criticities integrating in an organized and structured way several design tools. An Identify – Design – Optimize – Verify (IDOV) approach has been used and through Qualica QFD® has been possible to manage every project phase and the used methodologies like Quality Function Deployment (QFD), Value Analysis and Design Failure Mode Effects Analysis (DFMEA). In the Identify phase, QFD has been used in order to correlate the Voice of Customer (VOC) with the Critical To Quality characteristics (CTQs) and to calculate their importance. In the Design phase the Functional Surfaces methodology has allowed to characterize Functional Requirements (FR) which has been then correlated with CTQs through QFD. Then the Value Analysis has allowed to determine the Design Parameters (DPs) which need to be improved. The suspension Short Long Arm (SLA) is the most important DP, so a new DFSS project has been created to study it. In the new Design phase, Value Analysis has been repeated, Rod Ends and their mounts has proved to be the DP which needed to be improved. These DPs have been re-design, using a Design for Manufacturability (DfM) approach, replacing the spherical Rod End with groved one. DfM has allowed to plan manufacturing processes and to estimate costs with a Bill of Material.
In the new Optimize phase, the failure modes of the suspension SLA have been foreseen through a DFMEA. During this phase, a procedure to measure groving force and one to measure Rod End's friction coefficent have been identify, in order to improve the SLA reliability.
The created model has been used to study the innovation impact on costs and customers satisfaction. It will be used to design the rear suspension too because it has similar functional and structural requirements of the front one.

Keywords:
DFSS, IDOV, DFMEA, QFD, Formula SAE

1 INTRODUCTION
Design is an interplay between *what* we want to achieve and *how* we want to achieve it [1]. A winning product can't be designed intuitively, empirically and involving a trial-and-error process. Although experience is important, because it generates knowledge and information about practical design, it can't be sufficient because the context of application changes. So design knowledge should be organized in order to help designers to take correct decisions as quick as possible. The design world is made up of four domains: the Customer Domain, the Functional Domain, the Physical Domain and the Process Domain. These represent the domain where the concepts "WHAT we want to achieve" and "HOW we want to achieve it" lie (see the structural visualization in Figure 1).

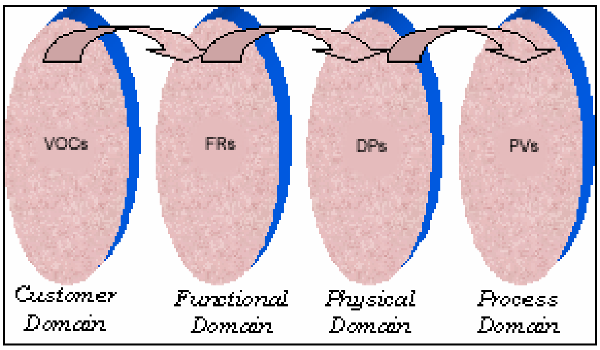

Figure 1. Design Domain

To define the WHAT concept, one starts from the Customer Domain, characterized by Voice of Customers

(VOCs) the customer is seeking in a product or system, and transforms them into a minimum set of independent requirements that completely characterize the functional needs of the product: the Functional Requirements (FRs). In order to satisfy the specified FRs, Design Parameters (DPs) were chosen for the Physical Domain. Finally, to produce the product specified in terms of DPs, a process, characterized by Process Variables (PVs) in the Process Domain was developed [2].

2 DESIGN FOR SIX SIGMA

Design For Six Sigma (DFSS) allows to develop a product or a process capable to meet customer requirements at six sigma quality levels. The classic Six Sigma approach focuses its attention only on reliability and reduction of variation during the production or prototyping phase, whereas Design For Six Sigma allows to focus its attention since the beginning of the development cycle (as showed in Figure 2) when cost of change is lowest and design alternatives are still available [3].

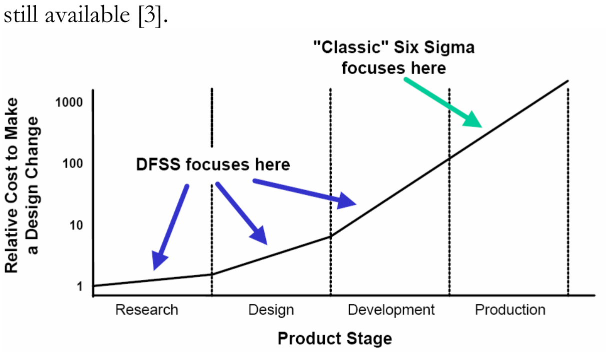

Figure 2. DFSS timing in product development cycle

New product development requires carefully balancing a wide range of needs and requirements. Development teams need to organize and fully understand this information in order to be able to develop a successful product within the boundaries of customer expectation, permitted costs, and available technology.

As will be showed, DFSS incorporates, in a more structurated way, the Axiomatic Design principles and increases their potential integrating them with other product development tools/methodologies.

When DFSS is applied to a new product design, the project is organized following a four-step approach: Identify, Design, Optimize, Verify (IDOV).

DFSS integrates QFD with advanced tools and methods, helping teams to constantly focus on the most important and critical aspects of their work, while keeping overall requirements under control. In Figure 3 are showed tools which can be used in every phase of DFSS project.

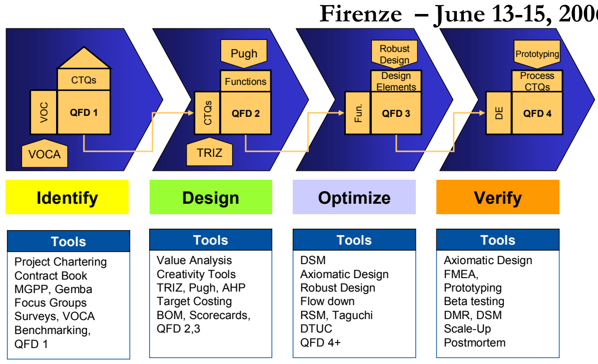

Figure 3. DFSS phases

3 IDOV

Formula SAE (FSAE) is the world championship of the cars designed by engineering students. This is the greatest car competition in the world, because it is joined by more than 200 universities coming from everywhere, which compete with the vehicle they designed, built and tested during one year. The winning car is the one that has an innovative design, a low cost, a high reliability and the highest performance. Every team has to plan its activities taking in account the short period available to build and test the car, and the low budget. The 2006 Formula SAE car of Università degli Studi di Firenze will adopt a Short Long Arm (SLA) suspension layout, that is largely used for racing cars because of the high control of the kinematical parameters, lightness and easy manufacturability [4]. The DFSS project has been created with *Qualica QFD*® software following the IDOV approach.

The Identify phase, treated in [5], has allowed to collect customers' needs related to the suspension and to transform them, through QFD, in CTQs in order to value the global quality. At the end of this phase, it has been possible to calculate the importance of every CTQ that will be used in the course of the DFSS project.

In the Design phase the Functional Surfaces methodology has been used in order to identify the suspension Functional Requirements (FRs). This method allows to analyze surfaces and geometry of the parts and define what the are needed for. FRs have been then correlated with CTQs through QFD 2 and with VOCs through QFD 1* [5].

After the identification of the suspension Design Parameters (DPs), the QFD 3 has been performed in order to correlate DPs to FRs, as showed in Figure 4.

Through a Bill Of Material (BOM) has been then estimated the cost of every DP. Correlations identified in QFD 3 and 2 have allowed to apportion the suspension cost on FRs and CTQs.

Functions 1 \ Design Elements 1		1 Ex-Side Rod End	2 Rod End Plate Ex-Side	3 SLA Plate	4 Push Mount	5 Trackrod Front	6 Trackrod Rear	7 In-Side Rod End	8 Rod End Plate In-Side	Number of significant relationships	Importance %	Costs %	Costs
1 Ex-Side Ro...	1.1 Define the suspension point position	9	1							1	1,5%	8,3%	5,71
	1.2 Trasmit forces from the Wheel to the Ex-Side Rod End Plate	9								1	8,4%	8,3%	5,68
	1.3 Permit the Wheel rotation around the Steering Axle	9	3							2	1,7%	8,4%	5,78
	1.4 Permit the Wheel vertical movement	3	1							1	1,5%	2,8%	1,92
2 Ex-Sid...	2.1 Host and block the Rod End		9							1	11,2%	0,4%	0,29
	2.2 Trasmit forces from the Rod End and Trackrods		9							1	7,0%	0,4%	0,29
	2.3 Permit the link with Trackrods with different angular position		9							1	2,6%	0,4%	0,29
3 SLA Pl...	3.1 Define Push Mount position			9						1	0,2%	0,1%	0,07
	3.2 Link the Trackrods			9						1	2,2%	0,1%	0,07
	3.3 Trasmit forces from Trackrods to the Push Mount			9						1	8,4%	0,1%	0,07
4 P...	4.1 Define Push position			1	9					1	1,5%	0,2%	0,12
	4.2 Trasmit forces from the SLA Plate to the Push				9					1	9,4%	0,2%	0,12
5 ...	5.1 Trasmit forces between Rod End Plates			1		9	9			2	11,0%	11,7%	8,00
6 In-Sid...	6.1 Define the suspension point position							9	1	1	1,5%	23,8%	16,31
	6.2 Trasmit forces from the In-Side Rod End Plate to the Chassis							9		1	8,4%	23,7%	16,24
	6.3 Permit the Wheel vertical movement							3	1	1	1,5%	8,0%	5,48
7 In-Sid...	7.1 Host and block the Rod End								9	1	11,2%	0,9%	0,65
	7.2 Trasmit forces from the Rod End and Trackrods								9	1	8,4%	0,9%	0,65
	7.3 Permit the link with Trackrods with different angular position								9	1	2,6%	0,9%	0,65
Number of significant relationships		4	4	3	2	1	1	3	3				
Importance %		0,11	0,19	0,11	0,01	0,01	0,01	0,09	0,20				
Cost %		27,66%	1,53%	0,36%	0,35%	6,29%	5,38%	55,33%	3,06%				
Costs		18,95	1,05	0,25	0,24	4,31	3,69	37,90	2,10				

9 9 strong correlation
3 3 some correlation
1 1 possible correlation
0 (possible negative correlati

Figure 4. SLA QFD 3

In the classical DFSS approach, the critical FRs and DPs are identified on the basis of their importance calculated in QFD 2 and 3. In the QFD 1, it is emerged that the suspension cost is one of the most important CTQ, so it has been decided to select the FRs and DPs to improve with a Value Analysis (VA). VA allows to calculate the value of a FR or a DP, defining it as the ratio between Importance and Cost. The VA has allowed to determinate that suspension's more critical FRs and DPs are the ones related to the Short Long Arm (SLA). A new DFSS project has been developed to study in depth this issue. QFD 1, 2, 3 and VA have been repeated for the Lower SLA and Rod Ends have proved to be the DPs which needed to be improved.
The goal of Rod Ends re-design is to reach CTQs target, fixed during QFD 1, in order to improve the global quality and customers' satisfaction. In Figure 5 are showed the SLA 10 most important CTQs.

CTQs 1	Optimization	Importance	Target Value	Metric Uni
3 Design Time	↓	10,60%	8	hour
13 Operating Cost	↓	10,08%	2,8	$
5 Reliability	↑	10,06%	120	MTTF
2 Resistance	↑	7,58%	327	MPa
7 Impact resistance	↑	7,12%	1000	N
19 Component's number	↑	7,07%	7	num
10 Environ. impact during USE	↓	6,51%	1,5	Pt
1 Mass	↓	5,70%	0,32	kg
15 Disuse Cost	↓	5,48%	9	$
6 Pointed surfaces	○	5,47%	0	num

Figure 5. SLA 10 most important CTQs

At the first beginning of a new Rod End design, a load analysis has been made and it has showed that the wheel-side Rod End (see Figure 6) was over-dimensioned.

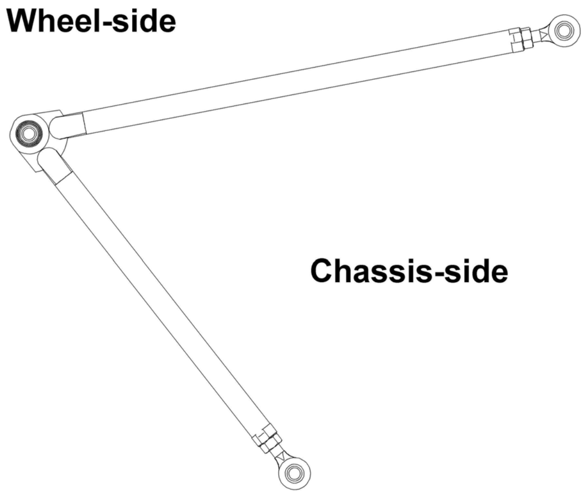

Figure 6. Suspension SLA

So it has been decided to reduce Rod End dimension; conseguentely it has been necessary to re-design the Rod End Mount, showed in Figure 7 left, mantaining the same layout of the previous suspension.
A Design for Manufacturability approach has allowed to plan manufacturing processes and assembling procedures in order to reduce machining time and costs.
The chassis-side Rod Ends (see Figure 6) were over-dimensioned too, so it has been decided to replace Spherical Rod Ends with groved ones in order to improve reliability and to use a unique Rod End type. For these reasons it has been then necessary to design new Rod End mounts, showed in Figure 7 right.

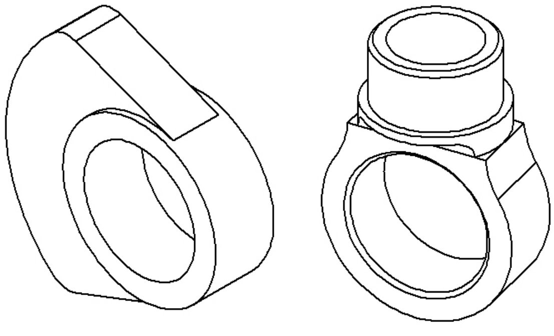

Figure 7. Rod End Mounts (Wheel-side and Chassis Side)

During the Design phase has been possible to verify that the new SLA design has allowed to improve some CTQ (Design time, Resistance, Impact resistance, Environmental impact during use, Mass and Disuse cost), as showed in Figure 5.
As the previous phase the suspension reliability has identified one of the most important CTQ, in the Optimize phase a Design Failure Mode Effects Analysis (DFMEA) has been performed, following the SAE J-1739 standard.
The DFMEA supports the design process developing a list of potential failure modes ranked according to their effect on the customer, thus establishing a priority system for design improvements and development testing [6]. During QFD 1 has been fixed a target MTTF equal to 120 hours for every SLA component. The DFMEA Form Sheet is showed in Allegate A.
During the Optimize phase, the product architecture has been modified in order to improve reliability, following the recommended actions. In details to reduce the *occurrence* two experimental tests are defined:

1) groving force measuring test;
2) Rod End resistance force measuring test;

The first one allows to make a more accurate design of the production process whereas the second one allows to verify that the groving process has been done correctly.
On the other hand to improve *detection* the Rod End clearances are measured.
At the end of DFMEA, through taken actions, the analysis of new RPN (and in particular occurrence and detection) shows a real improvement in terms of Reliability and Operating cost.

4 CONCLUSIONS

An innovative approach has been used to design the front suspension of the Formula SAE race car of the Università degli Studi di Firenze.
The approach proposed in this work is based on DFSS that has provided tools and methodologies to manage every phase of the suspension design. QFD has been used to correlate VOCs with CTQs and to calculate their importance. Value Analysis has been used to determinate the critical FRs and DPs.
The front suspension SLA has been re-designed, using a Design for Manufacturing approach, replacing Spherical Rod Ens with groved ones. Rod End Mounts has been re-designed reducing dimensions, mass and machining costs.
A Bill of Material has allowed to plan manufacturing processes and to estimate costs of every component since the Design phase.
The new design has allowed to improve seven of the ten most important CTQs. A Design FMEA has been performed to foresee the suspension SLA failure modes and to identify design actions and experimental tests capable to reduce *occurrence* and to improve *detection*.
The created model has been used to study the innovation impact on costs and customers satisfaction. It will be used to design the rear suspension too because it has similar functional and structural requirements of the front one.

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6 ALLEGATE A

Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes / Mechanisms of Failure	Occurence	Current Design Controls	Detection	RPN	RPN Treshold	Recommended Actions	Responsability
Define the suspension point position	Rod End breaking	Loss of wheel steer capability	10	Wheel overload	4	-	8	320	150	Avoid Rod End Clearance	-
	Rod End clearance	Toe	7	Teflon wear	8	-	5	280	150	Wheel functional control + SLA disassembly / Avoid Rod End Clearance	Production Team
	Rod End / Rod End Plate clearance	Loss of correct suspension point cinematics	7	Light caulking	9	-	6	378	150	New caulking check procedure	Production Team
Permit the wheel vertical movement / Host and block the rod end	Rod End housing exit	Loss of correct suspension point cinematics	7	Light caulking	9	-	3	189	150	Avoid Rod End / Rod End Plate clearance	Design Team / Production Team
Permit the wheel vertical movement / Permit the wheel rotation around the steering axle	Rod End crushing	High steering torque	6	Heavy caulking	9	-	5	270	150	New caulking check procedure	Design Team / Production Team
Trasmit forces from rod end to trackrod	Rod End Plate breaking	Wheel loss	10	Wheel overload	3	Kinematics Analysis	9	270	150	-	-
Trasmit forces from rod end to trackrod / Permit the link with trackrods in different angular positions	Rod End Plate Weld breaking	Wheel loss	10	Wheel overload	4	Kinematics Analysis	9	360	150	-	-
Define push mount position	SLA Plate bending	Partially loss of suspension bump and rebound capability	7	Wheel overload	5	FEA Simulation	7	245	150	FEA Simulation / Visible Inspection	Mechanics
Define push mount position / Link the trackrods	SLA Plate breaking	Loss of suspension bump and rebound capability	8	Wheel overload	4	FEA Simulation	9	288	150	FEA Simulation	-
Link the trackrods / Trasmit forces from trackrods to the push mount	SLA Plate Weld breaking	Loss of suspension bump and rebound capability	8	Wheel overload	4	-	9	288	150	-	-
Define push position	Push Mount bending	Partially loss of suspension bump and rebound capability	7	Wheel overload	5	-	7	245	150	Visible Inspection	Mechanics
Define push position / Trasmit forces from the SLA plate to the push	Push Mount breaking	Loss of suspension bump and rebound capability	8	Wheel overload	4	-	9	288	150	-	-
Define push position / Trasmit forces from the SLA plate to the push	Push Mount Weld breaking	Loss of suspension bump and rebound capability	8	Wheel overload	4	-	9	288	150	-	-
Trasmit forces between rod end plate	Tube breaking	Wheel loss	10	Cone crush	3	-	9	270	150	Crush FEA Simulation	-
Trasmit forces between rod end plate	Tube Weld breaking	Wheel loss	10	Cone crush	3	-	9	270	150	Crush FEA Simulation	-