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PhD THESIS ABSTRACT

RESEARCH REGARDING THE OPTIMIZATION OF THE SUSPENSIONS OF AUTOMOBILES USED IN ROMANIA

THE IMPORTANCE AND THE MOTIVATION OF THE PRESENT STUDY

This doctoral thesis approaches an interdisciplinary field, namely the mechanical engineering in general terms, the automotive components design and optimizations resulting from computer science field.

The achievement of this thesis is based on multiple reasons, among which I mention: the need for applied engineering studies, with the aim of optimizing the building of automotive parts, the favorable social impact such a study has, usefulness of developing computer-assisted systems to improve the management of car maintenance and the reliability of their predictions, the importance of interdisciplinary approach, the own experience as an engineer for vehicle repairer.

CHALLENGES IN THE VEHICLES RELIABILITY

Reliable system design is concerned with making systems work even in the face of internal or external problems. In the automotive domain reliability refers to designing a car that is safe. In this sense it should be developed applications that control real-time vehicle. The modern automobiles are complex technical systems which require control systems that are physically distributed around the vehicle (15 to 20 base aggregate subsystems with different functional responsibilities and mechanisms). Networks have been designed specifically to meet the needs of real-time distributed control for automotive components. The basic fact that drives the design of control systems for vehicles is that they are safety-critical systems. Errors of any kind - component failure, design flaws, exceeding the number of kilometers that have made technical revision, etc. - can injure or kill people. Not only must these systems be carefully verified, but they also must be architected to guarantee certain properties [1].

In the operation process and even in downtime period of vehicles occurring phenomena leading to worsening functional indicators and partial or total loss of functional capacities and performance. Preservation in time the whole system performance leads to vehicle reliability. An important parameter that defines cars reliability is the Reliability Index [2], a score that is calculated as a combination of the number of times a car fails, the cost of repairing it, the average amount of time it spends off the road due to repairs, the age of the vehicles. Influencing factors resulted in operating conditions can be related on the one hand the quality of the various materials used to maintain the functionality of the vehicle such as lubricants, fuels, liquid cooling system, brakes, actuators, etc., and on another part of the travel and transport conditions highlighted by road and climatic qualities, operating system, quality management and others. During vehicle operation are continuous interaction between parts, mechanisms and materials and operating units. Depending on their properties, it speeds up or slows down the degradation of parts and depositing the material residues, with secondary influence on the aggregates' functioning, it changes the consumption of operating material and vehicles productivity. Adopting of operating materials must comply constructive and technological peculiarities of motor vehicles, their technical status and operating conditions. Basic factors of operating conditions that influence reliability and durability are the road conditions, weather conditions, operating mode, quality management, quality maintenance and quality auto repair. Due to operating conditions, the car manufacturers differentiate the period in which they perform maintenance revision, depending by country, geographic area, etc. [3].

The reliability domain is extremely large. When discussing about cars even we have to split the diagnosis in two: the electronic system reliability and the mechanical system reliability. Therefore, in this paragraph we first intend to explain some basic concepts about reliability and then to focus on some challenges in terms of vehicles' reliability, mainly of mechanical's system, exemplifying with OPEL cars.

Basic concepts

The *availability* of a system at time *t* is the probability that the system is operating correctly at time *t*. The *reliability* of a system at time *t* is the probability that the system has been operating correctly from time zero until time *t* [2]. However, many times reliability is less appropriate metric. In the event of a catastrophic system failure car, reliability is a less useful metric than availability. *Maintainability* is the probability that maintenance of the system will retain the system in, or restore it to, a specified condition within a given time period. Reliability, availability, maintainability (RAM) are fundamental features of any system and the RAM performance should be optimized to get the best value from the engineering design and enable a system to meet the service expectations.

After duration and mode of occurrence there are known three kinds of faults and errors:

- *Transient* (due to electronics circuits),
- *Permanent* (due to physical wear-out, fabrication defects or design bugs)

- *Intermittent*.

The complicate design of technical systems, in order to assure high performance may represent, in some cases, even their degradation sources. In these conditions, it can reach a critical level of development and improvement of systems, in which the recovery time would equal the production of new products. Avoiding such situations is the basic principle of terotechnology which involves a continuous improvement in reliability in parallel with technological development [3].

AUTOMOTIVE SUSPENSION SYSTEM

Suspension system is a subassembly of the vehicle that connects the rolling elements with the passenger compartment of the car. The functional role of the suspension must be regarded in a double sense, on the one hand is designed to retrieve and transmit evenly to the ground the loads and forces applied on the vehicle and on the other hand it isolates the passenger compartment of the vehicle by the stresses received from the roadway, thereby the comfort of the journey is enhanced.

From designing point of view, a vehicle suspension includes: elastic elements (springs), which constitutes the effective suspension, rolling subassemblies, damping and stabilization subassemblies.

Automotive suspensions can be classified after several criteria such as:

-after the guiding device;

-after the elastic element;

-after the type suspension feature.

According to the first criterion of classification (guiding device) suspensions can be dependent or independent.

Elastic element type, suspensions are classified into:

-Suspension with metalic elements;

-Suspension with pneumatic elements;

-Suspension with hydropneumatic elements;

-Suspension with rubber elements;

-Suspension with mixed elements;

Finally, the third criterion of classification - type of the elastic feature - divides the suspensions as follows:

-with linear characteristic;

-step by step characteristic

-with progressive characteristic.

Within the present thesis there have been presented in terms of design the main types of suspensions, used nowadays in automotive construction, as well as theories regarding rolling motion:

A. Independent suspension with helicoidal spring
B. Independent suspension with elastic foot type helicoidal spring
C. Independent suspension with lamellar resilient element transversely disposed
D. Independent suspension with stabilizer bar resilient element
E. Independent suspension with pneumatic resilient element
F. Stabilizer bar
G. Rolling motion

THESIS OBJECTIVES

The general objective is to contribute to increasing the reliability of Opel cars operated in Romania and the passenger comfort by optimizing their suspension.

In accordance with this overall objective, this doctoral thesis proposes the following specific objectives:

1. Synthesizing and structuring the actual stage of the researches;

2. Accomplishing an analysis of reliability and maintenance of passenger cars by implementing a relational database and the creation of a software application for the management of maintenance thereof;

3. Implementing of multi-objective optimization algorithms for optimization of suspension system as the main vulnerability;

4. Mathematical modeling for kinematic and dynamic simulation of the suspension system.

5. Advanced optimization of suspension parameters in order to achieve the target of stability and comfort in different operating conditions;

6. CAD three dimensional modeling of the anti-roll power link

7. The topological optimization and carring out static analysis through finite element method of the anti-roll power link body.

8. Experimental study on mechanical and elastical characteristics of the raw material of the anti-roll power link and its behaviour at the most important stresses in operation.

IMPLEMENTING A RELATIONAL DATABASE TO SURVEY CARS' RELIABILITY EXPLOITED IN ROMANIA

In this section, starting from Microsoft Excel documents we developed a crawler module and we designed a relational database that supports time analysis of defects cars. By highlighting common patterns present in car service and parts production failure, and through their intelligent analysis may result important information regarding to cars' reliability and maintainability. Experimental research was to study the behavior in operating a well-determined period of time of Opel cars and data collection from invoice services documents. With the help of this software application it can gather huge history information from any car service indexing files system and, through further investigations, the manager obtains an extremely agile understanding of the common malfunctions that a car system can suffer and even point out to parts producer, patterns that appear in their design.

The main aim of this chapter is to implement a relational database to survey cars' reliability exploited in Romania. By emphasizing certain patterns (spare parts / maintenance services) that frequently occur in the automotive services and through their intelligent analysis may result important information regarding to cars' reliability and maintainability. This will improve the quality of spare parts production through focusing on specific directions depending on the geographic area, the infrastructure of the region, environmental conditions, characteristics of fuels, etc.

The scientific approach is based on Data Mining - an interdisciplinary field of computer science that aims to discover patterns in large data sets. Methods involved are at the intersection of artificial intelligence, machine learning, statistical and database management systems. As we detailed further in section III paragraph C, we developed in Microsoft Visual Studio 2012 (using C# programming language), .NET Framework, using Microsoft SQL Server 2008, a software application that extract the relevant data from archive of orders with maintenance service operations, automotive components and spare parts. Further, these commands will be called briefly invoice services (IS). The application's input consists in information from any car service indexing files system. Currently, these information are office documents of Microsoft Excel and Microsoft Word types. The purpose of the application (output) is to design, implement and populate a relational database with extracted data. As more data are extracted as more accurate will be the analysis. At present, the database is customized to serve at AutoHaus Huber SRL Sibiu, OPEL dealer, but with small modifications it could be extended to any auto service from Romania or outside.

The present application is extremely useful because the processing and interpretation of data extracted obtain a fairly accurate understanding of the common faults that may occur in operating a motor vehicle, may determine the causes of breakdowns, can identify abnormal wear. Also, it can track mode troubleshooting and even it can suggest to manufacturer the templates that appear in spare parts design. This type of analysis is called “Business intelligence” and it is becoming one of the key factors in planning marketing strategies. With this pattern recognition ability the management team can easily take decisions that in the past were consider risky and dependent on the manager skills on the subject.

The further organization of this section is as follows: Section 4.1 describes the Database Architecture. It starts with a theoretical background regarding Database design, then it introduces the developed three-tier architecture, it details the business layer concept and finishes with Database mapping, presenting the data structures and relations between tables.

DATABASE ARCHITECTURE

A. Explaining the basic concepts

Because our paper has an interdisciplinary character applying domain-specific tools computer science in industrial engineering, specifically road vehicles and transportation engineering, we start this section by explaining some main concepts regarding databases. The first step in order to implement a relational database that supports time analysis of defects cars is data collection and analysis and implementation of a conceptual model. At this stage are considered nature and the use of data. Identified data will be stored and processed, and are divided into logical groups and establishes relationships between groups. This stage should be according with client's requests (in this case OPEL). The most important feature in database design is the normalization. This technique eliminates / avoids certain anomalies and data inconsistencies. Thus, the data should not be redundant and data manipulation operations (update / insert / delete) must ensure database integrity. A design tool of conceptual model of relational databases is Entity Relationship Diagram (ERD). An ERD developed during the conceptual data modeling phase of the database development process is generally transformed and enhanced through normalization principles during the logical database design phase. The next design step is to transform conceptual model into logical schema of data model. The database model is not just a way of structuring data, but also defines a set of operations that can be performed with the data and also defines a set of rules in order to keep database integrity. One of the most common data models, and which we used in our application is the relational (due to the simplicity of data types, text only). The data is organized as tables, there are relationships between them. Relational model based on relational algebra made possible development of relational languages as software that assists the implementation of databases. One such language used in this application is SQL (Structured Query Languages).

B. The proposed three-tier architecture

We use 3-tier architecture in our software application. Commonly, 3-tier architecture consists of the following three tiers (levels):

- ***Presentation tier*** as known as Frontend

This is the topmost level of the application. It is the layer which users can access directly such as a web page or application GUI (graphical user interface). Through the presentation tier the user / client ask for information such “Get the most replaced component?” or “Which is the most performed operation to a certain car?” It communicates with other architectural tiers in order to output, finally, the text or graphical results.

- ***Logical (Application)*** tier that includes Business layer and Data access layer, as known as middleware

The logical tier is pulled out from the presentation tier and, it controls an application’s functionality by performing detailed processing based on set of rules. The Business layer includes the Crawler module that is responsible for data mining in office documents, parsing, computing, and synchronizing. The extracted data are collected and indexed. With their help, in the Data access layer (software implemented in the Database module), are conceived and designed the conceptual scheme of database, tables and relationships. This layer manages accesses to database by means of SQL, transforming customer requirements from the Presentation layer in database queries. After Database tier provide the requested data these are forwarded back to the Presentation layer.

- ***Database tier as known as Backend***

This tier is the physical storage layer, responsible for data persistence and consists of database servers. Here information that comes from processed data during the Logical layer is stored and retrieved and forwarded back to Logical layer. This tier keeps data neutral and independent from previously two tiers. Giving data its own tier also improves scalability and performance.

By splitting the application's architecture into 3 logical layers - presentation, application and database access, are improved the development efforts, allowing re-usability and extensibility as much as possible, increase maintainability and by division of work ensure a faster development. The idea is to reduce the overall maintenance and increase the scalability of your application.

C. Description of business layer concept

We developed a 3-tier database architecture. The application's input are office documents of Microsoft Excel type that represent the invoice services collected for last 5 years from AutoHaus Huber SRL Sibiu, OPEL dealer.

The key aspect of this software implementation is the ability to gather information as easy as it can. This is due to the fact that larger history means higher accuracy rate. So to be able to gather information from all possible car services providers means we need an intelligent document template interpreter. This points our first software module *Crawling Module.*

"Crawler" is a generic term for any program (hardware - such as a robot or software - web application), used to automatically discover and scan new locations / sites by following links stepper or links from a Web page to another. In this case, the application requires such a module because every day, at every vehicle checked / repaired, new data appear in the system and even new pattern of faults. The Crawling module provides the interface with actual data present on client computers (in this case, OPEL Company). This module is responsible for collecting these data, index them (assigning indexes for different spare parts / operations, etc.) and then forward them to the next module, Database. Some of these data are field names in the developed tables and others will be field values.

In such real-time application, the synchronization and data consistency are very important. An issue consists in dynamically configuring of moment when the files are parsed and extracted dates, and then are inserted into database. Crawling module creates a hierarchy of files and ads in each folder a file with the extension .nrd used for indexing and synchronization.

In the process of normalization of data from Business layer, we face some integrity problems. The first error was due to car brand - "Marca" field from "Autoturism" table that does not correspond with the car driven series chassis. The second was due to incomplete synchronization of data. Some spare parts were assigned to “orders” in “ListaPiese” table that were not registered (yet) on invoice services (in “Comanda” table). The first error was eliminated by Crawler module implementation in a chassis code checker which automatically corrects and updates the “Marca” field. With our implemented solution for auto correction, we reduced by 70% the erroneous data. The second error was treated by resynchronization of data (after short period of time) and, if the error still persisted, these records were removed from the database. Another problem that has required attention in order to preserve the integrity of database consisted in aligning data text variables in varchar fields of databases tables and removing empty spaces from field names. Such situations may be encountered due to negligence of human operators who place wrong values or, leave empty spaces on invoice services.

D. Database mapping

After having data crawled and ready for storage there was needed a mapping structure in the database taking into account the obtained data and their type. The following tables are currently mapped in the database: Autoturism, Comanda, ListaOperatii, ListaPiese, Piesa. Figure 4.1.4 shows the implemented database structure, the component tables and main fields, primary keys, etc.

Database module is responsible for designing the conceptual scheme of database and mapping, performing database queries, being able to handle huge bulks of data. It is interfaced with the Crawling module and adds data in safe location data storage to be accessed later by all users. This way we connect our local extracted data to the global database (Database tier) thus creating a data share point.

These data mappings tables are created for a single file template, currently an Excel file. With the use of these tables, a data visualization module that we will implement as further work, will have enough available data for further management and marketing analytics.

As a short explanation of fig.4.1.4, basically there is a unique code (primary key) of car chassis ("sasiu" field in "Autoturism" table) but in "Comanda" table can find many records with the same car chassis (as the same car was repaired on several times using different invoice services). The link is named 1 to many relationship.

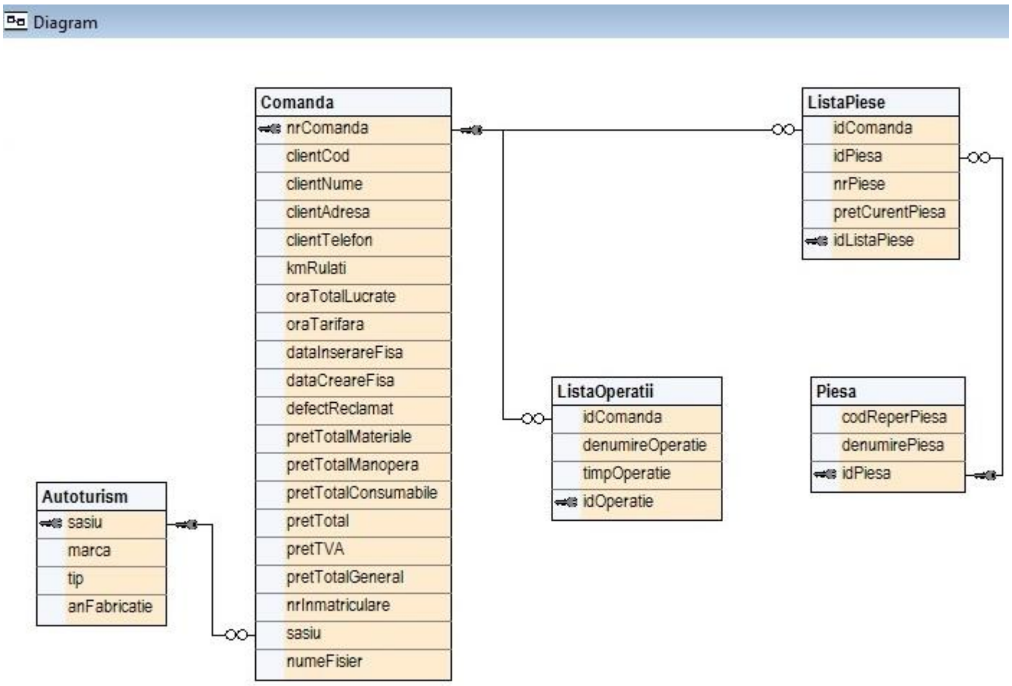

Fig. 4.1.4. Relationships between database tables

In this thesis section, starting from Microsoft Excel documents we developed a C# crawler module and we designed and populate a relational database that supports time analysis of defects cars. We removed some database integrity problems which were caused by employees that completed wrong some invoice services or due to later or no synchronization. The usefulness of application developed consists in efficiency interpreting of extracted data. These information could provide a fairly accurate understanding of the common faults that may occur in operating a motor vehicle, may determine the causes of breakdowns, can identify abnormal wear.

We intend to continue working on this application bringing new features, and to exploit the created database, in order to identify the main faults and the possibility of optimizing the operating conditions in Romania. Also, experimental validation proposals for improving technical quality using some CAD tools we plan.

RELATIONAL DATABASE MANAGEMENT SYSTEM

A. The main features of SQL

In practice, creating and using relational databases requires a standard language that allows these operations. Thus, it was developed a relational programming language as software that assists the implementation of databases. IBM has made in the middle of 1970s the first implementation of the SQL (Structured Query Languages). Today SQL is fully standardized and is recognized by theAmericanNationalStandardsInstitute (ANSI).

The SQL commands can be classified in 5 categories: Query commands, Data Manipulation Languages, Data Definition Languages, Transaction Control, and Data Control Language.

B. Database queries for highlighting the behavior in operating of OPEL cars'

In this paragraph we present the Database queries for highlighting the behavior in operating for a determined period of time of OPEL cars'. With the help of queries we intend to emphasize common patterns present in car service and parts production failure.

For accessing data in the database layer, we need to make some queries and return appropriate data. The following tables are currently mapped in our database: Autoturism, Comanda, ListaOperatii, ListaPiese, Piesa. Further, we exemplify some queries that we used in our application.

- Chassis identification in database in order to incorporate a new record in the cars' table ("Autoturism").
- What is the number of operations performed every day and how much cost the workmanship? Grouping records by date/time field in a predetermined range and ordering low revenues. Using aggregate functions.

SELECT dataCreareFisa, COUNT(*) as total_manopera, SUM(oraTotalLucrate*oraTarifara) AS suma_incasata_manopera FROM comanda WHERE (dataCreareFisa>'2009-1-1') AND (dataCreareFisa<'2010-1-1') GROUP BY dataCreareFisa ORDER BY suma_incasata_manopera DESC

- Ensuring integrity restrictions (deleting spare parts that appear in commands that do not exist in "Comanda" table) by using nested queries.
- Based on the relations established after normalizing of database may associate related tables in a formal way, easy to use, so that to combine data from multiple tables within the same query, while maintaining the flexibility to include only the interesting information for user. To do this, we used relational operators such as intersection, difference and Cartesian product of two or more tables.

C. The Data Visualization module

As we stated before, this section presents the Presentation tier of previously started 3-tier database architecture. This layer (implemented here in Data Visualization Module) is the topmost level of application by which users have directly access such as a web page or application GUI. Through the Presentation tier the user / client ask for information such "Get the most replaced component?" or "Which is the most performed operation to a certain car?” It communicates with other architectural tiers (Logical and Database – implemented by Crawling and Database Modules) in order to output, finally, the text or graphical results.

The Crawling Module offers the interface to the real data, present on computers of OPEL service station (extracted from invoice services). This layer has the task to gather this data, indexing it in and then present it to the next module, the database. For ordinary users data in a raw format (unformatted data, unstructured, unorganized) means headaches, and showing this data extensively proves nothing, even creating confusion. That’s why, for a higher impact on the subject special graphic libraries needed to be created or extended, because it is well known that “A picture is worth a thousand words!” Despite the fact that the design is appealing it also brings the user the possibility to “grab” graphs and navigate them for a better understanding and take the proper decisions.

Our application provides a user friendly output interface. First, you can select the range time for study. The next step is to choose whose is applied the analysis: individual or general.

However, for a time analysis, we consider quantifying the frequency of defects' occurrence on certain types of cars (general view) and vice versa, by introducing a certain type of car to get parts with the lowest reliability (On what cars occur the most defects?). Other facilities of our application are:

- Identifying the operations frequently carried out to a certain (all) car(s) for a well-defined period of time by choosing “TopOperatii” option, or determining how many times was performed a certain operation.
- Identifying the most commonly replaced parts to a certain (all) car(s).
- Time analysis of revenues. Financial approach of company based on the repaired cars.

EXPERIMENTAL RESULTS

One of the main features of our developed application is flexibility. We may extract a lot of interesting statistics very helpful for mechanical engineer or manager. By highlighting common patterns present in car service and parts production failure, and through their intelligent analysis may result important information regarding to cars' reliability and maintainability. Experimental research was to study the behavior in operating a well-determined period of time of Opel cars and data collection from invoice services documents.

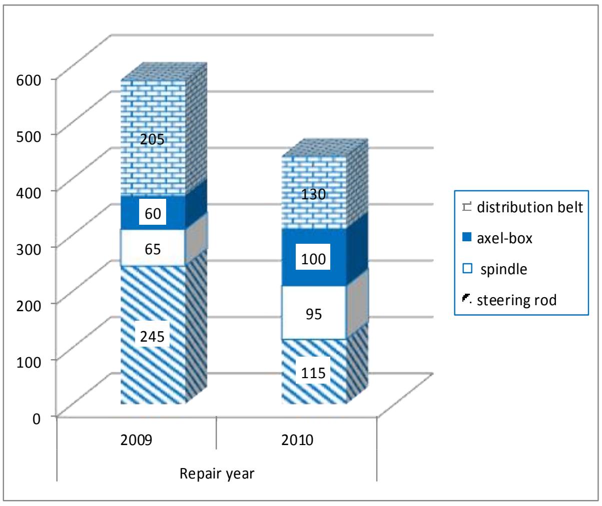

Fig. 4.3.5. Comparative statistics on years of relevant mechanical components that were repaired

The information from figure 4.3.5 may be correlated with the roads degradation in Romania, which influences among others the engine operating conditions, the number of connection and disconnection of the clutch, braking and steering systems.

The evaluation methodology of operational reliability at OPEL cars

In this section we attempt to answer the following questions: What are the most replaced components? Why do these failures occur? What can be done to predict the failures? What solution to apply in order to optimize the system?

In order to answer to first question, in Fig. 4.3.7 we present the parts sales analysis from AutoHaus Huber Sibiu starting with 2007 until 2013 focusing on the best sold spare parts.

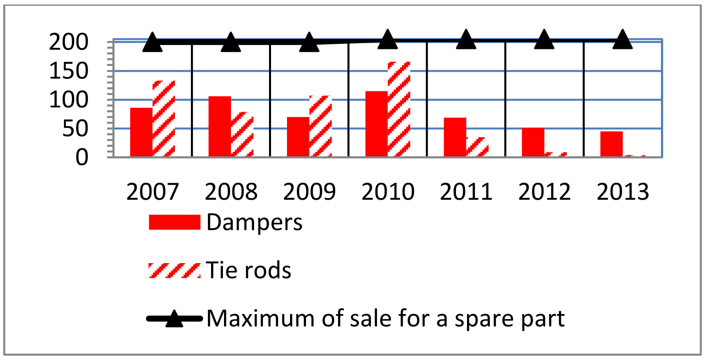

Fig. 4.3.7. Spare parts sold by years.

Among all the sold pieces, there were at most six types of pieces that have been sold more than dampers and tie rods. However, all of these are consumables (filters, antifreeze, engine oil, clips, rivets, spark plugs). In conclusion, the main parts to be considered and whose reliability must be studied are the suspension system components: tie rods and dampers. Therefore, further we focus the assessment only on the two components, by analyzing samples of failures on each 10000 km, until 150000 km.

Based on operational measurements, in our statistics we called as tie rods the following spare parts: inner and outer tie rods, steering rods, anti-roll rods, bushings, ball joints, sway bar links, jam nuts and control arms related. Also, we use the dampers term substituting the following spare parts: damper, bearings, coil spring, buffer, ring and flange related. Of the 3358 repaired cars in service Autohaus Huber Sibiu during 12.01.2009 ÷ 31.01.2011, 271 have damaged due the tie rods and 130 have failed because of the dampers, after a running up to maximum 150000 km. The number of defective dampers is about half of the tie rods and, as the following figure reveals, the maximum number of failures occurred within the driving range between 100000 km up to 110000 km.

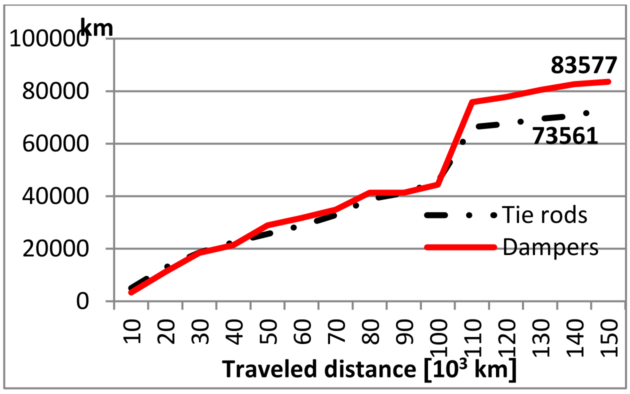

Fig. 4.3.10. Suspension system components: MTTF.

Analyzing the results it is observed that the failure of components is done unevenly and the dampers reliability is higher than that of tie rods. Increasing the number of failures in the range between 100000 km and 110000 km significantly increases the cumulative probability for failure (F) and decreases the reliability function (R).

The results show that the MTTF is about five years of running (estimated time for a travelling distance of 73500 km by a regular driver which runs about 250 km weekly, in the city, which performs yearly about 2000 km in holiday, and makes one or two trips per year outside of the village (about 1300 km). Although the manufacturer does not specify the average lifetime for these types of components, the OPEL experts suggest that these express a too short lifetime (only five years). It is obvious that one cause of failure consists in the road conditions (irregular with pits, etc). For example, if one wheel falls into a pothole, the link rod is exposed to a massive shock loading. If this happen in wet and cold conditions when materials used in the ball joint part of the rod are very brittle, then the ball joint becomes vulnerable to water and grit ingress, leading inevitable to total failure.

Optimization Techniques in the Design of Suspension Systems

The questionable quality of the roads represents the main factor of discomfort, being directly responsible for the accidents, affecting car components, but also the security of passengers causing death and serious injuries. According to statistics released by the World Health Organization, road accidents, in underdeveloped countries, tends to increase by 80 % in 2020 compared to 2000. In terms of road infrastructure, the low- and middle- income countries are characterized by a higher accident rate, reason for which the cars designers must approach the suspension problem slightly different and the parameters obtained by optimization algorithms should be different from the same model of car depending on where they will be driven / sold. This paper presents the optimization of a quarter-car model with two degree-of-freedom using evolutionary algorithms to determine the optimal parameters for a vehicle suspension, in order to improve ride comfort. I am concerned to improve suspension's system by optimizing the stiffness and damping coefficients in order to minimize the maximum bouncing acceleration of the sprung mass and minimize the average suspension displacement during movement on random roads, especially with bumps and potholes. We analyzed the quarter-car model (QCM) with two-degrees-of-freedom (2DOF) in order to find optimal parameters of stability and to keep high standard of ride comfort under different exploiting conditions, minimizing the discomfort during movement.

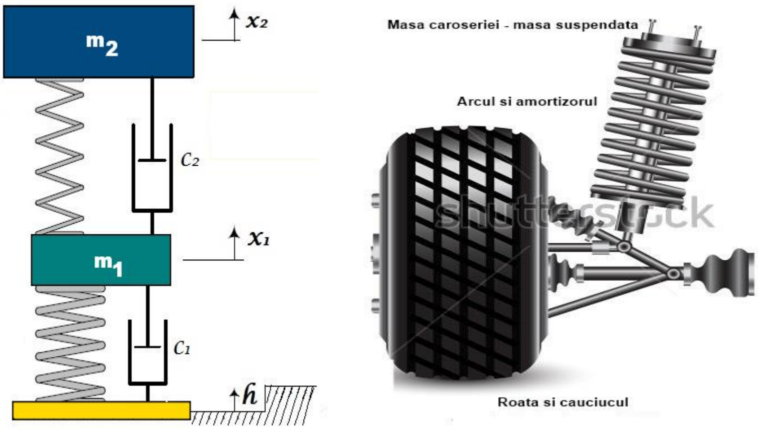

Fig. 5.1.2. The 2DOF QCM

The optimization problem consists in minimizing the sprung mass acceleration and sprung mass displacement subject to several constraints that arise from kinematic considerations. The vehicle model is considered to travel at a constant speed on a random road profile generated according to the ISO 8608 standard. The design variables to be optimized are the suspension stiffness and damping coefficients. We analyzed the algorithms in multiple scenarios so we can compare their performance in terms of fast convergence and solution diversity. The results showed that the optimization algorithms find solutions in small number of iterations, with slightly better performance obtained by Fast Pareto Genetic Algorithm.

MATHEMATICAL MODEL AND SOFTWARE SIMULATION OF SUSPENSION'S SYSTEM FROM OPEL CARS

The mathematical model used for describing and studying of the suspension is provided by a system of two simple differential equations of order 2. Differential equations constitute a major field of study in mathematics with wide applicability in problems of engineering (mechanic, electrical circuits, automata theory, etc.). With their help it is studied the evolution of processes that are deterministic, differentials and dimensional finite. An ordinary differential equation (ODE) is a differential equation that describes the predetermined relationship between an unknown function, its arguments and its ordinary derivatives. The order of a differential equation is given by the number of the highest derivative. A linear first order differential equation (or of order 1) is a differential equation in which the unknown function is a function of a single independent variable.

One of the usual methods for approximating solutions of differential equations is the “Runge-Kutta” numerical method having different orders of accuracy, developed around 1900 by the German mathematicians, C. Runge and M.W. Kutta [8]. The p order solution obtained by “Runge-Kutta” method is equivalent to the Taylor series expansion up to dp, where d is the difference between two points on the axis of the independent variable. Due to the high accuracy obtained it is preferred the “Runge-Kutta” method of order 4 (p=4).

Returning to the model of the suspensions system, a mathematical analysis theorem says that a system of high order differential equations can be transformed into a first order differential equations system by introducing new unknown functions. Generally, a system of k differential equations having k unknown functions, of order o1, o2, ..., ok, turns into an first order system with o1+o2+...+ok differential equations. Whereas in many scientific papers the model is presented only by the matrix equation of the kinematics system without providing of solving details, in the following we chose to present a method for solving the differential system of equations of the second order. We proceeded like this because, although there are some Matlab implementations or a standalone library for developers, in Visual Studio 2012 C#, that solves systems of differential equations by “Runge-Kutta” method, these are only first order equations. Thus, it is required transforming the differential equations system of order 2, into a first order system by introducing two new functions, and writing it as matrix equation: z’(t)=A·z(t), where z’(t) is the derivative functions array and z(t) is the unknown functions array, and A is the square matrix of whose elements should passed as inputs to our implemented software applications.

The kinetic of the 2DOF QCM are governed by the following matrix equation:

$$m_s \ddot{x}_s = -k_s(x_s - x_u) - c_s(\dot{x}_s - \dot{x}_u) \tag{5.3}$$

$$m_u \ddot{x}_u = k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u) - k_u(x_u - y) - c_u(\dot{x}_u - \dot{y}) \tag{5.4}$$

Advanced optimization of the suspension to achieve the target parameters of stability and comfort in different operational conditions

The main functionality of a suspension system is to isolate vibrations produces at the wheel level by the road conditions. These vibrations can make the body of the passenger vibrate violently which can make the ride uncomfortable especially when the exposure time is high. Thus, it is necessary to design competitive suspensions mechanisms that increase the ride comfort and maneuverability. Regarding the ride comfort, designing a suspension system involves choosing the right characteristics in such a way that the vertical acceleration and vertical displacement of the sprung mass are minimized. These objectives are usually conflicting: reducing one does not also reduce the other. Moreover, the existence of some design constraints complicates even more the designer's task. In this paper, we defined three constraints [8]. The first represents the maximum value of the sprung mass acceleration that should not exceed 1g (9.8m/s^2). The second constraint specifies the maximum displacement between the sprung and unsprung mass. The third constraint refers to the frequencies at which humans experience motion sickness. According to ISO 2631, humans experience motion sickness when exposed to frequencies in the interval 0.1-1Hz. Thus, the natural frequency (ω) of the suspension system should be greater than 1Hz.

$$\text{minimize } x_s \text{ and } \ddot{x}_s$$

Subject to

$$|\ddot{x}_s| < 9.8m/s^2$$

$$|x_s - x_u| < 0.1 \text{ m}$$

$$\omega > 1\,Hz$$

This makes the problem a perfect candidate for multi-objective optimization.

OPTIMIZATION PROCEDURE

First, the suspension model is initialized. The body mass, wheel mass, tire stiffness and damping are fixed parameters and will not change during the simulation. Then, the design variables are defined, the spring stiffness K_s and the damping coefficient C_s, which are represented as real numbers. The bounds of the variables are also set in this step. The next step is to establish the design constraints. For this paper we used three constraints which are related to the maximum acceleration of the sprung mass, the relative displacement of the masses and the suspension's natural frequency. The optimization's objectives are to minimize the sprung mass acceleration and the sprung mass displacement. Now an optimization algorithm is chosen and the optimization process is started.

The algorithms used in this paper belong to the evolutionary algorithms class. All of them will follow the same basic steps. An initial set of solutions called population is generated randomly. Then, an optimization loop will use the initial population in order to generate better solutions (new populations), using specific evolutionary operators. In this loop, the objective functions are evaluated, for a particular case in which the suspension's mathematical model is solved. Based on this evaluation, a *fitness* is assigned to each solution in the population. The fitness represents the quality or the chance of the survival on an individual. After the evaluation the best candidates are chosen which will reproduce to create a new population. The selection, crossover and mutation operators are used to achieve this process. When a new population is obtained, the optimization loop will execute the same steps until a termination condition is satisfied. The algorithm output is a Pareto front, a set of solutions considered to be optimal. The entire procedure is synthesized in Fig. 5.2.1.

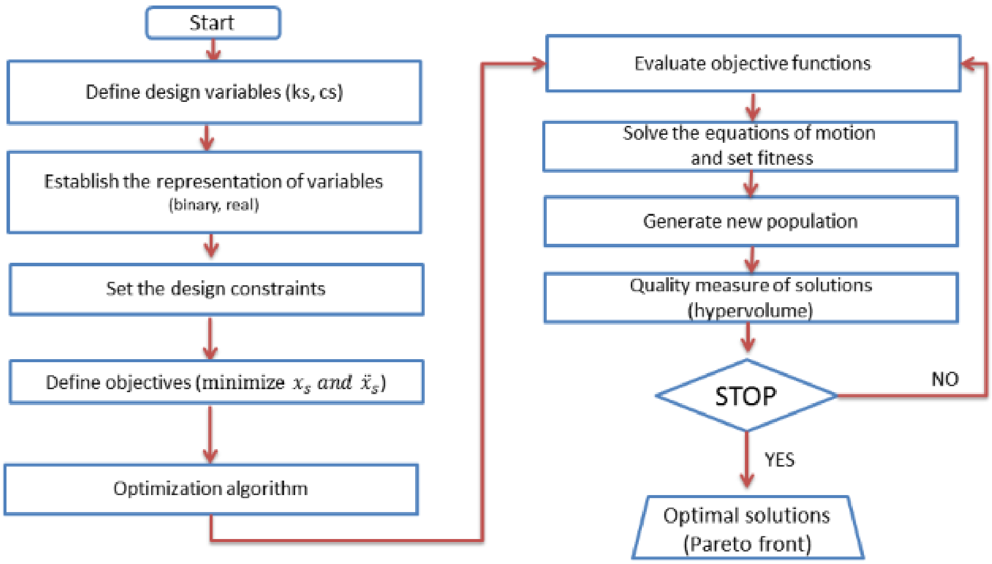

Fig. 5.2.1. Optimization procedure

Of great importance are the objective functions used by the evolutionary algorithms to evaluate solutions. Fig. 5.2.1.a shows the steps taken by such a function. The RMS value represents the Root Mean Square computed as:

$$RMS = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 \dots x_n^2)}$$

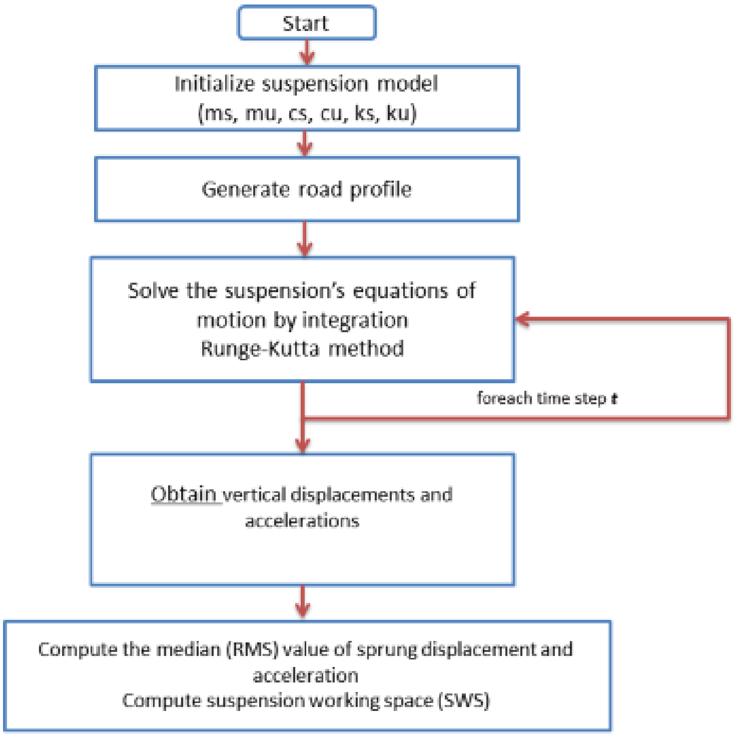

Fig. 5.2.1.a. ***Objective function (steps)***

SOFTWARE IMPLEMENTATION OF SUSPENSION'S OPTIMIZATION PROBLEM

This section presents a brief overview of the optimization algorithms used in this paper and that were software implemented for obtaining the experimental results.

- Non-Pareto techniques
  - *Classic GA with objective aggregation*
  - *Vector Evaluated Genetic Algorithm (VEGA)*
- Pareto techniques
  - *NSGA-II algorithm*
  - *SPEA-II algorithm*
  - *The Fast Pareto Genetic Algorithm*
- Swarm-intelligence-based techniques
  - *Speed constrained Multi-objective Particle Swarm Optimization (SMPSO)*

APPLICATION GRAPHICAL USER INTERFACE

Our application was written in C# language under Visual Studio 2012 environment. The software solution consists in two basic projects: EVA Framework and jMetal.NET. The first contains the application graphical user interface (GUI) which allows selecting the algorithm's configuration class, the optimization problem, and facilitates viewing and comparing the obtained results and viewing the values of individuals and of objectives. The second project's goal was to provide C# implementation of jMetal (a Java framework for multi-objective optimization with metaheuristics) by porting this library on .NET platform. It contains a subset of algorithms and the way they are setup, a number of problems and their subsets of solution representations, and the genetic operators from original library. For a proper run of application is required a performant PC, such as quad-core 2.4 GHz Intel P4 Xeon with 4GB RAM memory, Windows XP SP2 operating system or newer and 4.5 version of .NET Framework.

To start the application is launched the binary file EvaSuspensionFramework.exe. Then on full screen is displayed a user-friendly GUI (see fig. 5.4.1). This consists in: the main menu, an algorithm control panel, an optimization problem configuration control panel, a results list, an implemented metrics list, a panel designed for plotting the selected road quality. From the algorithm configuration panel (left side) the user may run the following actions:

- Selecting the optimization mode: mono / multi objective.
- Establishing the evaluation strategy of solutions: single-core, multi-core or distributed. In single-core assessment strategy the algorithm is performed just on one core. In multi-core mode, there are involved in processing all processor cores made available by the host station. In distributed way the evaluation is done on multiple workstations taking into account on their cores number.
- Choosing the optimization problem
- Setting the parameters of optimization (the population size, number of generations, the values of genetic operators, etc).
- Start/Stop the optimization procedure

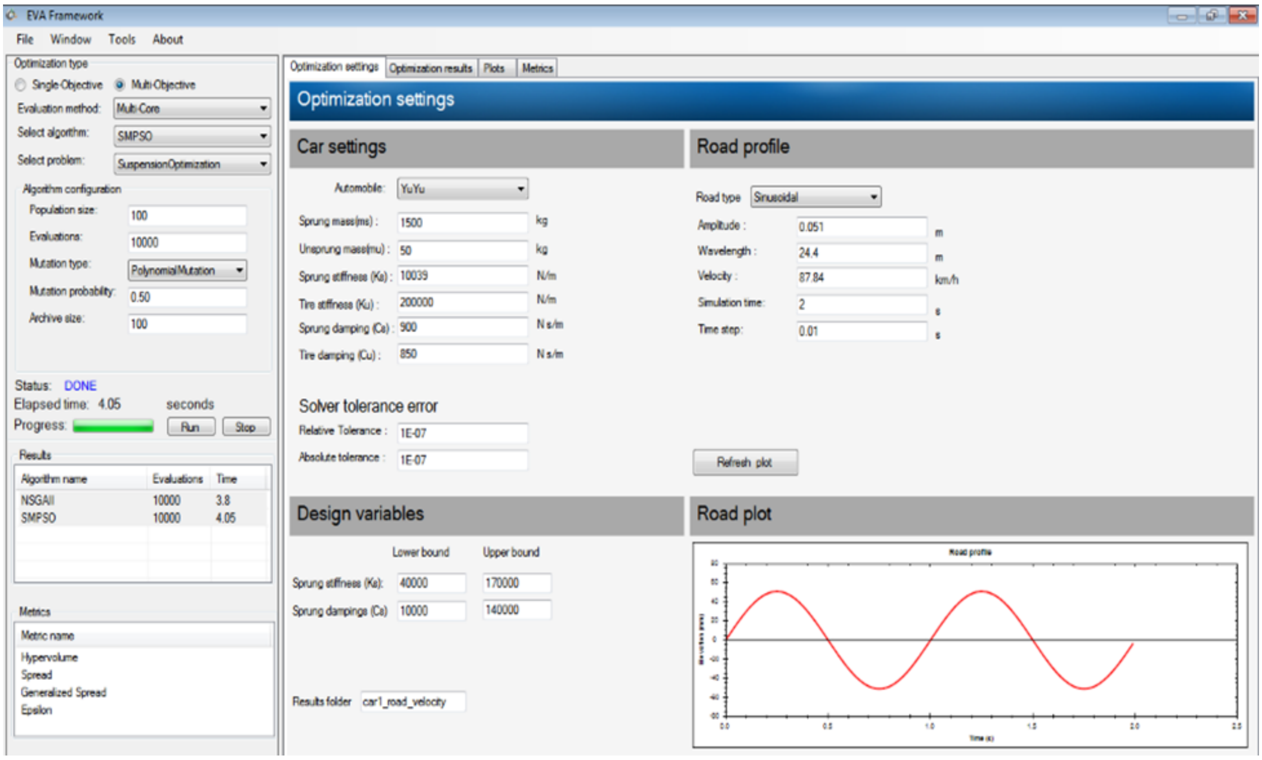

Fig. 5.4.1. Application's GUI

CAD ANTI-ROLL POWER LINK MODELING ON OPEL VEHICLES MANUFACTURING

Before proceeding to the actual modelling of the power link, it is appropriate to make some remarks on the construction and operation of this major auto part.

As regards the construction, we can distinguish three main parts, namely: body of power link and the two pivot sub-assemblies through which the anti-roll power link is assembled on the damper and respectively on the stabilizer bar of the vehicle (Figure 1).

Functionally, anti-roll power link is a component part of the vehicle suspension which has two basic functions, namely: reducing the leaning of the vehicle and adjusting the vehicle balance. On poor quality roads, the vehicle shall enter a rocking motion, and the motion depends on the construction of power link body or the material of which they are made.

Therefore, we believe that it is fully justified to perform a thorough study of power link body, even if the parts wearing faster within this subassembly are the pivot parts on the ends. Also, the body of anti-roll power link has been less studied in specialized literature compared to pivot wear.

Figure 1: Anti-roll power link of OPEL ASTRA G, ZAFIRA, MERIVA

3D modelling of semi-power link will be carried out in the classical manner by using the software package CatiaV5R20.

For modelling, there were carried out successively as follows: modelling of semi-power link body, modelling of seats for mounting pivots to the ends, modelling of perimeter rib and finally of transverse ribs.

As a principle, modelling was done in a generalized and parametrized manner. Even if sometimes it requires a more difficult modelling, this has the great advantage of allowing many customizations, resulting in many constructive forms that can be further studied by other methods such as the method of finite element.

For 3D modelling of the full body of semi-power link it was considered the origin of of triorthogonal system of the body within its centre of symmetry, for the future use of symmetrisation functions allowing flexibility in modelling.

The next step is the realization of the beam shape of equal strength in xOy plane. To achieve other recesses will be used the facilities of Catia software to mirror the constructive entities. After this symmetrisation is created the basic shape of the anti-roll power link body.

Further is modelled the perimeter rib that results by creating a pocket entity on both parallel sides of the yOz plane of the body. To achieve the perimeter rib on the opposite side it will be applied again the Mirror function for entities, and the recess previously created will mirror against yOz plane.

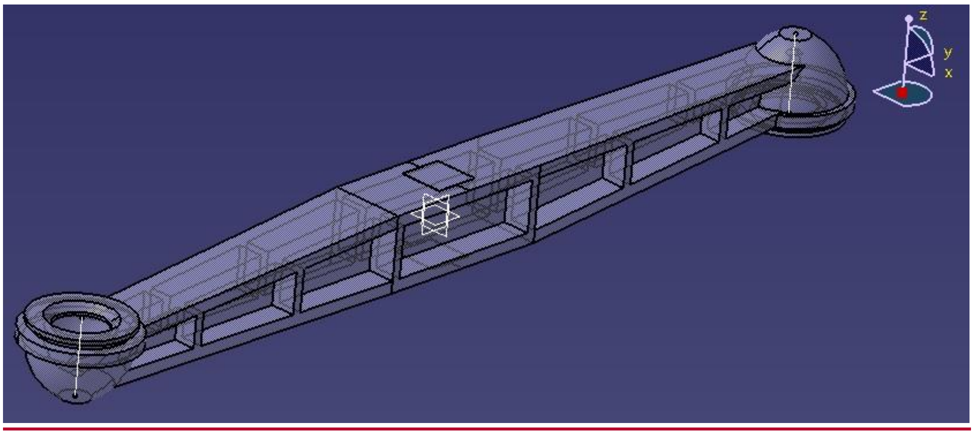

Figure 2: 3D anti-roll power link

We then proceed to modelling the ends of anti-roll power link, namely the seats for mounting pivots. Also for reasons of parameterization and subsequent flexibility, first will be modelled the outer surface of the seat. Using the same steps, will be realized the surface of inner revolution of the pivot seat. In terms of its constructive shape, the second seat is identical to the first, the only difference between them is its positioning towards the body of semi-power link.

To complete the model, further will be modelled the transverse ribs. After realizing the ribs located on the other side of the body, in the same manner, modelling of semi-power link is completed, the final model is shown in figure 2.

Since the model of the body of semi-power link was modelled after some parameters, by simply introducing new values to the parameters, it results customizations that may be object of further study.

Customizations proposed and models resulted are as follows:

- Changing the angle creating the beam shape of equal strength in xOy plane (figure 3);

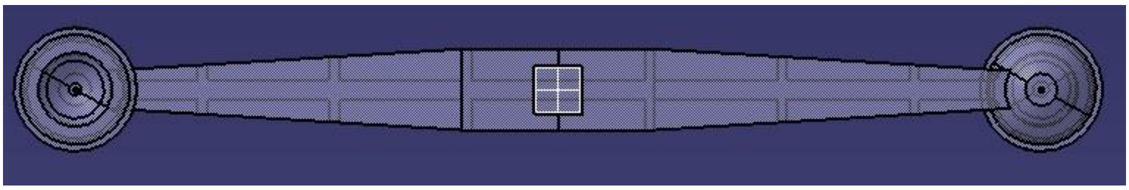

Figure 3. Constructive shapes with the angle of inclination of symmetrical surfaces changed in xOy plane.

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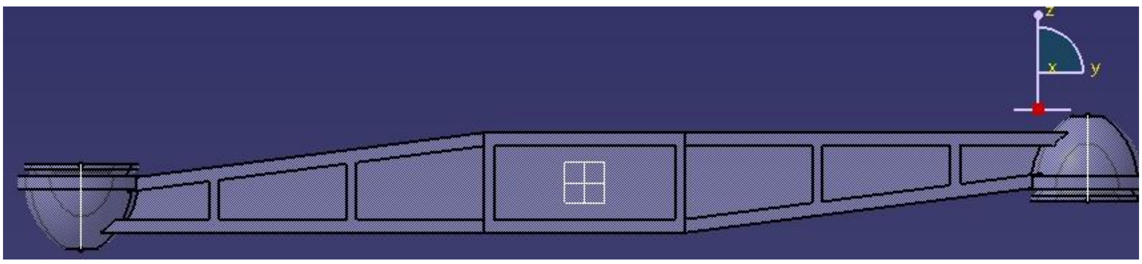

Figure 4. Thickened model in the middle area on zOy plane

Thinning or thickening of the middle area of the body in both xOy and yOz planes (figures 4, 5);

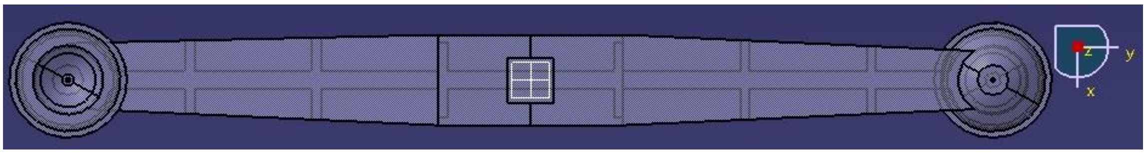

Figure 5. Thickened model in the middle area on xOy plane

- Changing the inclination of body surface in yOz plane (figure 6);

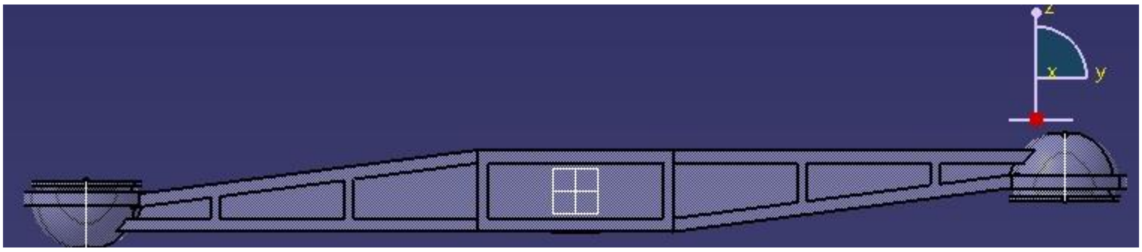

Figure 6. Model changed in terms of inclination of surfaces on zOy plane

- Thickening or thinning of perimeter rib (figure 7);

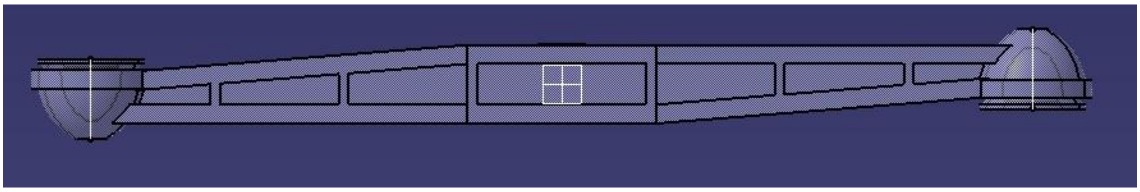

Figure 7. Model of thickened perimeter rib

- Changing the position of transverse ribs and of their sizes (figure 8)

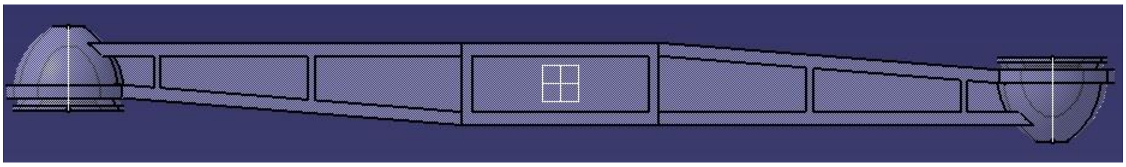

Figure 8. Model of thinned transverse rib and the increased distance between the ribs

As already seen, parameterized modelling enables a large enough study on constructive shape of anti-roll power link.

Starting from the modelling presented in detail through constructive adjustments, there are several types of anti-roll power link bodies that can be suggested.

So, if the idea of ribs modelling is abandoned, will result a semi-power link of whose body is full. Another version is featured by the absence of transverse ribs, the body having only the perimeter rib. Another body model can be modelled without transverse ribs, by replacing them with a longitudinal rib passing through the centre of symmetry of the body and medially including xOy plane.

Finally, the last suggestion is a model of high rigidity, being basically a combination between the original model with transverse ribs and the model with longitudinal rib. The model is shown in figure 9.

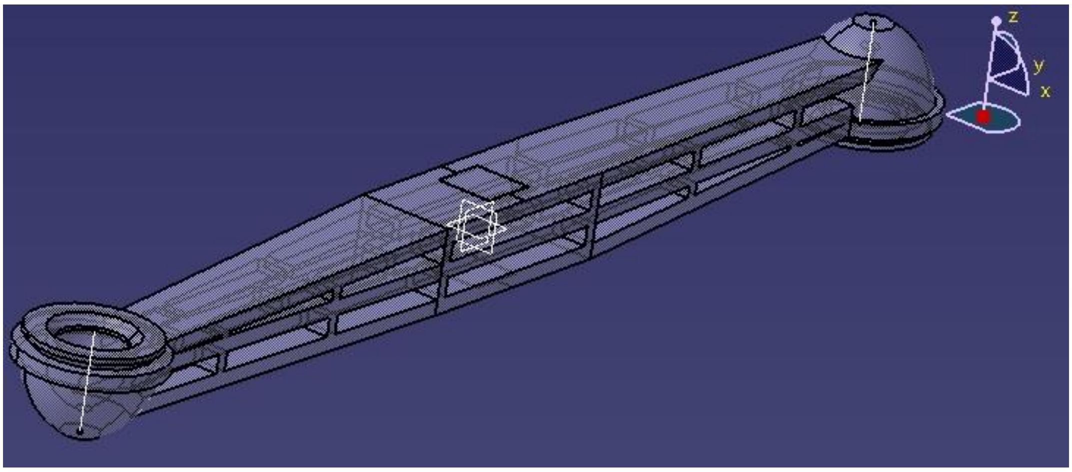

Figure ~~4.7.~~9. Semi-power link body with longitudinal rib and transverse ribs

The generalized design shown above is a starting point for constructive and functional optimization of the anti-roll power link body.

NUMERICAL SIMULATION USING FINITE ELEMENT METHOD OF ANTI-ROLL POWER LINK. TOPOLOGICAL OPTIMIZATION

- As a result of running the numerical analyses by finite elements method mentioned in this chapter can be drawn the following conclusions:
- the use of finite element method allowed highlighting the state of tension and destorsion present in anti-roll power link at the static stress as well as determining their own vibration modes, following the modal analysis;
- for all three types of anti-roll power links, the maximum value of the equivalent Von Mises voltage does not exceed the admissible strength of PA66-GF material, resulting in values between 6.23 to 5.82 for safety coefficient at static analysis;
- the maximum value of the nodal displacement for the three geometric patterns of anti-roll power links has values between 0.31 and 0.53 mm, acceptable values for anti-roll power links;
- in modal analyses were obtained values of the own frequencies between 218.2 and 1796.2 Hz;
- It should be noted that for all three models of anti-roll power links, the first own way has a frequency of over 218 Hz, frequency which lies outside the scope of work of road motor vehicles. For this reason the development of dynamic harmonic analysis which study the dynamic behaviour in the vicinity of natural frequencies finds no justification;

- I do consider optimum the optimized anti-roll power link by reducing the thickness of a transverse rib because it allows to obtain a good stiffness under conditions of reducing the volume of material with 7,57%. For these reasons, experimental research presented in Chapter 8 will relate only to this geometric pattern of anti-roll power link;
- geometric model of anti-roll power link with longitudinal stiffening rib is not recommended to be used for vehicles running on even roads but only for those running on rough terrain (off-road), because improving the mechanical strength does not justify otherwise high consumption of material for anti-roll power link body;
- numerical researches will be validated in Chapter 8 by experimental research on eccentric bending, pure bending respectively.

EXPERIMENTAL RESEARCH

For testing the anti-roll power link at eccentric bending, it was made a device (figure 2) that allows its fixing on Instron machine bed in the area for assembling the power link to stabilizer (torsion) bar. At the opposite end of the power link (the place of fastening on vehicle damper) it was introduced a cylindrical bolt, planely milled to one end so that it can be applied the load using the mobile cheek of the testing machine.

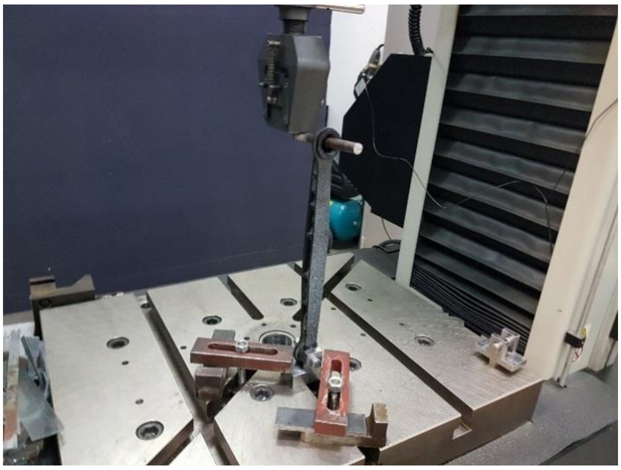

Figure 2: Anti-roll power link assembly – eccentric compression testing device mounted on testing machine

The applied force progressively increased up to a value of 1,000 [N], which is applied to an eccentricity of 100 [mm] to the longitudinal axis of tested power link, thus obtaining a bending moment of 100 [Nm].

The results obtained and recorded if the compression force reaches the maximum value of 1,000 [N] were as follows: major strain (Major Strain ε_1), minor strain (Minor Strain ε_2), equivalent strain (von Mises Strain), displacement on X axis, displacement on Y axis (compression force direction), displacement on Z axis. These results are shown is figures 3 … 8

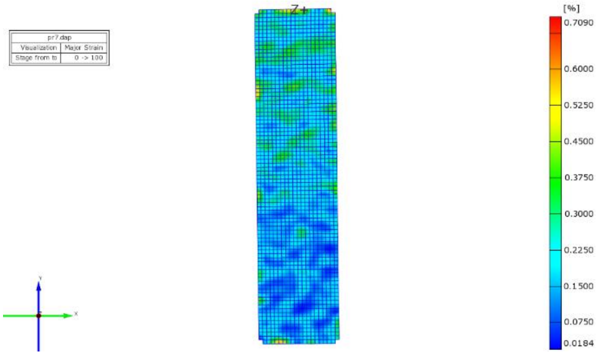

Figure 3: Major Strain ε_1

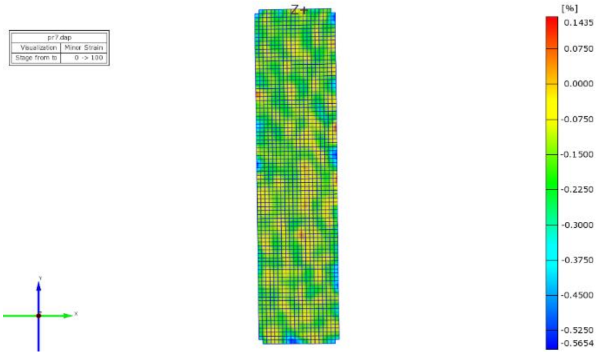

Figure 4: Minor Strain ε_2

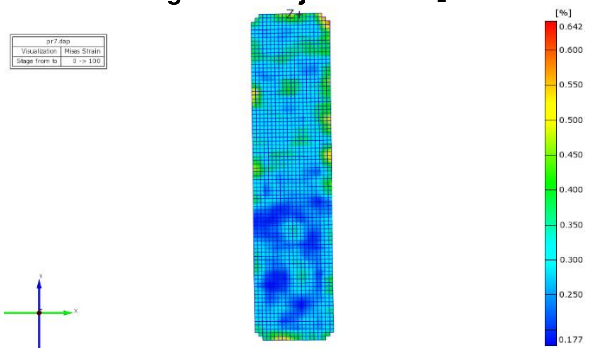

Figure 5: Equivalent Strain ε_{VM}

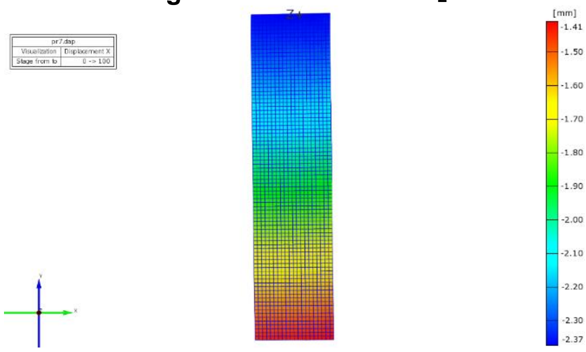

Figure 6: Displacement on X axis

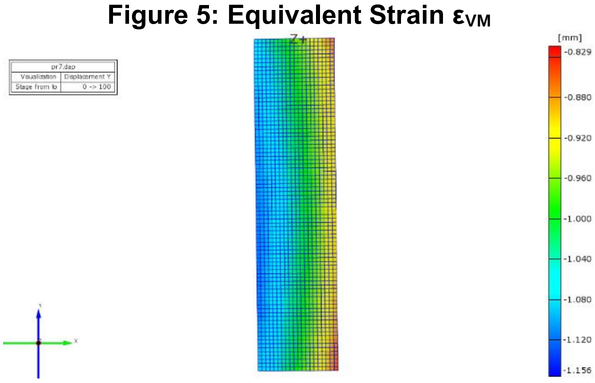

Figure 7: Displacement on Y axis

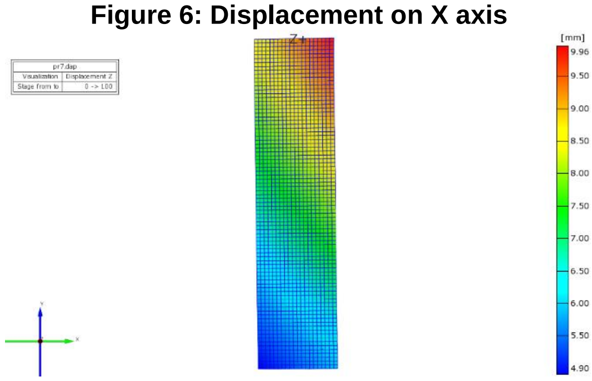

Figure 8: Displacement on Z axis

By using Aramis software, it was made a section in the axial direction of the power link studied (figure 9), so it could be drawn the variation graphs of displacement in the three directions (fig. 10. …12) and the variation graph of Equivalent von Mises strains along the same sectioning trace (fig. 13).

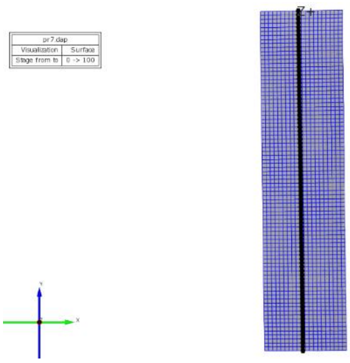
Figure 9: Sectioning trace on axial direction of power link studied

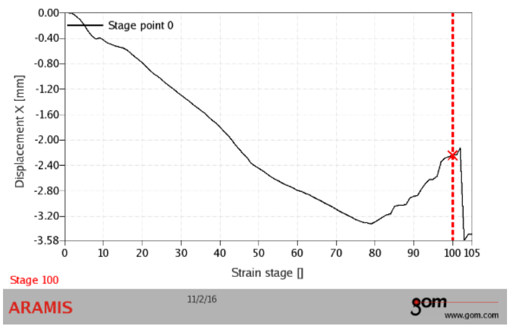

Figure 10: Variation graph of power link displacement on X direction, during the load

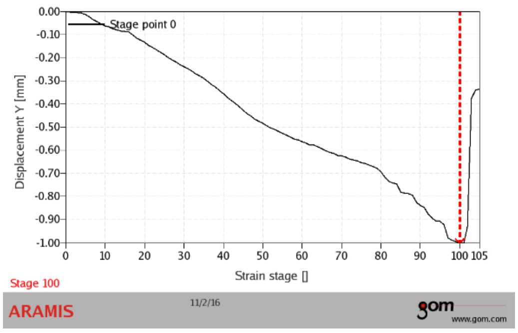

Figure 11: Variation graph of power link displacement on Y direction, during the load

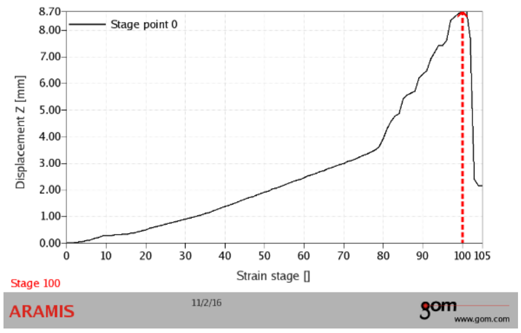

Figure 12: Variation graph of power link displacement on Z direction, during the load

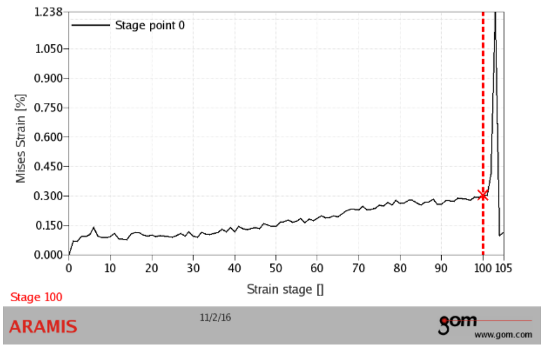

Figure 13: Variation graph of von Mises equivalent strain, during the load

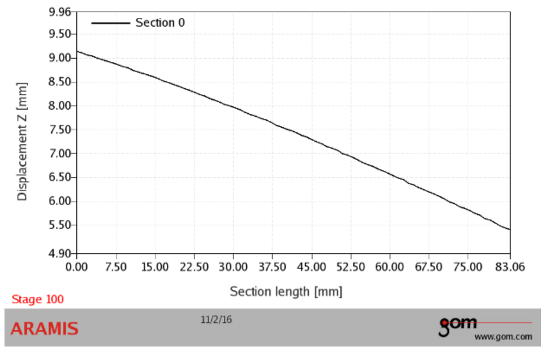

Figure 14: Displacement on Z axis (deformed medium fiber of power link)

It should be noted that when the test reached ‘stage 100’ took place the removal of the load on the power link while eccentric bending, which is why all graphs showing the variation way of displacements on the three directions and also the variation graph of von Mises equivalent strains reveal a gradual variation of these parameters determined by experiment.

By using the same sectioning trace could be determined and drawn the deformed medium fiber of the power link studied, on the part located near Aramis system cameras, which is shown in figure 14.

CONCLUSIONS. ORIGINAL CONTRIBUTIONS. FUTURE RESEARCH DIRECTIONS

This thesis has successfully combined a number of different scientific areas such as Computer Science (Artificial Intelligence, Reliability, Programming Languages and Distributed computing subdomains), Mathematics (Differential Equations), Road Vehicles Engineering and Mechanical Engineering in order to contribute to solve a real problem, even critical in Romania, meaning exploiting motor vehicles with an emerging infrastructure, where there are poor quality roads, too.

The main original contributions are:

1. Carrying out a thorough bibliographical study from which has emerged the need for studies;
2. Study of Opel motor vehicles behaviour in operation for 9 years (and not only Opel) through the pursuit of faults encountered in use, malfunction causes and of abnormal wear identification.
3. Design and implementation of a relational database allowing to study the reliability of OPEL cars exploited in Romania.
4. Adapting the solutions of differential equations systems of order 2 on the suspension issue and their algorithmic transposal, automatically solvable.
5. Software implementation of the optimizating multi-objective algorithms like Non-Pareto, Pareto and Bio-inspired (based groups behavior) in the design of the suspension system.
6. By using the software application developed in this thesis we will improve the quality of production of spare parts
7. Creating a parameterized 3D anti-roll power link model
8. Creating new models of anti-roll power link
9. Achieving the study of the tension stages and deformations and topological optimization of the anti-roll power link
10. Experimental determination of raw material characteristic curves, of the variation of the force in relation to movement and maximum and minimum main specific deflection for the stressed anti-roll power link.

Key words: power link, bending, displacement, major strain, von Mises strain, CAD modelling, finite element methods, stabilizer bar, parameterized modelling, static analysis, suspension optimization; quarter-car; evolutionary algorithms; genetic algorithms; multi-objective, reliability, road profile, Software Application, suspension system, database, data mining, maintainability,materials reliability, differential equations system, Quarter-Car Model, software application, suspension system, database, data mining, SQL.