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Two Approaches to Design Teaching in a Mechanical Engineering Curriculum*

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Different approaches to design teaching in a Mechanical Engineering curriculum should coexist in order to highlight different aspects in engineering design. Two examples are given, one emphasizing product development and the other engineering analysis.

Keywords: engineering design; engineering analysis; entrepreneurship; product development; structural mechanics

1. Introduction

Engineers are after useful artifacts and for them knowledge is not an end in itself; rather it is a means to a utilitarian end. Engineers must predict the performance of those artifacts, which makes engineering an intensely analytical and quantitative activity. Between the *things* that engineers *make* and the original ideas behind them is engineering design, a term that denotes both the process and the result of that intermediary step.

In traditional views of engineering, design is contrasted with analysis [1]. But analysis is used at every point in a design project, from operational principles and criteria and specifications to the various theoretical tools, experimental data and practical considerations, which are the categories of knowledge associated with design and with much of engineering knowledge [2], as detailed below.

This paper presents two independent experiences in teaching design in two courses of the Mechanical Engineering Integrated MSc degree curriculum[1] at Instituto Superior Tecnico (IST) of the Technical University of Lisbon, Portugal. It shows that different approaches to design teaching should coexist for the students to get a grasp of what engineering design practice is.

The paper is divided in two sections in which each approach is briefly described and their outcomes are presented. The reasoning behind these approaches is explained together with the students' attitudes towards them. Case study 1 is in line with other approaches done elsewhere [3, 4] and focuses on product development and on the role of entrepreneurship and intellectual property in mechanical design. Case study 2 describes a design-led approach to a structural mechanics course that explores the relationships between mechanical design and engineering analysis. The case study emphasizes the importance of carefully chosen, concrete projects, using umbrella design as an example.

2. Case study 1: product development and entrepreneurship

The course on Product Development and Entrepreneurship is taught on the ninth semester of the curriculum, just before the students' MSc dissertation. It goes through all the topics from product idea to production ramp-up, also dealing in some depth with the product's associated business plan and inherent intellectual property rights issues. Students start by proposing the development of a new product of their own choice, subject to approval by faculty. This is the prime motivation for their semester-long work in the course. It also contributes to building an innovative engineer with an entrepreneurial profile (one that finds the problem and solves it, instead of just fixing a problem that someone else brings to him) and not just a product developer [5]. The fundamentals of the product development process are taught as a guideline for the development of their new products. They also have to develop a business strategy to launch their innovative products in the market. So they have to think on 'How are we going to make money on it?' materialized in a preliminary business plan.

The course is elective. Every year a number of students from other degrees within IST enroll in the course. The student pool often has electrical, management, and materials engineering students, together with computer science students as well. The European student interchange program ERASMUS often brings to IST students from Italy, Poland, France, Sweden, Finland and Germany, giving an eclectic flavor to the course. As a consequence of this, the course has been taught in English

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[1] A five year integrated curriculum leading to a MSc degree, according to the European 'Bologna' convention.

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for the last five years. In 2008, a special arrangement between IST and the School of Economics of the Technical University of Lisbon allowed the mixing of the two student pools, and some very interesting projects resulted of this (see the cane for the blind in Fig. 3).

2.1 Course objectives

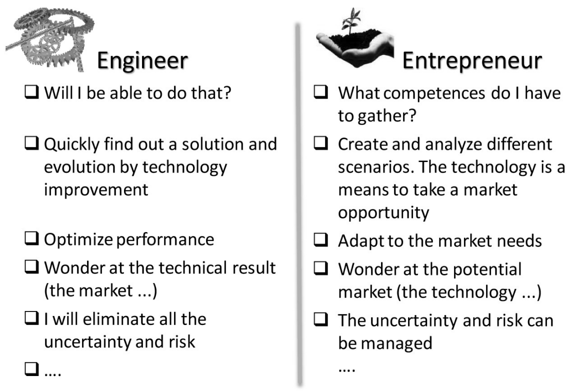
The course was structured around the idea that the typical engineer often has extreme difficulty in dealing with open ended problems, uncertainty, communication and business aspects of product development. As such, a generic methodology based on Ulrich and Eppinger [6] with the objective of turning customer needs into successful products (new or adapted) is proposed. At the end of this course, the student will be able to:

- Identify customer needs and translate them into product specifications;
- Understand the product as a whole, from the first design sketches to the final production stages and commercialization;
- Design a product inside a team, innovating and creating based on market needs;
- Implement a structured methodology, reducing uncertainty, risk and time spent from idea to market launch;
- Make a development plan with milestones and resource allocation for the different product development phases, establishing targets and partial objectives;
- Communicate with all the stakeholders, understanding clearly their role and the role of others.

Underlying all of these objectives is the notion that information is continuously passing from one stage of design to the other in various forms and that the design is driven by this information. Get the customer needs wrong, and the whole product will fail to address these needs; translate the needs into specifications in the wrong way and the product will address a different target market, and so on. The usual duality between the engineer and the entrepreneur is summarized in Fig. 1. One of the objectives of this course is to bridge the gap between the two ways of thinking, in such a way that engineers may feel comfortable in developing new products.

2.2 From market to design

As mentioned before, the students are encouraged to look for a market pain and solve it. The first step will naturally result in collecting market data and customer needs the team will have to address. Concurrently, and still without thinking in a concrete solution, the team should establish target specifications. A typical engineer will have thought of a solution before embarking on collecting market data and customer needs. However, this solution must not interfere too much with the process of customer needs collection, otherwise the data will be biased and future detours from this initial solution will strike insufficient market data.



Engineer	Entrepreneur
☐ Will I be able to do that?	☐ What competences do I have to gather?
☐ Quickly find out a solution and evolution by technology improvement	☐ Create and analyze different scenarios. The technology is a means to take a market opportunity
☐ Optimize performance	☐ Adapt to the market needs
☐ Wonder at the technical result (the market ...)	☐ Wonder at the potential market (the technology ...)
☐ I will eliminate all the uncertainty and risk	☐ The uncertainty and risk can be managed
☐	....

Fig. 1. The duality of perceived challenges and attitudes of engineers' and entrepreneurs' when facing a problem [7].

As an eye-opener for the importance of immersion in the customer environment, an unorthodox exercise is done in class. The students are presented with a couple of fresh oranges and a few orange squeezers and are simply asked to get some juice out of the orange, and then wash the squeezer and the table (and drink the juice, if they feel like it). Figure 2 shows one of these sessions. In the end, the orange squeezers are benchmarked based on functionalities and possible improvements are gathered. This exercise has been done every year for the past four years, and we notice that the outcome is strongly dependent on the type of orange squeezer that the student tests in class. For instance, if only manual orange squeezers are tested, no concerns about noise usually come up during the discussion. Conversely, if only electric orange squeezers are tested, possible solutions for new and improved squeezers are mostly power-assisted. In the end, these same questions are raised to the students, to let them understand the importance of immersion and why big companies are investing in ethnographic studies [8].

2.3 Design: from idea to prototype

The creative phase of product development is steered with the customer needs and product specifications in mind.

Students often find this phase most intimidating. The Engineering program is filled with courses that analyze existing artifacts, but the students are seldom asked to come up with something completely new. Dealing with uncertainty in the outcome is for them extremely difficult. They face the need to iterate and continuously improve their ideas and evaluate them with very limited information available. Students are used to exercise their analytical

Fig. 2. Typical situations during the orange squeezing exercise done in class.

skills in the presence of enough information, but the front-end of product development always lacks vital information, especially when designers have very limited experience.

The students are encouraged to build mock-ups of their products, to ‘feel and touch them’ during development. They have a fully equipped machine shop and rapid prototyping machine available at the university. Unfortunately, only one prototype is typically built, as students generally feel that 3D modeling is enough. However, building one prototype alerts for possible improvements and eventual corrections of functional parts of the product, which always comes as a surprise for the students. Other studies have reported that the willingness to build physical prototypes can depend on the experience of the design team and that the more experienced the team is, the earlier the team will start building prototypes [9].

2.4 From design to market

The students have to build a brief business plan for their product, based on the market research they performed and the product they developed. This approach is aligned with the experience of Papayannakis et al. and Bonnet et al. [10,11] who mention that students not only have to think of the product design itself and its production, but also to know where and what to buy from whom and who will sell it, where and at what price.

Students are instructed in intellectual property rights and a very brief introduction to the intricacies of patent filing is also provided. This is a powerful tool with which to assess creativity. Patent search engines are very useful in finding answers to problems or realizing that an idea is indeed innovative, if no patents on the subject are found [12]. Students are encouraged to file patents on their own ideas during the course (in Portugal, universities are free from paying patent filing fees). A hands-on approach to all the technical details, administration and legal issues of filing a patent is the only way to really understand the process. As a result, a total of 56 patents have been successfully filed by the students in the last five years.

At the end of the semester, students have to present their business plan to a panel of experts composed of faculty members and other external experts from the design community and financial institutions (NDA's are used when needed). The panel grades the students' performance along several lines: communication of the idea, robustness of the business plan and financial data, originality of the product, overall quality of the design. These grades are then used in the course grading system.

2.5 Course outcomes

Very interesting, simple products come out of this course. The simplicity of the products is a necessity, given the limited time the students have to find the market pain, develop the product, and build a business case. Figure 3 shows some examples of products. Of these, some examples of misleading assumptions made by the students that forced them to perform minor or major design iterations may be highlighted. The valve remover device had to be redesigned to feel more rigid: people from this target market are used to working with sturdy tools, and this particular tool felt very delicate, although all the calculations for strength and stiffness were in place; the students had to make it stiffer to 'look professional' in a rough environment as in the case of an auto shop. The case of the vibrating cane for the blind had to be redesigned to use vibration in the handle instead of a warning sound whenever an obstacle is found in the path; a warning sound would be difficult to discern in an already noisy city environment, and blind people use their senses in different ways from ordinary people. The crane for extremely heavy patients was only designed to withstand the forces exerted during operation, but it was intended for use at the patients' home environment, which is usually cramped with furniture and other equipments; it had to be redesigned to be foldable and storable underneath beds or behind doors when not in use. These simple examples clearly show that design requires constant contact with end users' needs to verify whether the initial assumptions from the design team were correct or not. The flow of information must be kept open

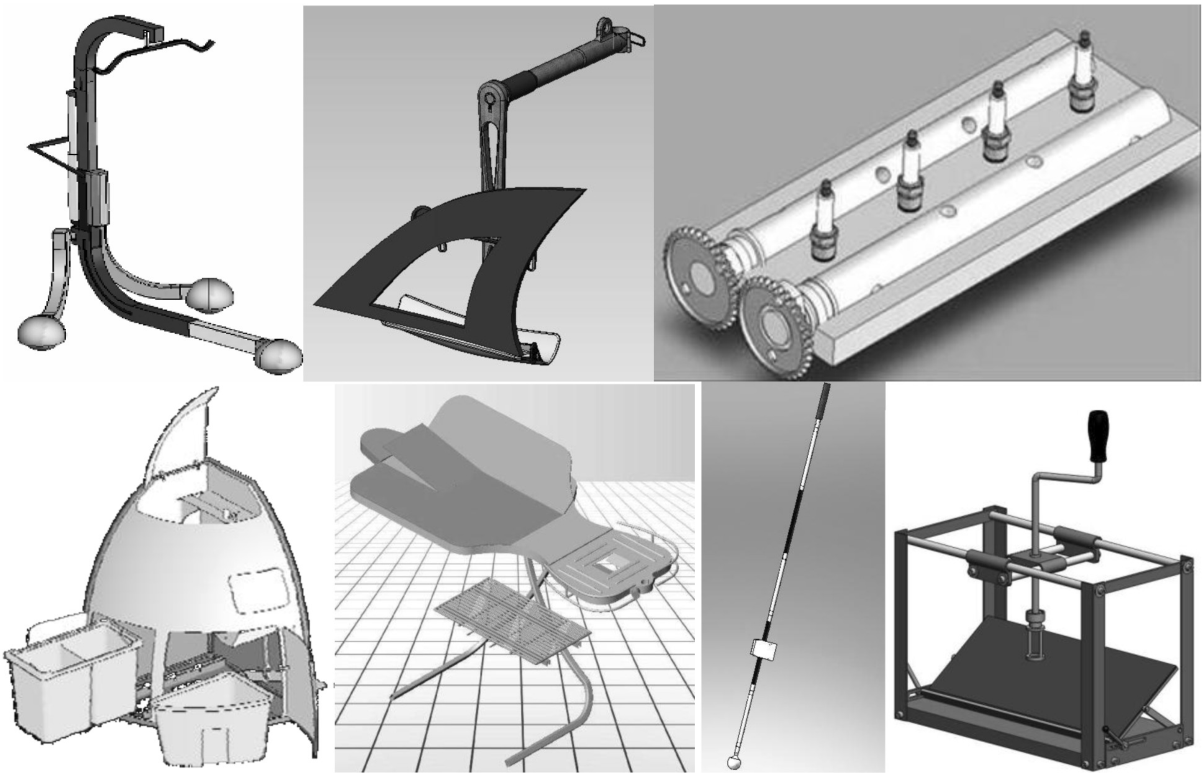


Fig. 3. Typical products developed during the course, from left to right and from top to bottom: crane for extremely heavy patients, 2004; bicycle support for surf boards, 2005; valve opener for internal combustion engines, 2006; eco-trash can, 2007; ironing board, 2007; vibrating cane for the blind, 2008; valve remover for internal combustion engines, 2010.

between design team and end user for the product to fulfill its intended function.

A survey done with a pool of 43 students (from a total of roughly 90 questionnaires sent out, corresponding to three consecutive years of students taking the course from 2005 to 2007) after they graduate show that they frequently use the knowledge acquired during this course even if most of them are not working as design engineers [4]. The learning outcomes that are most valued or even crucial for these novice designers are the enhanced understanding of competitiveness, the capacity to apply acquired knowledge in new situations, the ability to grasp engineering problems in a holistic perspective and a better understanding of the opportunities and drawbacks of intellectual property rights.

Table 1 shows an excerpt of the questionnaire taken by the students.

The project-based learning, hands-on approach taken in this course is being enhanced by the lessons learned not only in the course itself, but also from the PhD level Product Development course currently offered within the MIT-Portugal program. Another survey done with students from both courses and a course on Product Development running at MIT show that there are significant differences in the student pool, mainly attributable to cultural differences and level of previous experience of the students [3].

3. Case study 2: structural mechanics

The course on Structural Mechanics is taught on the seventh semester of the curriculum, after traditional courses on Solid and Fluid Mechanics and an introductory computational mechanics course. It is divided into two parts: a recapitulation of topics in elementary solid mechanics, from Mechanics of Materials to Finite Elements, followed by Theory and Analysis of Plates.

The first part of the course will be described in this paper. Its ultimate aim is to introduce the students to ways of thinking and methodologies used by engineers and develop the analytical capabilities needed for their tasks.

Our aim in this course is to explore the relationships between design and analysis using a strategy that is design-led; that is, the strategy uses, as inputs, the requirements of a design.

Examples and projects will be concerned with normal or evolutionary design as opposed to original design, which starts from a new concept and is addressed in the first part of this paper. Normal design begins with an existing product, operating on stable principles, and seeks to change it in ways that increase its performance or reduce its cost.

Normal design is not routine design and the knowledge both require cannot be sharply separated. They are different in ways not central to the course objectives and avoiding the additional complexities of original design allows focusing on those objectives.

The organization of different technological problems under a common theoretical framework, typical in most courses in the engineering curriculum, is clearly superior to the scattered treatment according to problems. It offers an opportunity to view engineering knowledge free of the complications that attend a particular application and it facilitates clear thinking about the complexities of a particular topic.

This organization of engineering knowledge presented to the students also favors the design-led strategy used in this course in order to develop, at some point, a workable synthesis of their training.

3.1 Exploring the relationships between design and analysis

The relationships between design and analysis explored in the course will be systematized through a categorization of engineering knowledge in normal design and a familiar and much used engineering methodology known as parameter variation.

The categories considered by [2] are:

1. Fundamental design concepts
2. Criteria and specifications
3. Theoretical tools
4. Quantitative data
5. Practical considerations
6. Design instrumentalities

Table 1. Excerpt of the questionnaire taken by the students*

Questions	Crucial or important
In terms of your creative capacity to be innovative, this course was . . .	82.7%
In terms of your understanding of problems and opportunities related to intellectual property rights, this course was . . .	91.2%
In terms of your understanding of competitiveness and competition, this course was . . .	85.3%
In terms of your capacity to apply your knowledge and skills in new situations, this course was . . .	92.7%
In terms of your understanding of engineering problems in a systemic and holistic way, this course was . . .	75.6%

* The range of answers was: crucial, important, indifferent, and counterproductive.

The first and the fifth are not essential for the course's purpose. Fundamental design concepts, addressed in the course on Product Development, concern *operational principles* and *normal configurations* which, in the course's examples and projects, are stable and given; practical considerations are knowledge derived from experience in practice, mostly learned on the job rather than in school.

Criteria and specifications concern the translation of the utilitarian, usually qualitative, goals of a device into specifications, i.e. concrete technical terms. In some cases they are simple and obvious, in others not clear or even obscure and may require a great deal of effort to be established. Determining the essential criteria often draws on engineering analysis.

Theoretical tools regard mathematical methods and physical theories to make design calculations. They comprise a continuum, with pure mathematical tools on one end and phenomenological theories and quantitative assumptions on the other. As mentioned above, they are learned in school free of the complications that attend a particular application.

Included in this category are also concepts from science like force and mass and others of a more engineering nature like efficiency, load factor and feed-back. These concepts must often be supplemented with data from the next category—quantitative data—to obtain a theory which gives definite results. This category also contains data of a prescriptive nature like safety factors for particular devices, standard performance specifications, etc.

The last category, design instrumentalities, consists of structured procedures, ways of thinking and judgmental skills, referred to in general as 'knowing how' to seek design solutions and make design decisions and is addressed in the course on Product Development. Engineering analysis is here essentially concerned with the following procedures: division of a system into subsystems, optimization and successive improvement of a design from experience of its performance in a previous version.

The relationship between design and analysis will be detailed and put in concrete form in the next section with respect to a particular design project; it will now be further discussed in connection with the engineering methodology known as parameter variation.

Parameter variation can be defined [2] as the procedure of repeatedly determining the performance of some material, process or device while systematically varying the parameters that define the object of interest or its conditions of operation. The method is so familiar to the engineering community as to seem only common sense.

Parameter variation may be carried out by experimental, numerical or theoretical means. It is used to provide a useful collection of systematic design data, thereby bypassing the absence of a quantitative theory and to aid the development or refinement of a theory or theoretical model.

It is also used to optimize a device by choice or adjustment of the design parameters.

The application of parameter variation requires the assumption of a functional relation, a defined measure of performance and identification of parameters in which the performance depends. In this sense, it is a second stage process and the connection with engineering analysis is clear.

Two additional comments are in order regarding this engineering methodology and its use in a design-led course in Structural Mechanics:

1. Trends in the structural behavior of a device obtained by numerical or theoretical parameter variation may lead to establishing new or unidentified relationships among relevant parameters. Here the role of the teacher may be significant.
2. Comparison and reconciliation of both numerical and experimental results is critical to the course success and may be achieved through careful selection of examples and projects.

3.2 Illustrative example

The example chosen to illustrate a typical course project is umbrella design. Umbrellas have a long history and began as ceremonial and status symbols and as a protection from the sun (the name derives from a French or Italian diminutive of umbra, Latin for shade). By 1800, the parasol and the umbrella had achieved separate identities: the parasol had become a luxury item of fashion and the umbrella a functional protection against the rain. Today some 40 million umbrellas are sold every year in the US, mostly imported from China, while in Britain that number reaches 16 million.

The umbrella is also a remarkable example of structural engineering since very few structures can be erected or pulled down so quickly [13]. Figure 4 presents its three-dimensional geometry, consisting of a frame composed by a shaft, stretchers and ribs that tension the fabric cover.

Umbrellas weren't a common sight until the last half of the 18th century, as they were cumbersome and heavy.

As designs improved, so did use. First came U-shaped steel ribs and stretchers, then synthetic fabrics replaced heavy oiled leather and canvas. Today the market is changing with the introduction of new materials for the frame and fabric, new coatings and new functions.

What were then the explicit objectives of this

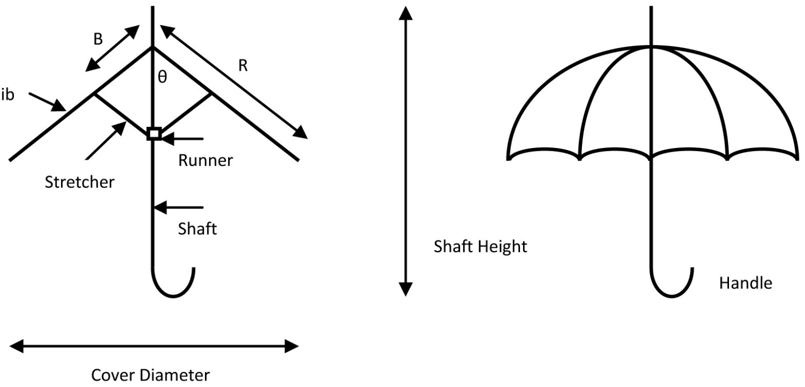


Fig. 4. Umbrella geometry, structural components and essential dimensions.

structural mechanics course project in umbrella design? Firstly, the development of product specifications, translating qualities into analytical performance parameters and user requirements; secondly, the selection of the correct level of analysis, understanding the function of each component; thirdly, the definition of the model or models for analysis, from Finite Element techniques to analytical relationships; fourthly the formulation of strategies to verify the model's results, with tests or otherwise; fifthly, the use of analysis results to establish new or unidentified relationships among parameters and sixthly suggestions for product redesign, enhancing its performance or reducing its cost.

Existing umbrellas were the starting point; in its mass-market version, they are an inexpensive and ubiquitous product that can be tested easily to verify the modeling and analysis results.

A product specification given was the cover diameter and the number of ribs (see Fig. 4). That, in turn, fixes the base size of the triangular shaped fabric segments. Standard specifications for umbrella fabric strength and stiffness are defined in ASTM D 4112.

Other given specifications are less simple: solid but still lightweight, easy to open and close, wind resistant. Their translation into analytical objectives and constraints was considered afterwards, as the analysis progressed.

The function of each component was understood by handling the umbrella: the ribs are loaded in bending; the stretchers in compression and both tension the fabric. A radial cut causes the ribs to straighten, confirming dominant tangential stresses in the fabric.

After some basic measurements a simple Finite Element model was set up, using beam elements for the ribs, bar elements for the stretchers and fabric and taking into account symmetry. Material properties were defined from tables after material component identification by inspection. The displacement results presented in Fig. 5 for the ribs were unexpected since they don't reflect the behavior of a beam in bending.

Several strategies were defined to reconcile the numerical results with the umbrella real behavior: tests to verify the validity of the FE results, by analyzing parts of the structure with simple analy-

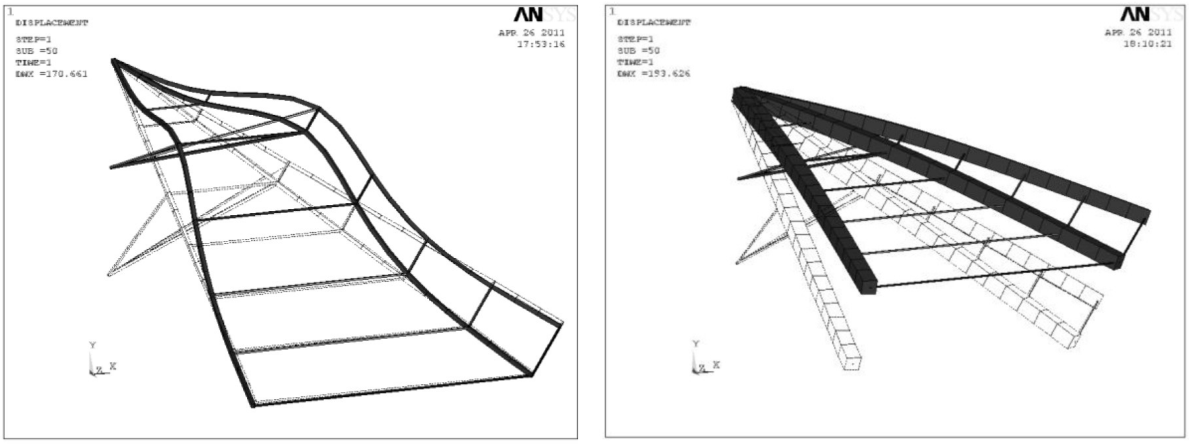


Fig. 5. Finite element displacement results for different rib inertias.

Table 2. Parameters considered for the improvement of the umbrella structural behavior

Values	θ	B	E	I
Base –15%	1	1	1	1
Base	2	2	2	2
Base +15%	3	3	3	3

tical solutions (for example, the stretchers stress and deformation), and experimental tests to verify the material properties assumptions for the fabric. These tests, performed with simple tools, showed an anisotropic behavior for the fabric with the correct assumed order of magnitude for the modulus and a very low shear modulus. Therefore, in order to avoid puckers and creases, the cover needs to be made of several triangular pieces oriented along the fabric principal material directions.

The unexpected displacement results for the ribs have a different explanation. The ribs are beams on elastic foundation, provided by the fabric, and behave as typical beams only when their bending stiffness falls within certain bounds of the stiffness foundation k_f [14], given by:

$$k_f = 2E_f \ t \ cos^2 \ \theta \ sin \ 22.5^\circ \ / \ (x \ sin \ \theta)$$

where E_f denotes the fabric modulus in the tangential direction, t its thickness, x the distance measured along the rib from the top and θ the angle made by the rib with the vertical direction. The 22.5° angle in the formula derives from the eight ribs in the selected umbrella. The dependence of k_f on $cos^2 \ \theta \ / \ sin \ \theta$ denotes a strong geometric nonlinearity that needed to be considered in the analysis.

The bounds referred above force the bending stiffness of the ribs to lay between certain limits if the umbrella is to assume the usual deformed bell-shape. A typical FE result is shown in Fig. 6.

Suggestions for improving the umbrella struc-

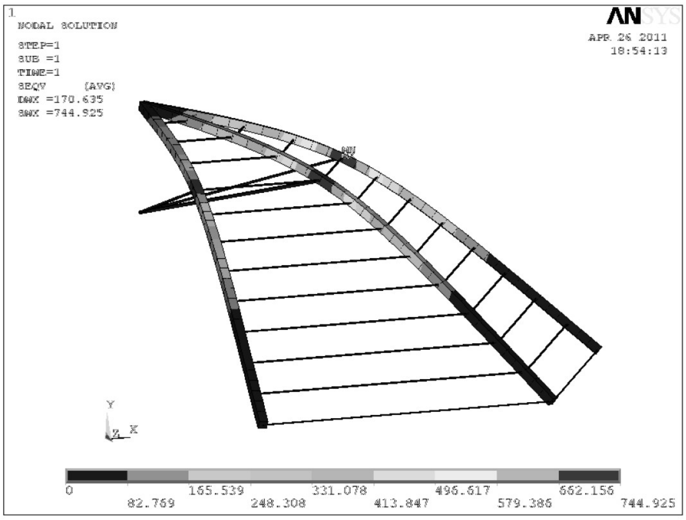


Fig. 6. Stress distribution and deformed rib shape.

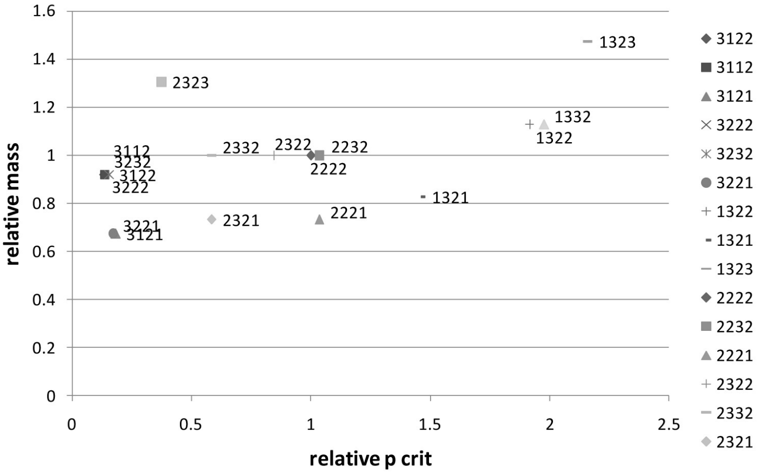


Fig. 7. The tradeoff between lightness and wind resistance in an umbrella.

tural behavior were analyzed by the method of parameter variation. Minimize frame mass and maximize pressure on the fabric were the objectives considered by most students, subjected to constraints on umbrella cover diameter and maximum stress on the structure. An example is given in Fig. 7 with the following parameters: the initial angle θ, starting at 60° and varying +/– 15%, the length B, starting at 0.4 R and varying +/– 15%, both defined in Fig. 4, and the rib E modulus and inertia I, starting at typical umbrella values and varying +/– 15%. Table 2 shows the 81 possible cases considered.

In Fig. 7, the parameter variation results are identified with an ordered quadruple following the parameter presentation order.

A typical tradeoff surface emerges from the parametric study displaying the relative importance of the different parameters and this is as far as most students went in the time available.

Most students worked hard in the umbrella project, incited by the need to resolve the contradictions between the results of sophisticated engineering tools and the actual behavior of a humble device. As already mentioned, this possibility of easily comparing theory and experiment is critical to the course success and may be achieved through careful selection of examples and projects.

4. Conclusions

Engineering knowledge is mostly about designing. However, in an engineering degree most courses do not deal explicitly with design. Structural Mechanics is one of those courses, where the necessary skills are mostly analytical. But design involves analysis, and this is where a point of contact may be developed. A possible strategy is a design-led course in Structural Mechanics as described in this paper, trying to foster the students' design capacity, while reinforcing their analytical skills at the same time.

The mechanical engineering degrees are being pushed for a few years now to incorporate more soft skills, more management, more entrepreneurship, more social science topics, more ethics . . . The problem is always the same: fitting an already overloaded curriculum with extra topics. The need to incorporate entrepreneurship is now being felt and some engineering degrees are already doing it, but in a way that is seldom correct, although traditional: it typically involves offering a course on entrepreneurship at the expense of a course on some other topic, or offering one extra elective course on entrepreneurship. Our vision is that entrepreneurship is best introduced in an engineering curriculum together with a product design and development course, as each topic needs the other to make complete sense to a student, in an integrated way.

Summarizing, we believe that now and in the future what will distinguish a good engineer from an outstanding one is his ability to have a broad perspective (an engineering systems perspective, as some would say) on technological products and systems. This leads us, faculty, to the necessity of having, ourselves, an engineering systems perspective in order to devise courses which are not just independent modules to fit in an already cramped engineering curriculum, but that adopt instead an engineering systems point of view.

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