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Integrated Use of PLM and Life Cycle Energy Analysis Software in Teaching Automobile Life Cycles*

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The high degree of competitiveness among companies in the automobile sector together with ever stricter regulations means that manufacturers have to produce designs that are more and more complex and demanding and need to take account of all the stages of a vehicle's life cycle and study them in depth. In this sense, due to increasing environmental awareness, it is becoming necessary to consider the energy cost of each stage of the vehicle's life cycle as part of the design process. This paper presents how both points are integrated when teaching young engineers on the Master's course in Automotive Engineering at Madrid Polytechnic University (UPM), using PLM SmarTeam software and the life cycle energy analysis program GaBi 4. This teaching is based on practical applications for a hybrid vehicle designed and constructed at the INSIA, taking energy and environmental cost as design criteria for the vehicle.

Keywords: PLM; energy analysis; environmental impact; automobile

INTRODUCTION: METHODOLOGICAL APPROACH

DESIGNING COMPLEX PRODUCTS requires specific, rigorous management, which is particularly important when multidisciplinary workgroups are involved that are often not in close contact [1–3]. Design in the aviation and automotive sectors imposes a work style that future professionals studying in Engineering Schools should learn and assimilate, with certain issues being critical, such as working together [4, 5], an ability to innovate and solve problems with open-ended solutions [6] and knowing how to relate the knowledge and skills acquired [7]. However, this comprehensive management is backed up by computer programs that adapt to the specific characteristics of the problem and offer solutions that can be extended to the analysis of the product's entire life cycle.

As part of the Master's in Automotive Engineering taught at the University Institute for Automobile Research (INSIA), a public research and development centre that is part of the Industrial Engineering School of Madrid Polytechnic University, there is a comprehensive training approach for students in the automobile industry field, where special emphasis is placed on the product [8]. The Master's course, which has now completed 17 editions, has over 80 Ph.D.s and professionals from major automobile manufacturers and related companies who transmit their vision to the young engineers who are just starting out in the sector. The educational programme is divided into different areas that range from vehicle systems and vehicle dynamics to commercial management and official approvals (Table 1); this means that students acquire an overall knowledge of the different disciplines in the automobile field.

Training in PLM tools is part of the Master's in Automotive Engineering in two subjects. The first, Computer Technology Applied to Vehicle Engineering (Module 4.New Technologies Applied to the Automobile), is taught using several types of vehicle development oriented software, such as CATIA V5 [9] for 3D geometric design, ANSYS [10] for calculus by finite elements or Carsim [1, 12] for dynamic performance analysis. Designing the vehicle in its different stages is the leitmotiv for developing this subject, from the vehicle's very conception right up to its structural analysis and road performance, making use of the concepts dealt with in Module 1: Vehicle Engineering (Product). Thus, throughout the course, the project's key points are approached. In this context, PLM is put forward as a key element in the process of innovation and development, managing the design, manufacture, logistics and recycling of the vehicle [2, 13–14]. In addition, these tools let the whole process be carried out in a competitive atmosphere. The program used for training in PLM tools is Dassault Systèmes' SmarTeam.

The second subject where PLM tools show what they are capable of is the Environmental Impact of the Automobile (Module 5. Socio-environmental

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Table 1. Programme of subjects in the Master's in Automotive Engineering (Note: a credit is the equivalent of 10 teaching hours)

	No. credits
MODULE 1. Vehicle Engineering. (Product)	
1.1. Vehicle Theory	5
1.2. Internal Combustion Engines and Fuels	6
1.3. Systems and Components	5
1.4. Laboratory Practice	2
MODULE 2. Manufacturing and Production Engineering	
2.1. The Automotive Industry. Manufacturing	4
2.2. Production Management. Supplies and Logistics	4
MODULE 3. Managing Automotive Companies	
3.1. Quality Engineering	3
3.2. Commercial Management and After-sales	4
3.3. Financing and Costs	2
3.4. Human Resources	2
MODULE 4. New Technologies Applied to the Automobile	
4.1. Computer Technology Applied to Vehicle Engineering	6
4.2. Electronics and Instrumentation	4
4.3. New Materials	2
MODULE 5. Socio-environmental Impact of the Automobile	
5.1. Road and Vehicle Safety	2
5.2. The Environmental Impact of the Automobile	2
5.3. Regulations and Official Approval	2
End-of-Master's Project	5
TOTAL	60

Impact of the Automobile), where the environmental impact of the automobile is studied. The philosophy behind the course is not only to evaluate and quantify the impact of a vehicle at each stage of its life cycle but also to set the guidelines for helping to reduce this impact. On starting the Master's all students are fully aware of the pollution caused by a vehicle [15–17]. In fact, since the recent plans in Europe to introduce duties on vehicles and limit their emissions, all manufacturers are required to declare the amount of CO_2 emissions in g/km. However, the considerable environmental repercussion of the vehicle in its other stages, that is, the manufacture of its raw materials, assembly, maintenance, and recycling, is not so well known, and in many cases, students are not fully aware of its magnitude. To evaluate these stages, the full vehicle design is analysed, just as was done in the previous subject, integrating it into the project and basing it on what was dealt with in Module 2: Manufacturing and Production Engineering.

In this sense, GaBi 4, a commercial program oriented towards energy analysis [18], has shown itself to be a highly important instrument for evaluating and showing this impact; because it is part of SmarTeam [19], the repercussions from using certain components, materials and manufacturing methods can be examined in depth and compared with others, which are all included in the training scheme shown in Fig. 1. Also, a sensitivity analysis can be conducted, evaluating the repercussions from every possible aspect (economic cost, manufacturing time, energy costs, etc.), of replacing, for instance, one component with a different one but with an identical functionality.

In this way, students are introduced to an additional design criterion, such as environmental cost, so they will go on to evaluate this cost during the different life cycles of the vehicle, evaluating, for example, if greater production costs will be offset during the vehicle's useful life or vice-versa.

The comprehensive use of all the previous computer programs in teaching the life cycle of an automobile on the Master's in Automotive Engineering where the inclusion of GaBi 4, interconnected with the rest of the design through PLM, is of major importance (Fig. 1) are considered below. Additionally, as another relevant part of training, a hybrid powered vehicle designed and developed at INSIA is used to test the applications on a real case. This means in-depth knowledge can be imparted and applied to a specific product

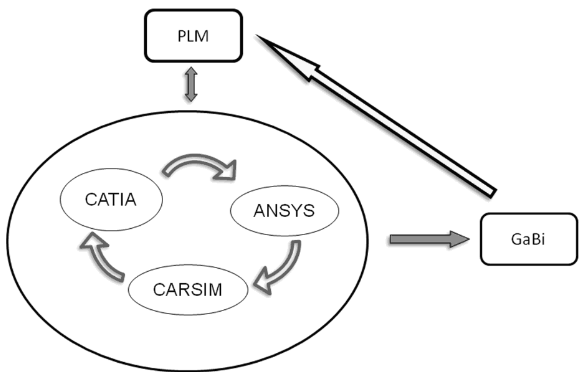

Fig. 1. Comprehensive training outline.

known to the students who can use all its specifications right from the first steps of the preliminary design. This vehicle has been conceived with the same premises as those taught on the Master's.

VEHICLE DESIGN PROCESS

Training on the postgraduate Master's course is aimed at a theoretical-practical approach, which is why it is oriented towards concepts being applied to actual cases. To this end, developing the design and analysing the life cycle must be performed on a real vehicle of which all the design details are known without the limitations generally imposed by manufacturers for reasons of confidentiality. That is why the vehicle under study is a hybrid vehicle recently developed at the INSIA for light urban applications. The design and development of this vehicle, called EPISOL [20], was requested by a Spanish urban services company. It has the capacity to transport two people in the cab plus a small interchangeable load box. It can be adapted to different uses, like garden maintenance or parcel services. It has a tubular metal chassis and glass fibre-reinforced polyester bodywork. Two types of hybrid propulsion have been developed; a low cylinder capacity thermal engine connected to a generator and a fuel cell fed from a hydrogen tank. Both systems feed a battery set and an electric motor connected to the rear axle to drive the vehicle. Due to the client's express wish the vehicle is fitted with solar panels on the cab roof and the load box, which help recharge the vehicle's batteries, although to a lesser degree. The effective power transmitted to the wheels is 15 kW.

Throughout the vehicle's design stages, CATIA was used as the 3-D modelling program, which proved particularly useful for ergonomic design and analysing the tolerances and interferences between components (Fig. 2).

Developing a relatively complex product like the EPISOL vehicle, where not only engineers from the INSIA were involved but also personnel from various supply companies, was greatly aided by using a PLM life cycle management program, namely Dassault Systèmes' SmarTeam program [19]. The possibility of working together and managing and sharing the considerable volume of information generated during the vehicle's design, analysis and manufacturing process turned out to be a key factor in achieving all this within the preset costs and timeframes.

ENVIRONMENTAL ANALYSIS OF VEHICLE'S LIFE CYCLE

Life cycle analysis is a tool for examining the environmental impacts of a specific product throughout its useful life, from its moment of conception until it is scrapped [21]. It is very useful for a global vision of its effects on the environment by its manufacture and use and to be able to suggest alternatives or measures to reduce these effects as far as possible. It also serves to compare the benefits of one product or another on an environmental level.

A life cycle analysis usually comprises four stages:

1) Definition of objectives and scope: important for deciding if one study can be compared with another.
2) Life cycle inventory: when energy consumption and emissions, etc, of product-related processes are recorded and quantified.
3) Evaluation: final assessment. Normally, an environmental impact analysis is conducted in line with different methods available and those being continuously developed.
4) Interpretation: in light of all results from previous stages, conclusions are drawn and recommendations made.

To make this energy analysis easier, several programs and databases have been developed, such as Ecopor, Esoscam, SimaPRO and GaBi 4. The latter is a complete tool developed by Volks-

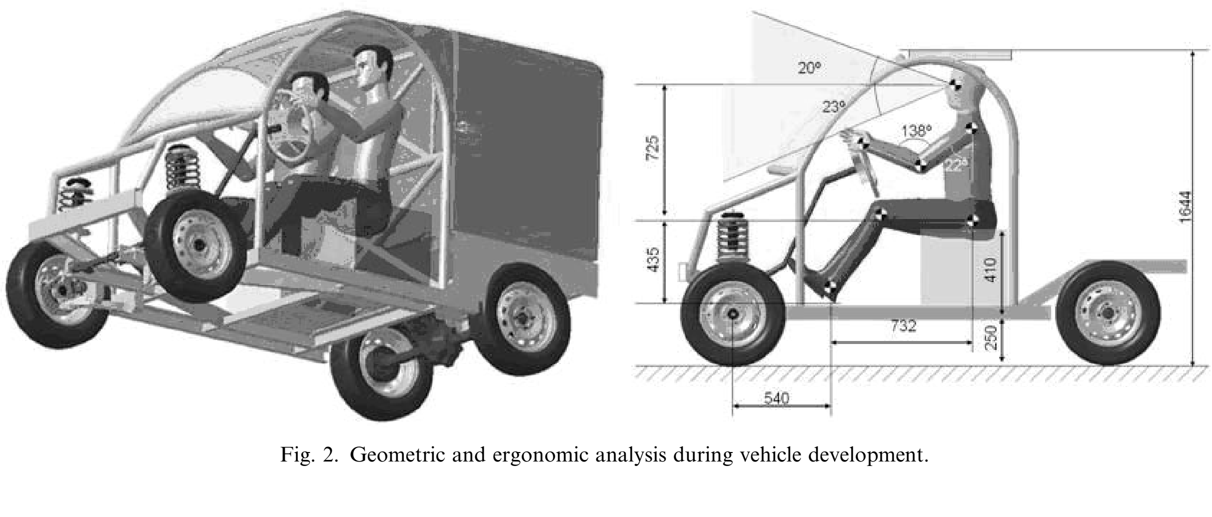

Fig. 2. Geometric and ergonomic analysis during vehicle development.

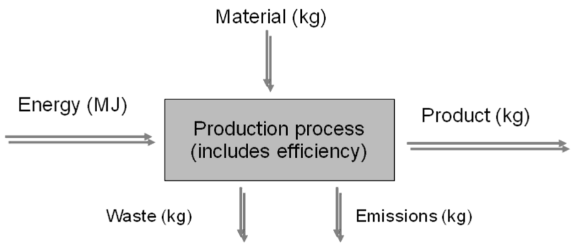

Fig. 3. Outline of typical GaBi 4 process.

wagen AG and the University of Stuttgart, which specialises in the automobile industry.

With different databases, such as Buwal, Ecoinvent or Plastics Europe, the graphic interface guides the engineer to characterise the material and energy flows involved in all the manufacturing and assembly processes. Therefore, it is very simple and quick to evaluate the energy and environmental impact of different design alternatives, as the program lets mass, energy and waste products be evaluated.

The GaBi 4 program is a tool for conducting product life cycle analysis [18] to evaluate a series of typical processes in a product's useful life: these processes have input flows (energy, material resources) and output flows (products, emissions, waste products). Each process means evaluating mainly mass and energy; when all the processes have been related, a final or global evaluation is calculated. The most important features of the program are:

a) It makes carrying out the life cycle inventory stage easier.
b) It carries out all evaluation-related tasks:
   i) Mass assessment
   ii) Energy assessment
   iii) Emissions
   iv) Waste products
c) It carries out different analyses when the evaluations have been obtained:
   i) Scenario analysis: Different parameter values that form part of a specific process are set and an evaluation is made, comparing results.
   ii) Analysis with a variation in parameters: As above, but instead of setting specific values, an evaluation is made for a whole range of parameters. The variation interval is set.
   iii) Sensitivity analysis: As above, but instead of setting an interval, a percentage of variation is set, with upper and lower limits.
   iv) Monte Carlo simulation: Likewise, but with a random number sample.

The GaBi 4 graphic interface allows processes to be viewed with the flows following a scheme such as that in Fig. 3.

Its true potential is in the database that is part of the program. It contains data on numerous processes, taking account of reference consumptions and outputs in respect of the output unit, be it 1 kg of material or 1 MJ of electrical energy.

Since the program lets a simple process level be reached, it can be applied to very diverse circumstances in current industry. GaBi 4 even manages to evaluate the environmental cost of producing raw material and auxiliary services like electricity (Fig. 4), which will be used subsequently in stages that simulate vehicle manufacture.

This life cycle analysis methodology was applied to the EPISOL vehicle from the outset. Energy consumption and CO_2 emissions associated with each of the stages comprising its life cycle were studied [22–24]. The characteristic stages were thus defined (Fig. 5) and the scope and most important hypotheses decided.

Material production stage comprises processes for extracting raw materials and their processing to the form required for making the vehicle parts. It

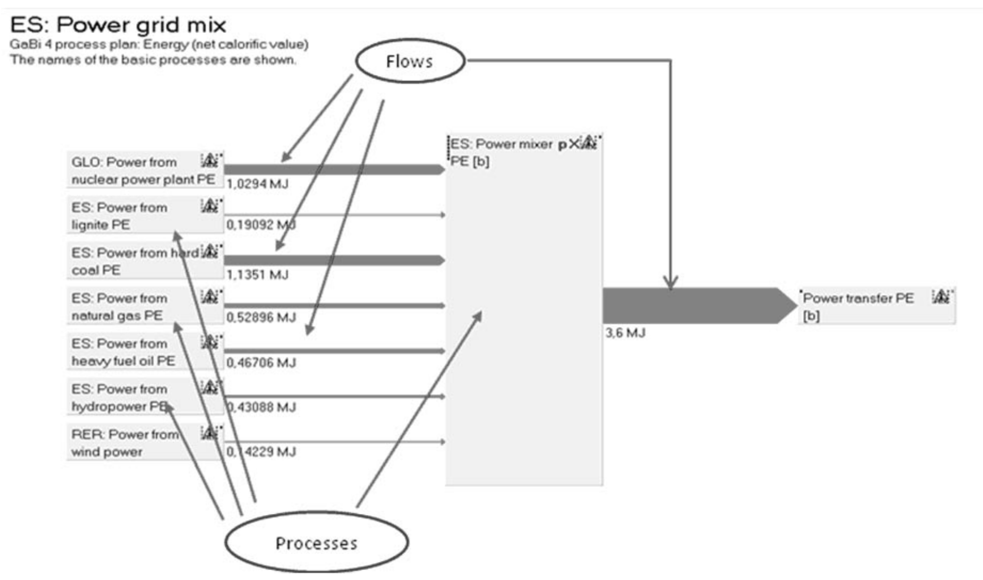

Fig. 4. Outline of how electricity production costs are evaluated using GaBi 4.

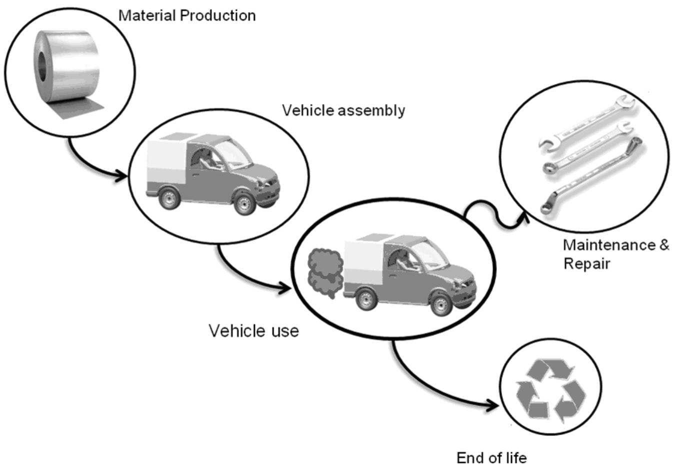

Fig. 5. Typical outline of automobile life cycle.

includes extraction, processing and transport. It is assumed that the energy needed for each process is proportional to weight, each material possessing a different constant of proportionality, obtained either from the bibliography available on automobile life cycle analysis [25, 26], or from the GaBi 4 data base.

Vehicle assembly stage comprises the process of manufacturing and mounting parts on the assembly, up to the time of the vehicle's use. Given the complexity of this stage, in the bibliography available on automobile life cycle analysis, energy is usually estimated as being proportional to the vehicle curb weight [27].

Vehicle use stage comprises the time interval in which the vehicle is to be used for the purpose for which it was conceived. It does not include fuel production, in this case petrol. This stage was modelled using the MatLab-Simulink program by introducing some usage hypotheses, like the number of km travelled, road profiles, stops made, etc. In the theory model all the EPISOL power components were listed and the approximate driving cycle to be realised was taken into account, which was the cycle followed by a typical Madrid urban bus, with constant accelerations and braking, since, as this vehicle is for urban services it is assumed that its route would be similar. The main features of this vehicle are: average speed: 13.64 km/h; duration: 8 h; distance travelled: 108 km; maximum speed: 50.6 km/h. With regards to its total life, given the vehicle's purpose, an average of 230 days per year for 10 years was taken as a working regime, with a constant average daily consumption during this period.

Maintenance and repair stage comprises production of spare parts the vehicle will require during its lifetime and their estimation. Production also requires energy and there are emissions associated with this production process. The following hypotheses were made:

- The parts and components common to a conventional vehicle can be supposed to follow a

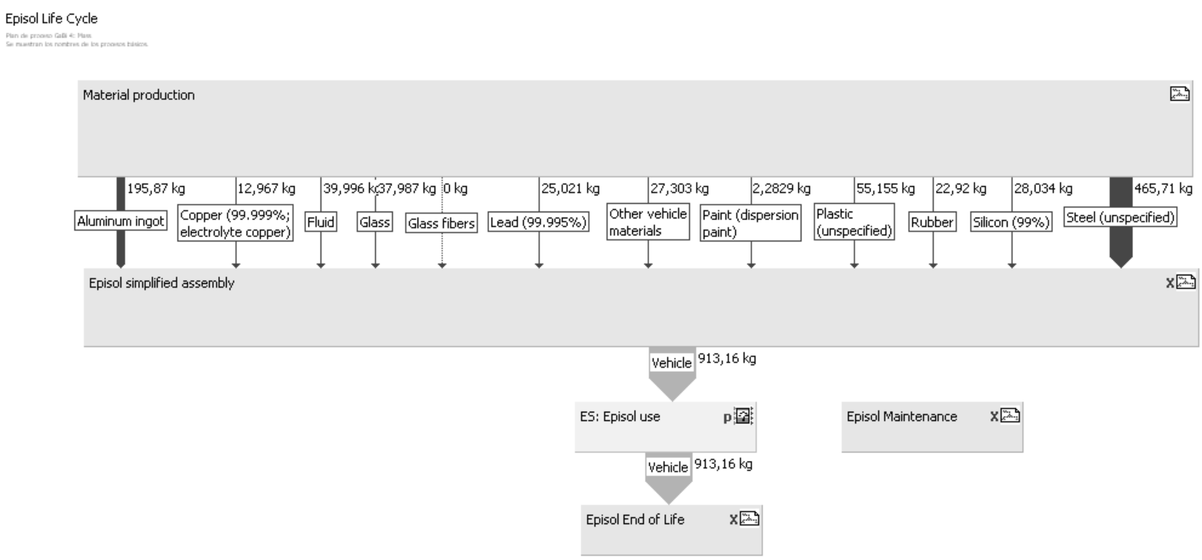

Fig. 6. Modelling EPISOL life cycle.

replacement pattern similar to this one, which can be obtained from the bibliography since it has been dealt with by different authors [28, 29].

- For maintenance of the thermal engine the dedicated manual that came with the purchase of this component was followed.
- Electric motor and generator maintenance would be minimal as there are few parts in constant contact using lubrication.
- Solar panel maintenance was considered to be zero, as this component is usually prepared to be resistant to shock, scratches and bad weather, etc.

End of life stage comprises the processes planned for dismantling, reusing and recycling vehicle components. Once again, electrical and thermal energy production is taken into account. Here an attempt is made to establish some measures for dismantling and reusing vehicle parts. Due to the characteristics of the vehicle, a model has been established to make use of 100% of the materials. This is in line with an actual goal of the automobile sector and is in agreement with the EPISOL's philosophy.

Using all the data, a model was built from the recycling processes included in the GaBi 4 data base [18, 25]. Electrical and thermal energy production was taken into account at every stage.

Figure 6 shows the plan in GaBi 4 of the EPISOL's life cycle, divided into its different stages, and Table 2 shows the most important results.

Table 2. Results obtained for EPISOL life cycle

	Energy (MJ)	CO_2 Emissions (kg)
Material Production	50.019	3.130
Vehicle Assembly	26.221	1.384
Use	254.646	18.417
Maintenance	26.281	1.354
End of Life	7.887	501
TOTAL	**365.054**	**24.785**

The figure for energy consumption during use reached 68.4% of the total, which confirms that it is the highest energy consuming stage of the entire life cycle; in any case, the percentage of the total is much less than for vehicles with conventional engine sizes (around 85%). This is followed by material production, which is 14.3%. Finally, the end of life barely represents 2% of the total.

ENVIRONMENTAL COST AS CRITERION FOR DECISION-MAKING: INTEGRATING GABI 4 AND SmarTeam

Throughout a product's or system's development process there is a constant need to make design decisions based on a series of determining factors, either explicit or implicit. This will lead engineers to reject many possibilities or options that are theoretically feasible and stay with others more in accord with existing guidelines. Compliance with specific legislation, ease of assembly, reliability and durability are logically key criteria when it comes to choosing certain designs, materials and manufacturing methods compared to others.

Price and weight are two ever-present criteria, usually incompatible in vehicle design. In this way, light components manufactured in aluminium or magnesium are slowly being introduced in the automobile industry in spite of their higher cost compared to steel, since less weight in equal conditions of strength provides better performance and lower fuel consumption.

However, as mentioned previously, in an environment of increasing concerns about energy consumption and environmental degradation, a rigorous analysis of energy costs, not only in the usage stage but also throughout the vehicle's entire life cycle is becoming a key design criterion, which in the near future, will be a marketing argument to be taken into account. This is currently the case, for example, with the classification that certain organisations, like Euro NCAP, assign to vehicles because of their structural resistance to impacts.

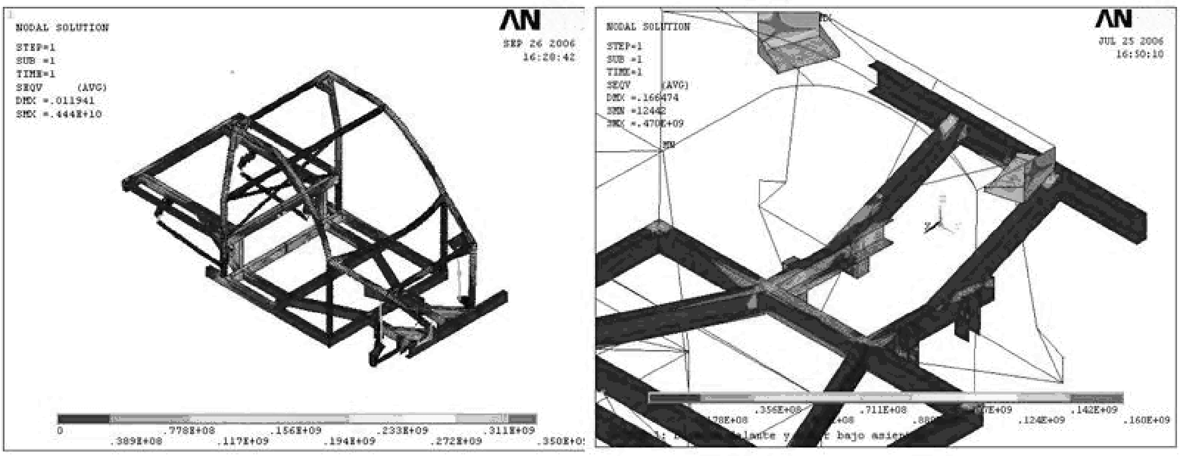

Fig. 7. Images of finite element analysis in ANSYS.

Table 3. Results from evaluating alternatives for chassis design

Energy (MJ)	Steel chassis	Aluminium chassis	Variation	**Emissions CO_2 (kg)**	Steel chassis	Aluminium chassis	Variation
Material Production	50.019	65.360	**+30,7%**	Material Production	3.130	3.851	**+23,1%**
Vehicle Assembly	26.221	24.895	**−5,1%**	Vehicle Assembly	1.384	1.131	**−5,1%**
Use	254.646	243.237	**−4,48%**	Use	18.417	17.591,7	**−4,48%**
Maintenance	26.281	26.281	**0%**	Maintenance	1.354	1.354	**0%**
End of life	7.887	7.458	**−5,4%**	End of life	501	462	**−7,7%**
TOTAL	**349.404**	**367.232**	**+0,60%**	**TOTAL**	**24.785**	**24.573**	**−0,85%**

To show how this factor could be used as a decision-making criterion when designing the EPISOL vehicle, replacing the tubular chassis for an aluminium one was evaluated.

With both materials the structural resistance required was identical, which was no other than that demanded by official approval tests for this type of vehicle. To be precise, the limits were set for the demands made of the chassis under normal conditions of use, so it would perform correctly under such circumstances as sudden acceleration and braking, pot-holes (vertical acceleration), passing over bumps (elevation of one of the axles), bends, torsion of one of the wheels (mounting a 10 cm. high kerb), etc. Besides this, performance limits were set for a possible head-on collision and rollover, so that protection of the users would be guaranteed. To ensure the strength of both chassis designs an iterative process was begun between the CATIA design program and ANSYS, for finite element calculus (Fig. 7).

As an end result, a 127 kg steel chassis was obtained and another in aluminium weighing 84 kg with similar geometries and identical structural features.

Having obtained the new figure for vehicle weight as well as the distribution of materials for the two alternatives proposed, the results were then evaluated in the model built in GaBi 4, which led to the results compared in Table 3.

Thus, with the aluminium chassis, the energy dedicated to production was greater due to the aluminium requiring a more complex process. However, the energy dedicated to the other stages was less due to lower weight, which means that the initial disadvantage was partially offset. The final result is, nevertheless, higher in the second case.

A similar trend for CO_2 emissions can be observed. But in this case, the final result is slightly better in the second material. This is not surprising, as it is known that processes in each case are different and present therefore different characteristics.

Thus the importance of weight was verified, since it significantly affects vehicle in-service consumption and also other stages of the vehicle's useful life. For example, the energy required for manufacture if the second alternative were chosen would be reduced due to the greater ease of working aluminium. The model presented here does not take account of this circumstance, but it does reflect it in the actual reduction in weight. The same conclusion can be reached regarding the end of useful life. Aluminium has a lower melting point than steel and therefore would be easier to smelt for recycling, which means that less energy would be required in this process.

Since CO_2 emissions are proportional to energy consumption, the foregoing conclusions are equally valid for evaluating them.

Apart from analysing the two alternatives shown here, it is not only possible but advisable to conduct some sensitivity analyses for different parameters, with the purpose of examining any possible variations in any of the stages of the life cycle. For example, to evaluate if it would compensate to manufacture higher quality or tougher components with a longer lifetime in exchange for reducing the number of spare parts needed for the vehicle.

The database that SmarTeam assigns to each component designed with CATIA, allows new areas of attributes to be configured. So, for every part and set, fields have been added listing the value assigned by GaBi 4 to energy consumption, for each life cycle stage. These figures are then exported to a spreadsheet where they are incorporated into the data provided for the other vehicle components. This makes it simple to calculate total figures for a specific vehicle configuration or compare different alternatives.

However, it must again be pointed out that the environmental criterion is simply one more in the decision-making process when it comes to deciding between one material and another. As previously stated, there are other criteria like economic cost, ease of assembly, durability, etc, which are a huge determining factor for design. This study shows the advisability of taking not only the usual points into account but also energy and emissions. The project manager should decide for each case which criteria prevail over others.

ASSESSING THE EXPERIENCE

So that the experience can be assessed on completion of each subject in the Master's, the students are invited to complete an assessment questionnaire, where, apart from indicating their level of general satisfaction with the scientific, technical and teaching level used in class, they also indicate the importance of the concepts explained and to what extent they could be applied to their working life in the automobile sector. Both subjects receive a very high overall score from students, this last course being given a score of 4.3 and 4.6 points respectively out of a maximum of 5.

However, since students assess the whole subject not only use of PLM and GaBi 4, of greater interest are the comments and responses obtained from open questions, such as, 'Indicate the most positive and negative aspects of the subject' or 'What parts of the subject do you consider most useful for your working life?'. This is where the high degree of usefulness perceived by students for the works presented becomes evident, both because the subject matter is up-to-date and relevant and because it is a simple-to-understand method but nonetheless rigorous regarding calculation.

In general, students also positively assess the fact that all the methodology taught is applied to a vehicle for which all the real data required can be obtained, without any limitations of confidentiality, since it has been produced wholly by the same institution that teaches the Master's. The students also very positively assess the fact that a single example is used as a leitmotiv to lead them through different subjects in the Master's since it helps them to consolidate the concepts explained in different modules and in work on a case that is close to reality.

Teachers' opinions concerning the use of SmarTeam are also very positive, as it allows a full, structured teaching of the design process, which, moreover, offers an opportunity to place an emphasis on additional collateral issues which are nevertheless highly important, such as vehicle life cycle energy assessment.

CONCLUSIONS

Using PLM in the educational field of the automobile sector has been posed as a basic issue given the real complexity of vehicle and parts design and the fact that numerous companies participate simultaneously in each project. For this reason, in the Master's in Automotive Engineering at the UPM, a global approach to automobile design has been preferred that involves various computer tools and managing the versions and options with CATIA PLM. To be precise, apart from design using CATIA, finite element analysis was included using ANSYS, and vehicle dynamics studies using CARSIM. As an original contribution to complete the design criteria, environmental cost analysis was included for every life cycle stage using the Gabi 4 program.

Although students do not have enough time during theory classes and practical exercises to attain great skills in handling any of these tools, some of them decide to do their Final Project using them, which leads them to contribute interesting studies and cases.

On the other hand, the example set for life cycle study is a vehicle designed and built at the INSIA, which enables a minutely detailed study to be conducted at every stage. This is perceived by students as very positive since a real, tangible case is involved where a high level of detail is accessible to them.

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