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SYSTEMATIC APPROACH TO PRODUCT DESIGN USING AXIOMATIC DESIGN: APPLICATION TO A DIESEL LOCOMOTIVE

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Abstract

The objective of the work is to develop a systematic approach to design that will allow the designer to choose the best solution, as regards product functionality and reliability, in the early design phases. The advantages offered by the use of a systematic approach to design include a shorter time to market and the related cost savings for product development. Moreover the use of a common and unique design process allows company designers to work much better as a team and to share duties easily. This gives the company more flexibility enabling it to adapt more readily to the needs of an increasingly competitive market. The cycle time is reduced in terms of trial-and-error time and money-consuming design iterations. Such results can be obtained by simultaneously analyzing all the characteristics of the product and considering the influence of new technical solutions on all these characteristics.

Keywords: Axiomatic Design, Concurrent Engineering, Product Design & Development

1. Introduction

The design model proposed in this paper regards the identification and analysis of critical requirements which take system level trade-offs and constraints into consideration. This situation is one of the most common in design and it is the most influential aspect in terms of project efficiency and effectiveness. Nowadays the literature provides information on various tools for resolving this problem with a systematic approach: TRIZ, for instance, is very useful, especially when technical conflict arises during the design phase and the physical principles or laws relating to the examined issue are known. Unfortunately the weakness of this method lies in the ability to find the right physical law using the existing database. This is one of the reasons for which there is considerable research activity in this field; this paper presents one possible approach using Axiomatic Design (AD) [1, 2] methodology to simultaneously take into account many aspects of design from the concept of the product to the real product. This is obtained by combining Axiomatic Design with other *ad-hoc* methodologies, such as Functional Analysis (FA), Failure Mode and Effect Analysis (FMEA) [3, 4], Fault Tree Analysis (FTA) [5, 6] and Montecarlo Simulation.

The role of AD is to provide a framework not only for the functional representation of the product, but also for information exchanged among the tools used. This allows the designer to use AD as the core methodology for *product design and development* and to evaluate the best design solution considering roadblocks (e.g industrial strategy), constraints (e.g. laws) and general requirements (e.g. costs) from the beginning phase. First of all, the integration of AD is obtained by comparing the Design Matrices, that represent product functionality perspective, directly to the FA correlation matrix, creating *best practices* that enable the FMEA table and FTA decomposition to be built using AD breakdown. It is then possible to evaluate the general product's probability of success in AD sense, from a statistical characterization of each component. This new model has been tested and optimized by applying it to an innovative diesel locomotive. The new feature of this product consists in the use of common rail fuel injection instead of the classical injector-pump solution. In particular the chassis and the engine of the locomotive were analyzed, and new technical solutions provided in order to enable the design products to better satisfy customer expectations using predictive reliability methods to improve quality before building prototypes (Predictive Design in Quality).

2. The Design Matrix as a framework

Axiomatic Design Theory uses a matricial representation in order to describe the relations between CNs-FRs, FRs-DPs and DPs-PVs. This representation allows an easy understanding of the system functioning with the possibility for improving the information content of the matrix by considering different matricial values for different fields of interest (functional, reliability, cost, etc.) in order to realize concurrent engineering [7].

This advantage gives the design the possibility of using a new developing path for the industrial product. The basic idea of the proposed approach is to use AD representation (design matrices) to create a framework within which all the possible analyses for *"product design & development"* can be performed. This framework would be used to store all this data so all the aspects of a product in terms of its specifications (functional, financial, design, reliability, quality, etc.) could be simultaneously deployed. The idea of the common framework is summarized in Figure 1.

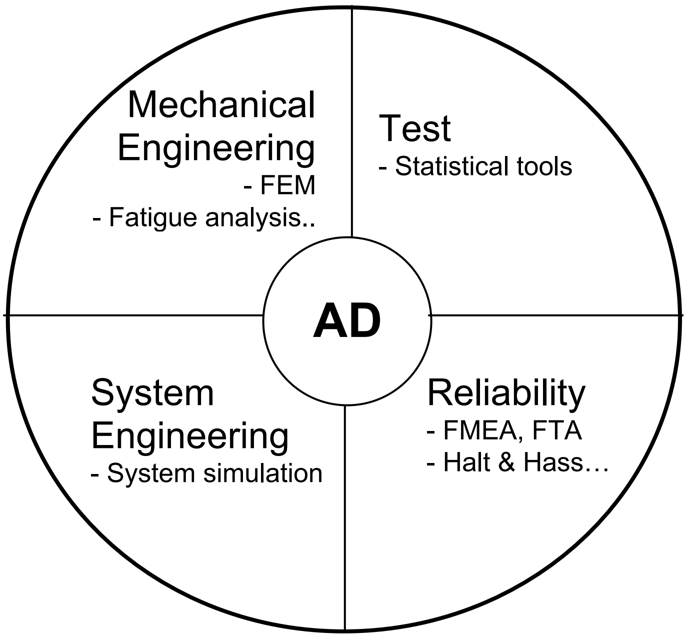

Figure 1. AD framework for product development

The tools and analysis that can share their results (each of these tools provides different information) within this framework might be QFD (Quality Function Development), FA (Functional Analysis), Robust Design, Capability Analysis, DOE (Design of Experiments), FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis) and others. This paper focuses on Reliability Engineering, in particular it integrates FMEA and FTA. These methodologies are used to estimate product reliability, the particular focus of this paper. Other publications by the authors deal with the other aspects [8, 9, 10, 11].

The idea of the model is to start from a functional representation of the product, conceptually given by the integration of AD-FA [11], in order to simplify FMEA development. FMEA is a basic tool used for identifying the root causes of potential product failure at the design stage. Then the information obtained from FMEA is inserted in the design matrix structures to be used by FTA.

The information regarding the analysis done on the product can be stored as a vector of possible value not as a single value of information with each vector relating to a different aspect of the product. This allows for easy representation on the software platform used by industrial designers (the information can be stored as a vector) like the example shown in Figure 2 in which 4 information cells are considered. This new representation is called Extended Design Matrix (EDM) by the authors.

	DP_1		DP_2		DP_3	
FR_1	X	6, 120	0	R	0	--
	1	OR	0	OR	0	AND DP_{12}
FR_2	X	--	X	7, 84	0	--
	0,4	AND DP_{22}	1	OR	0	--
FR_3	0	--	X	--	X	5, 100
	0	--	0,7	--	1	OR

Functional	FMEA (Severity, RPN)
FA (relative importance)	FTA

⇐ EDM legenda

Figure 2. EDM scheme

3. Reliability estimation

The roadmap of the proposed method is constituted by two main steps: the product FMEA, obtained with the help of the functional information stored in the design matrix and FTA of the specific topics identified by FMEA as critical. This second step is performed using the same information that was created by the FMEA process. A flowchart of the process is shown in Figure 3.

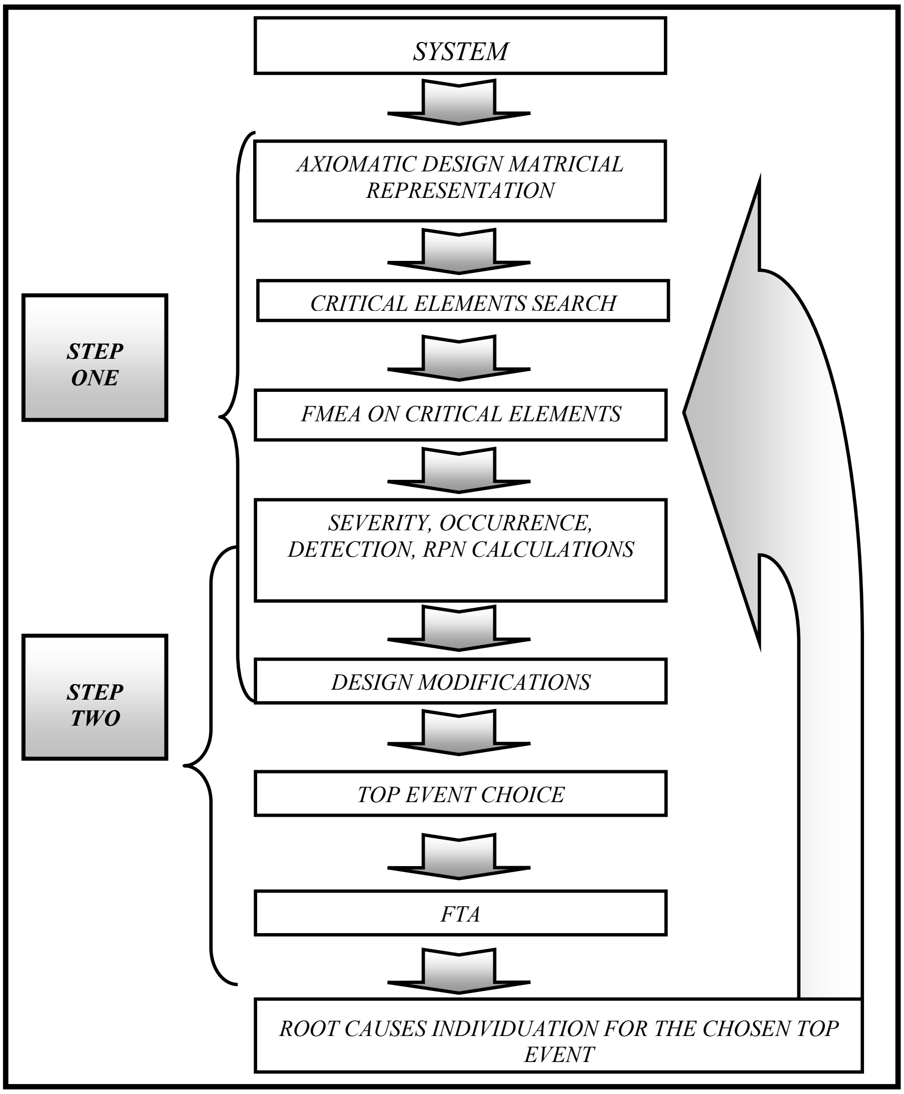

Figure 3. Reliability prediction roadmap

The FMEA process is developed using a simple set of rules. First of all it is necessary to develop a new Design Matrix for the product that considers not only the functional relations between the DPs and the FRs, but is also able to consider the reliability relations. A reliability relation can be defined by the question: "if DP_i is broken will FR_j be satisfied?". Obviously if a functional relation exists between a certain DP and a certain FR then a reliability relation will also be present; the reverse situation has not been proved. The reliability relations will be the same as the functional ones plus a certain number of interactions. This phase will produce a reliability design matrix similar to classical AD representation: an X will be written if the relation is present and a 0 will be written if it is not. From this starting point a high level FMEA has to be carried out on the first level DPs. The objective of this FMEA is to find the most critical branches of the AD breakdown. This FMEA is not so accurate because of the high level examination being carried out. This step is used for reducing the number of branches needing a complete and detailed FMEA. This analysis requires that, for each high level DP, the severity and RPN of the worst failure that could happen due to the failure of the system represented by that DP be identified. The idea is that, if the worst system failure is not critical, it is unnecessary to search all the system components to find the root failure that causes the worst case. A branch that does not have a critical worst case failure will not decompose further with other FMEA. The analysis will focus only on the critical branches: the FMEA will be repeated until the leaf level of the AD breakdown is reached by the critical branch with the same rule, the non-critical branches will not be decomposed further. To evaluate if a branch is critical or not two threshold values are used for the RPN and severity. These values are lower than the usual FMEA threshold values to take into account the possible uncertainty of FMEA performed at high levels. This solution has been chosen to reduce the risk of bypassing critical elements of the product. On the other hand a considerably higher number of branches and elements were analysed than would be the case if these values were considered equal to the classic FMEA approach. For example, given a FMEA threshold of 7 on the Severity parameter and 100 on the RPN (Risk Priority Number) parameter, the screening analysis proposed could use a value of 6 for the Severity and 80 for the RPN, about 20% lower in both cases. A flowchart of the screening analysis preformed on the case study, a diesel locomotive, is shown in figure 4.

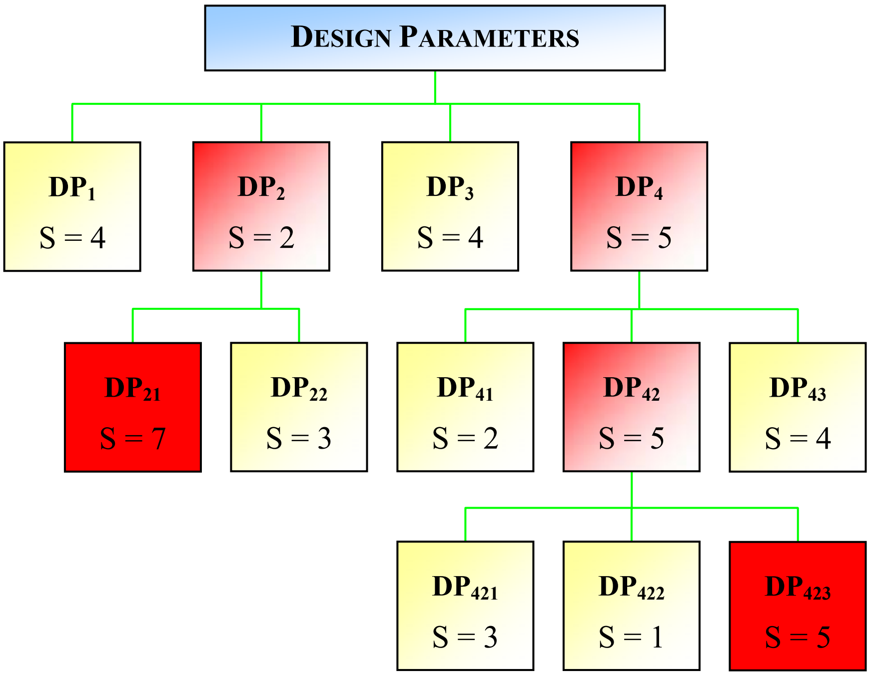

Figure 4. FMEA process based on the AD representation

The advantages of this approach are that the component FMEA is performed only on a part of the whole number, which reduces developing time; moreover the FMEA based on AD representation is more reliable because it is easier to identify the final effect on the product. The information obtained is stored in the EDM in Figure 2 by writing down the value of Severity and RPN where a reliability correlation has been discovered and studied and a R where there is a reliability correlation not studied in detail. The R is given for the reliability correlation belonging to non-critical branches.

The second step consists of detailed analysis to reduce the RPN or Severity values of the critical failure indicated by the previous FMEA. This analysis is carried out using the FTA technique. This technique allows the designer to evaluate the root causes that generate the critical failure and to identify the most effective optimization for reducing the probability or the effect of the critical failure. This critical failure is called Top Event in FTA analysis. So the first phase of FTA is to choose a Top Event according to the FMEA obtained. Having chosen the Top Event it is necessary to find the component failure that generates it. These causes are correlated with the Top Event by means of a Boolean gate: OR, AND, NOT, NOR, Priority gate and so on. The AD representation of the product is then used to find the possible causes and the type of correlation they have with the chosen Top Event. A diagram representing FTA is shown in Figure 5.

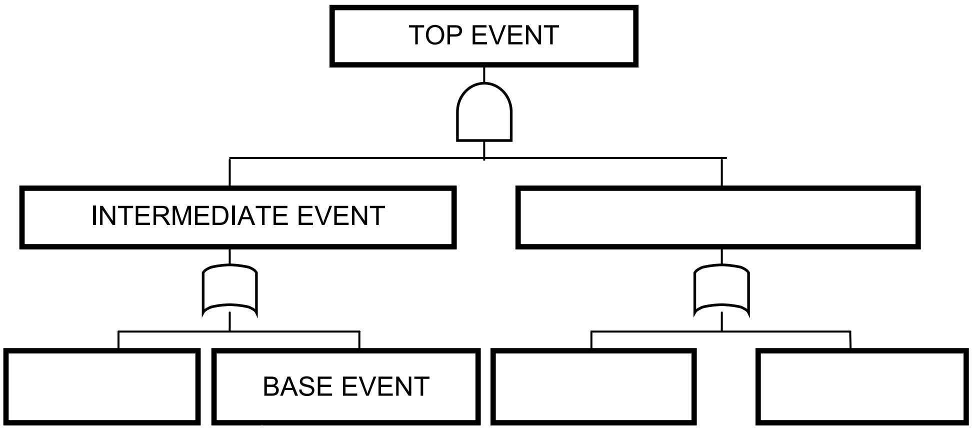

Figure 5. FTA scheme/diagram

The integration of AD representation with the reliability data (a reliability design matrix instead of a functional matrix) make the creation of FTA decomposition very easy. In fact, if the reliability correlation is already available, all that is required to complete the FTA is the identification of the correct gate to connect the causes. The starting point is to create a graphical decomposition that represents the reliability design matrix, then the correct gate is added by analysing the product. The rule for creating a reliability decomposition is simple: the event to be considered is the failure of the DPs; the Top Event is connected to the failure of the DPs of the first level, each of these failures is connected with the failure of DPs beyond the decomposition hierarchies, this decomposition is carried out till the reach of the leaf DPs. The presence of a reliability interaction is given in the EDM by the presence of a value or a R. During FTA decomposition it is necessary to analyze whether all the cause-effect relations are represented in the tree. Sometimes the relations that are related to the AND gate are not present in the reliability analysis performed for the FMEA. The FTA decomposition is to be implemented with these relations. Once the FTA decomposition has been created it is possible, with the use of classic FTA tools. to focus on finding the best improvement for reducing the probability of the Top Event or for reducing the criticality of this failure. The final aim is to reduce the Severity or RPN value associated with the Top Event, as indicated by the previous FMEA. The feedback that the FTA has with the EDM is to report the gate that links a DP to the upper level DP or to the Top Event. In case of an ‘AND and Priority’ gate the DPs to which the gate is referred must also be added. To summarize, the advantages of this FTA process are mainly a reduction in the time required for performing the analysis thanks to an already-made reliability tree, and to the Top Event being chosen on the basis of a previous FMEA.

4. Diesel locomotive case study

The approach proposed has been applied to a new-design V8 diesel engine locomotive, developed for public transportation. This locomotive is equipped with the new common rail injection system, which, until now, has only been used in the automotive field. The use of the common rail system at high power and torque level necessitates some adjustments to the system and these might present reliability problems. Our group applied the approach proposed to fix the possible problems at the design stage, thereby reducing development time and testing costs. Our work has focused on the locomotive engine and this article proposes some solutions regarding the injection system. The engine is represented in Figure 6.

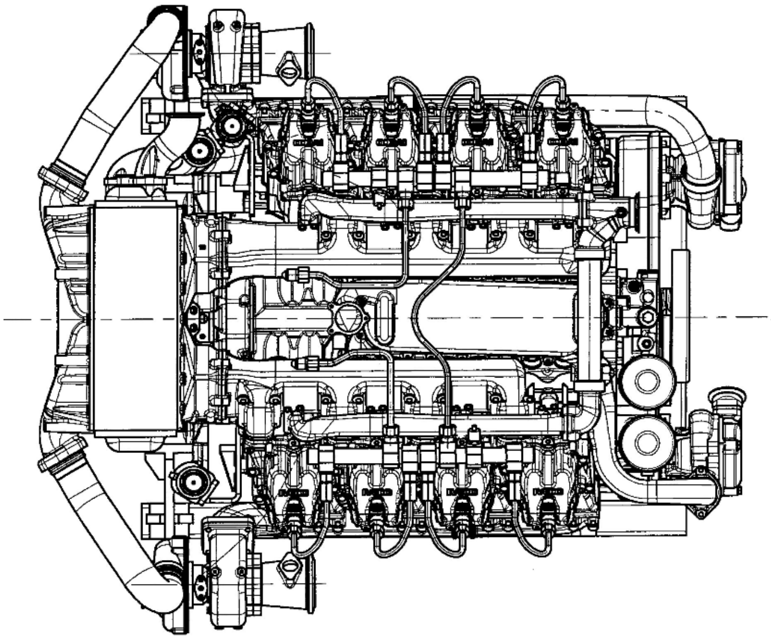

Figure 6. the locomotive engine

The AD representation of the engine was used to develop the FMEA. The FMEA combined with the AD reduced the number of component failures requiring investigation by 60% thereby reducing the time needed for this analysis by about 50%. Two of the most important problems are the probability of the engine catching fire and the probability of the cylinders overheating. Two FTA were set up on these two critical events. The results obtained for fire prevention regard the injection system: the new layout of the diesel hoses and the gasket of the fuel pumps reduced the risk of fluid leaking onto the hottest parts of the engine. Figure 7 shows where these modifications took place.

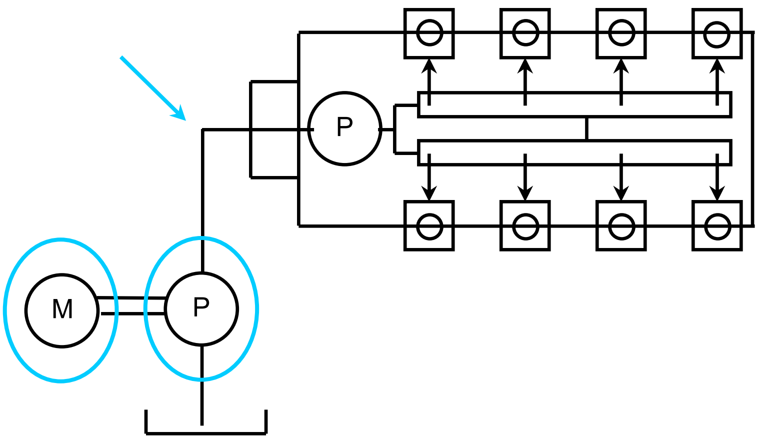

Figure 7. Intervention on the injection system for fire prevention

The proposed interventions regard the control and activation parts of the cooling system to reduce the overheating risk. The need for a flux meter valve and for some temperature sensors in the system was identified. By iterating this approach for all the critical events identified by the FMEA the reliability of the product reached the chosen goal level.

5. Conclusions

The goal of this article is to present an integrated approach which takes care of product reliability throughout the product design stage. This approach enables the designer to reduce the time needed for reliability estimation and improvement thereby reducing development time. The main output of the approach is the EDM, a matrix based on AD representation which stores all the information required for product design (functionality, reliability etc) thereby enabling concurrent engineering to be carried out. This article studies how product reliability could be improved by integrating the FMEA and FTA analyses within the AD framework and the resulting approach when applied to a mechanical case study (a diesel locomotive) proved effective in finding technical solution to boost the reliability value.

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