TEACHING MATERIALS IN THE 21ST CENTURY

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RESUMEN

Vivimos en una época de continuos cambios. En la rama de la ingeniería, a los objetivos de siempre como funcionalidad; seguridad e integridad, se les ha unido el dominio en el uso de los ordenadores; las nuevas presiones económicas y la preocupación por el medio ambiente, la disponibilidad de recursos energéticos y el buen funcionamiento de las cadenas de suministro de materiales. Los estudiantes necesitan una educación que les permita comprender y tratar con estos cambios, ahora que el crecimiento en el número de estudiantes, expectativas y competencia en los recursos supone un reto para el profesorado- particularmente para los más jóvenes.

Los ingenieros crean cosas a partir de materiales. ¿Qué necesitan saber los estudiantes de ingeniería para seleccionar y usar los materiales de forma segura, eficiente económicamente y con el menor impacto ambiental? Esta pregunta nos lleva a la introducción del enfoque de diseño, que empieza con complejos requisitos de diseño proporcionando de entrada el conocimiento, los datos y las herramientas necesarias para que los estudiantes puedan tomar decisiones. Esto no significa ignorar la ciencia- esta es necesaria para comprender los problemas de ingeniería -sino que se introduce para poder entender las propiedades que limitan el diseño, y no como una disciplina sin relación con diseño de ingeniería.

Esta conferencia introduce brevemente alguno de los nuevos aspectos de la versión 2011 del programa CES EduPack. Esta herramienta desarrollada por Granta Design apoya y ayuda a los estudiantes de primeros cursos de ramas como la ingeniería, el diseño o la ciencia en el estudio de los materiales. CES EduPack se usa en más de 850 universidades e institutos de todo el mundo, y está en continua evolución para poder ofrecer una nueva versión en enero de cada año. Los cambios y nuevos aspectos están enfocados en dos vías, una activa (como el desarrollo de Eco Selector y la herramienta Eco-audit) y otras en respuesta al feedback de los usuarios. Esto último ha permitido el desarrollo de un software más intuitivo y fácil de utilizar.

Palabras clave:
Enseñanza de Materiales, formación para el diseño y selección de materiales, herramientas de soporte a la docencia,

ABSTRACT

We live in an era of continuous change. In the branch of engineering, beyond the usual and pressing objectives of functionality, safety and integrity, computers are now used pervasively, new economic pressures and concern for the environment are looming, and the availability of energy resources and proper functioning of materials supply chains are ever more important. Students need an education that allows them to understand and deal with these changes, in a time when growth in the number of students, expectations and pressure on teaching resources is a challenge for professors, particularly for younger academics.

Engineers create things out of materials. What do engineering students need to know to select and use materials that perform as expected, are safe, economically efficient and have the least environmental impact? This question leads to the introduction of the design approach. Knowledge, data and tools are necessary for students to make decisions that meet complex design requirements. This means that science is introduced in a way that facilitates understanding how to meet design requirements and select materials and processes.

This paper also introduces briefly some of the new aspects of the 2012 CES EduPack. This tool developed by Granta Design, supports professors and helps students of both introductory and advanced courses in branches such as engineering, design and science in the study of materials. CES EduPack is used in more than 850 universities and institutes around the world and is continually evolving to offer a new version each January. Changes and new features are focused on two pathways, one active (eg development of Eco Selector and Eco-audit tool) and another in response to feedback from users. The latter has made the software more intuitive and easy to use.

Keywords: Materials teaching, design led approach, materials selection, teaching support tools

1. INTRODUCTION

The present paper is about the transmission of materials knowledge in ways that recognise the broader technical, economic and social conditions in which it takes place. It is important for students to appreciate both the history of their subject, its linking role in modern engineering, and its potential impact on society in the future.

An educator’s appreciation of the balance needed between breadth and depth of knowledge is fundamental if we are to produce Engineers that can tackle the highly complex problems of this century. Materials are firmly set at the interface of multiple disciplines and will play a decisive role in the future of humanity. Engineering education is morphing into an all-encompassing discipline, in which data is at the core of systems' decisions and design. It is broadening its scope, from typical silos like Mechanical, Materials, Electrical or Civil Engineering into Engineering Systems, Environmental Engineering, and so on. Even within the silos, attempts are being made at broadening their scope, using design and systems thinking as tools to understand the broader challenges that face engineers.

However, breadth and depth are competing skill sets, in that one or the other is achievable, but it is difficult to accommodate both in an undergraduate curriculum. Materials research & development in the 20th century has greatly extended the portfolio of engineering materials and the underlying understanding of materials properties.

Advanced research, especially that developed inside higher education institutions, has been absorbed into the engineering and science curricula and made specialization the preferred route for course development. The world outside academia, however, is so varied that it is not possible to equip students with all the knowledge they will need. Hence the undergraduate degree should provide a set of basic building blocks upon which different types of future engineer can build his/her specialism through on-the-job training, professional development and further education.

It is therefore important that degrees focus on teaching students to learn, a skill they will require throughout their whole lives to acquire the breadth and depth that they need for their professional development. Learning synthesis and analysis (or induction and deduction) coupled with a design led approach is one way of achieving breadth without losing too much depth.

The interdisciplinary nature of materials means that students have the opportunity to make materials an overarching theme on which to build their knowledge network and practice induction and deduction on a design led approach.

2. PAST AND PRESENT OF MATERIALS EDUCATION

The subject of Materials can trace back its history for at least 4000 years, a history longer than that of any of the other "disciplines" shown in Figure 1. It evolved from early Metallurgy, which was itself informed by alchemy and by tradition enshrined in folklore. Today, the subject sits at the intersection of Physics, Chemistry, Geo and Bio Sciences, Environmental Science, and Engineering – that is to say as a bridge between the applied sciences and the pure sciences. This breadth is unusual and makes the subject uniquely well-placed to contribute to the solution of many of today's challenges, particularly by:

- Encouraging interdisciplinary thinking that bridges the disciplines shown in Figure 1, an essential ingredient for innovation from cross-fertilisation (1).
- Devising ways in which materials and processes can be made more efficient, less expensive and less environmentally damaging – one of the central challenges in advancing materials in the 21st century.
- Thinking creatively about material needs to meet the changing demands of industry in the next 30 years, and in doing so, linking the science to the engineering (2).
- Introducing students to the Grand Challenges of our time such as future mobility, clean energy and sustainability, all of which require an approach combining information from several of the disciplines shown in Figure 1, plus an appreciation of the role of technology in society (3,4).

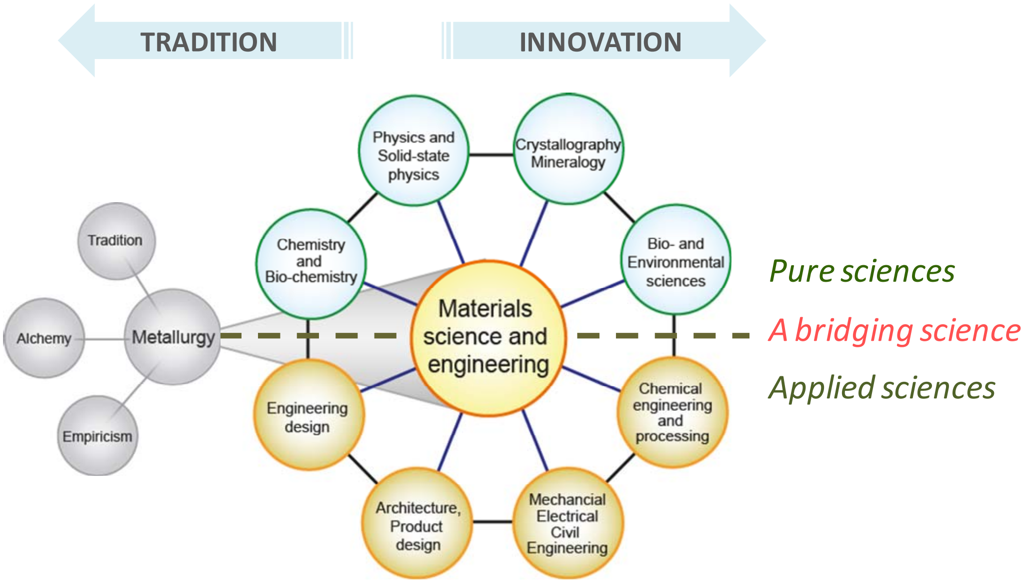

Figure 1: The past and present of materials.

A balanced Materials education today must include both depth, providing expertise in the subject, and breadth, allowing material issues to be judged in the light of contemporary economic and societal concerns; looking both at the present and the future and giving engineers the skills to take their ideas forward (Figure 2). This is consistent with the increasingly integrated nature of technical education. Innovative design, today, must include an understanding not only of the technical aspects of products but also of stakeholders' interests and the context in which the products will be used. We have role-models exemplifying visionary engineers able to combine depth and breadth: Leonardo daVinci, Gustave Eiffel, Isambard Kingdom

Brunel, Wilhelm Daimler, James Dyson and Steve Jobs are examples. We cannot teach all our students to emulate their success, but it remains our responsibility to train students who are not merely specialised experts or non-specialised generalists, but rather a balanced combination of both.

The evolution of materials teaching over the last 40 years has been one of increasing integration. At one time metallurgy, polymer science, and glass and ceramic technology were taught in different Departments, even at different Universities; today they are generally integrated into a single program under the heading of Materials Science or Engineering Materials. Broadening perspectives when teaching Materials and Design should come naturally in a subject that has a tangible, global impact on society. Consequently, there is now a move towards what we will call Materials Systems and Design, integrating broader technical, economic, environmental and social (TEES) issues into an entity.

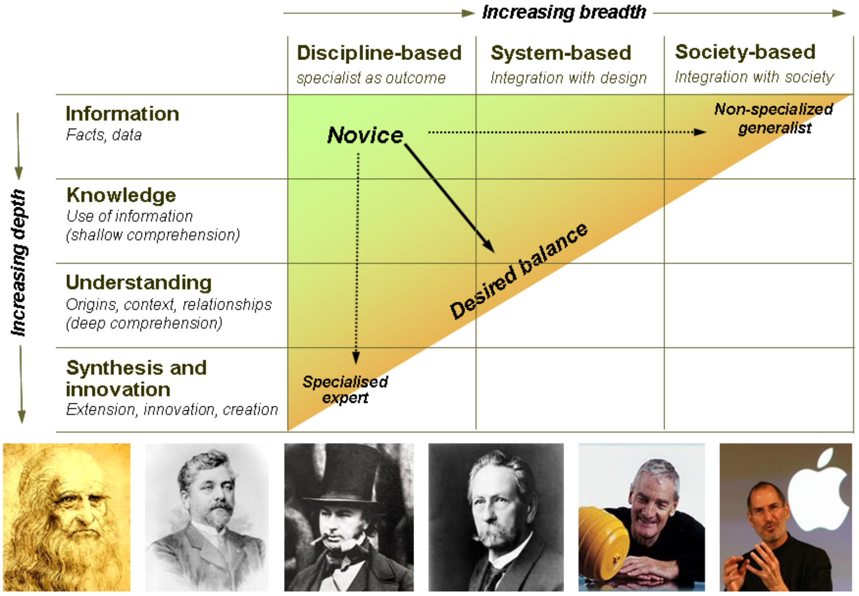

Figure 2. The balance between breadth and depth. The images are those of engineers who, par excellence, combined depth and breadth

Figure 3 intends to project past and present into a possible future of materials teaching. The trend has been to take each of the material realms from the past and create a Materials Science discipline to encompass all of them. Today Materials Science is taught together with other topics like Mechanics, Structures, Design, Environmental Science, and so on. These topics will be brought together in a way that will integrate them under the umbrella of Materials Systems and Design, broadening our understanding of Materials in a global context where TEES issues come into play. Interpersonal and leadership skills will undoubtedly play a critical role in the future. Engineers will have to master these skills if they are to contribute to the advancement of mankind in a sustainable way and have their ideas realised.

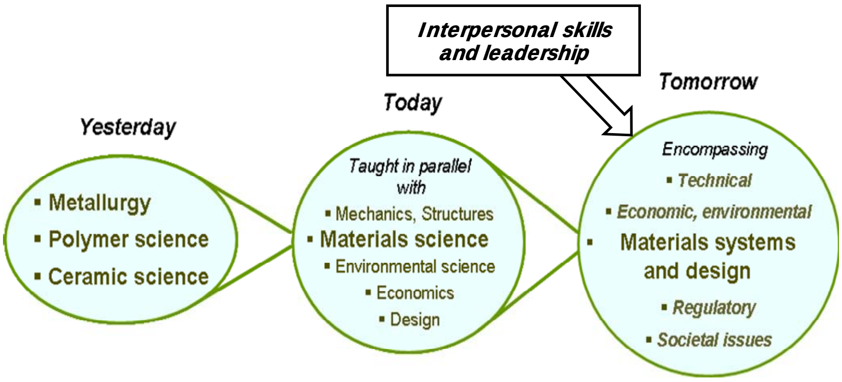

Figure 3. Past, present and possible future of materials.

3. DESIGN LED VS SCIENCE LED APPROACHES

The science led approach to teaching typically sets the basic building blocks of scientific knowledge on top of which students will then develop their academic and professional activities. However, this approach seldom attempts to create relationships between each of the blocks.

This means that students have a wealth of disconnected knowledge silos and no tools to build relationships among these silos. The way that is traditionally used to overcome this situation is to have a capstone design course, usually in the final year of study, in which the students use all their knowledge to solve a design problem. However, this may not be enough to capture all the technical, economic and social/environmental issues that arise in real life design (1).

A constant awareness of this broadness is necessary for the students to tackle design from day one on their undergraduate degree. The whole idea of design thinking, teaching and learning is handsomely explained by Clive Dym and his co-authors (5).

The design activity is inherently broad in scope. The breadth of design is only limited to some extent by the design brief. Our students can learn to tackle this broad perspective supported by a project based learning approach. The tools our students need to learn will primarily have to provide breadth, supporting depth when needed. This provides meaning to the most difficult topics. Learning depth with an objective is fundamentally different then learning it just because. Figure 5 provides a visual representation of the science lead and design led approaches.

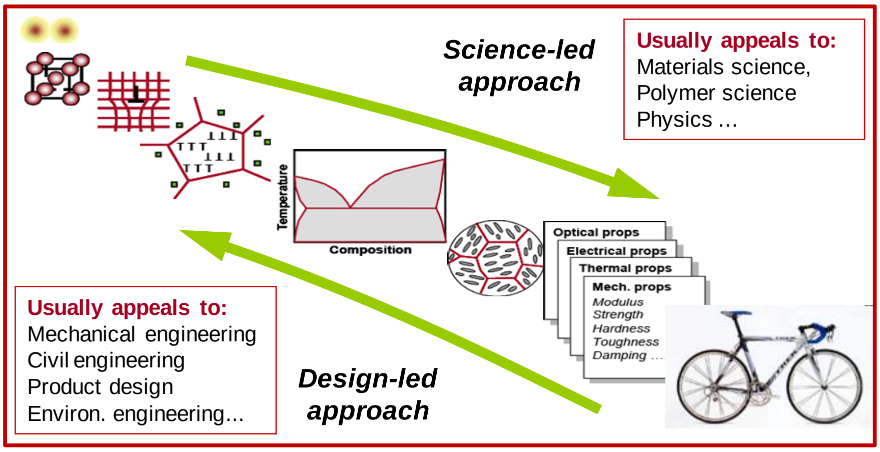

Figure 5. The science led approach and the design led approach.

A way of teaching and learning about engineering materials, especially with students from typical engineering degrees, like mechanical engineering, is to make a parallel between the process of design and the process of materials selection, explaining the flow of information between the two processes (see Figure 6). Since these two processes will influence and be influenced by manufacturing, this too will have to be studied. And because design can be performance-driven or cost-driven, manufacturing plays differing roles in each. Figure 7 depicts in a simplified way the relative importance of materials and manufacturing process selection in design. For a performance driven design, the selection of the materials is crucial, and the manufacturing process is secondary in that it is selected as a consequence of the performance needed from the product. If cost is driving design, the manufacturing process becomes the most important parameter and the major factor in early design stages. The material will be a consequence of what the manufacturing process dictates. In real life, however, nothing is that straightforward, but for teaching purposes, explaining the extremes is usually enough to have students thinking critically (6).

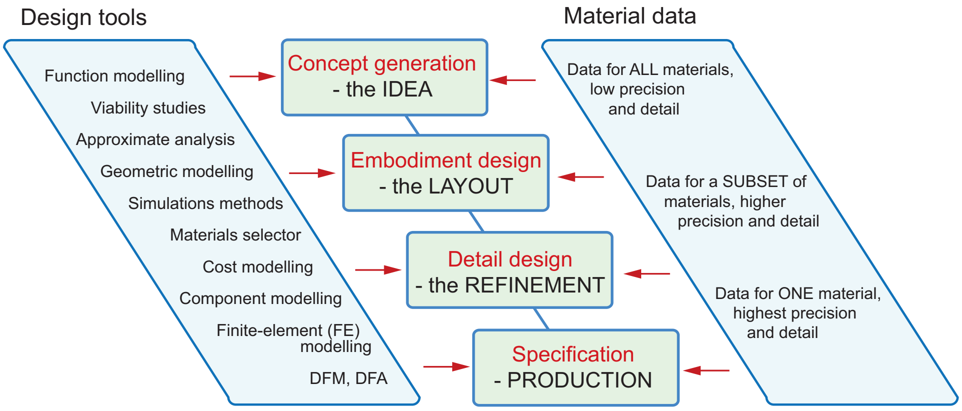

Figure 6. The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage,

but at very different levels of breadth and precision.

Figure 7 also shows different regions for both materials and processes. This comes from the database structure of CES Edupack. It divides the material universe – the wealth of all materials available in it – into families (metals, polymers, elastomers, ceramics, glasses and hybrids) and then subdivides each of these into class, subclass and member with increasing accuracy of data provided.

The same happens with the process universe: it is firstly divided into processes for shaping, joining and finishing, and these are further subdivided into class, subclass and member, the member being each of the individual manufacturing processes. With this structure, the designer is able to evolve both the selection of materials and manufacturing processes in parallel with the progress of the design itself, with the degree of accuracy needed at each stage (6).

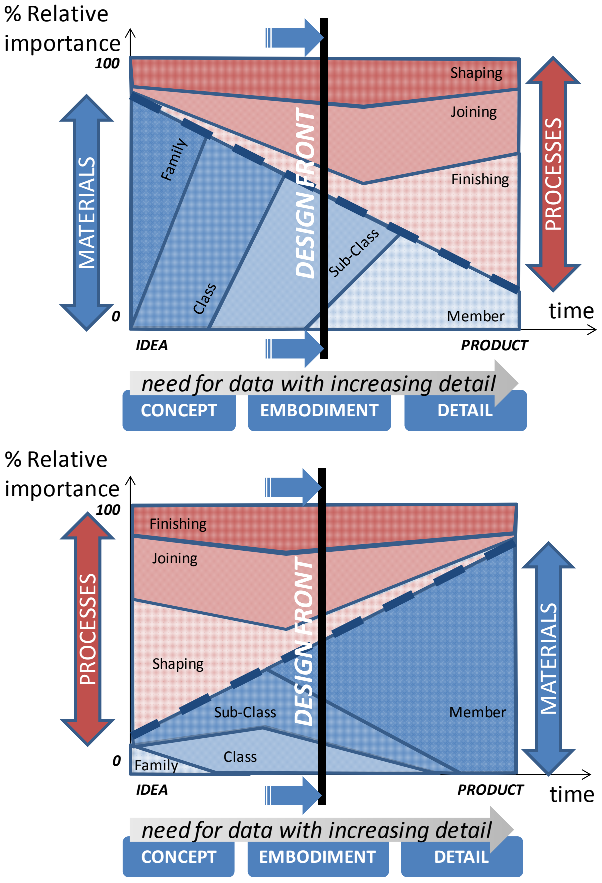

Figure 7. Relative importance of materials and processes across design of performance-driven (left) and cost-driven artefacts (right).

Here is an example of a design-led project assignment. The requirement is for a sustainable means of in-land transportation. A bicycle is a possible solution. The first decision in the design of the bicycle is the configuration. From this follows the loading of the components that make up the configuration – the first constraint is that the choice of section and of material must carry these loads safely. The material choice is further refined by adding constraints of tolerance to atmospheric corrosion, expected life, provision for acceptable end-of-life process, etc. (7). The required material properties can be obtained by a combination of processing and/or alloying; this is made possible by the specific primary elements needed and their bonding and crystal structure or other micro structural arrangements.

Thus the design requirements provide a reason to "drill-down", so to speak, to a discussion of materials properties, processing and microstructure. Now looking at the environmental impact of the bicycle (remember that it should be sustainable) you than need to reason in a different context: what materials impact the most on the environment? Would the bicycle require maintenance? How will it be disposed of at the end of its life? What is the cost of ownership? Should the person own the bicycle, or should it be rented? There is the question of ethical sourcing of materials: are they produced locally? If not, are they sourced from a country with an acceptable record of treatment of its work force? Is a bicycle a respected means of transportation culturally? Would it encourage other people to have bicycles too? Would it have a social impact in your local community? Would a "green" bicycle impact well on the public perception of the company for whom this design exercise is carried out?

This is just a very brief example of the breadth of concepts that a design led approach enables. This breadth naturally requires an adequate support. The CES Edupack is a teaching tool that helps in answering some of these questions in an exploratory virtual environment but using real life data about materials properties, behaviour and environmental impacts. It was designed to support teaching in ways that augments both the students' experience and knowledge about materials.

The visual nature of this tool helps the student capture at a glance where materials stand in relation to each other along one or several dimensions. Easy to construct plots, like the one in Figure 8 help students grasp both the range of properties in each material family, and enquire why the differences among different materials arise. This enables a discussion on the reasons for this behaviour, exploring materials architectures, bonding, microstructure and chemistry. It sets the stage to understand how thermal and mechanical treatments affect some properties but not others and it ultimately facilitates a way into materials processing and manufacturing costs, also supported by CES Edupack.

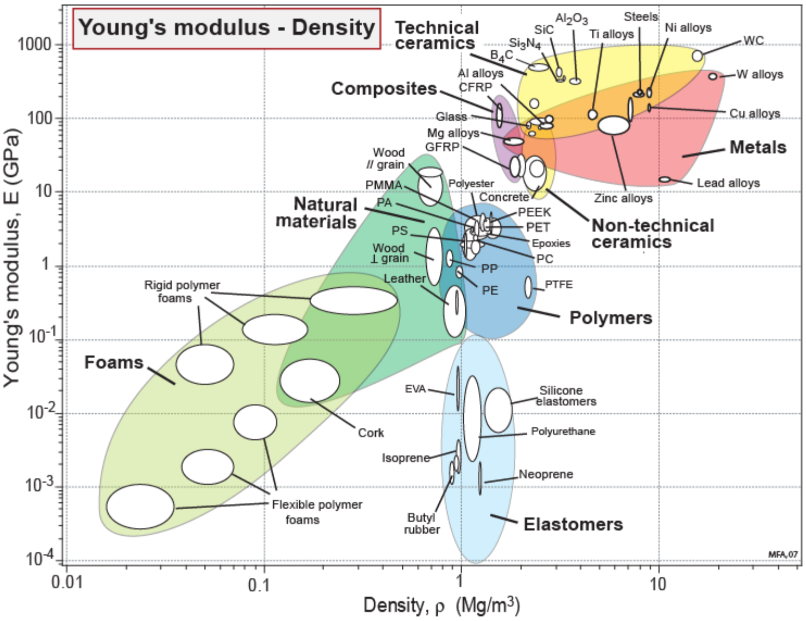

Figure 8. Past, present and possible future of materials.

The student can also think more broadly with CES Edupack. Using the Eco-Audit tool, what-if scenarios of different materials, manufacturing processes and end of life potentials can be compared in terms of energy and CO2 emissions. A separation of both energy and CO2 emissions in the various phases of life of the bicycle (raw materials production, manufacturing processes, transportation of raw materials during manufacturing, use, disposal and end of life decision) help the student figure out where he/she should focus his/her attention to minimize the environmental impact of the bicycle, as Figure 9 shows. If the production of the raw materials is the most energy consuming phase of life, than the student should look for a material with a lower embodied energy, or use less material. If the use phase has the most impact, the weight of the product (in this case, the bicycle) should be minimized. CES Edupack suggests strategies to minimize environmental impact, but care must be taken with other factors, as often a change in design may affect other aspects that were not foreseen. This again enables a way into a fruitful discussion of the implications of design changes.

The amount of data available in CES Edupack can be presented in a way that is suited to either first year undergraduate students or more advanced students. Specialized editions can be used for research in specific areas like aerospace, bio-engineering or architecture, with further information on materials specifically used in each field.

4. AN IMPLEMENTATION

As mentioned before, introducing all of this in a degree is not simple, and introducing it in a single course is even harder. One of the authors of the present paper made an attempt at introducing the Grand Challenges in an Engineering Materials course from the second year of a five years integrated MSc degree in Mechanical Engineering at the Technical University of Lisbon, Portugal, from 2009 onwards. The course follows another on Materials Science, where the basics are laid out. The Engineering Materials course was previously set around mechanical testing, thermal and mechanical treatments of metals and a long and exhaustive description of each material family: polymers, elastomers, ceramics, glasses, metals and hybrids. During the 14 week semester, students would gradually stop coming to class (except for the lab classes, which were compulsory) and from a pool of around 250, only 50 odd students would turn up by the end of the semester.

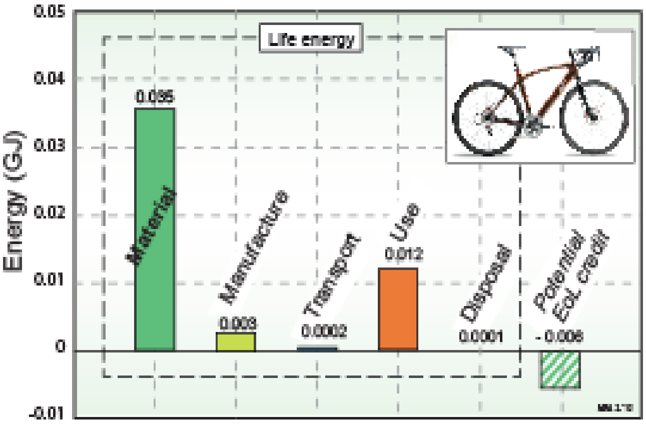

Figure 9. The impact of each of the phases of life of a typical bicycle (values for 1000 passenger.km).

From 2009 onwards a new approach was tried. Instead of describing phenomena, the course was set on a design-led approach, where the basics are dug out when needed, starting from products and ending up in the atoms, when appropriate. If one needs to design a new bicycle frame, what materials could be used? Starting from design requirements – function, objective and constraints – the class would then find the appropriate material families to do the job, taking into account all the technical aspects like shaping, joining and surface treatment and their influence in the mechanical behaviour of the bicycle frame. This lets the instructor mention thermal treatments for the metal frames, as an example, and explain their influence in the mechanical properties, or talk about fiber orientation in composites to maximize stiffness and strength and look deeper into the bonding between fibers and matrix as a decisive parameter in obtaining the desired mechanical response. This approach is much more engaging for the students and provides constant contact with real life and artefacts that students know (or think they know).

Going one step further, an introduction to sustainability was introduced from 2010 onwards, on the last two weeks of the 14 week semester. These two weeks – 6 hours of lectures – start with a historic perspective, with the evolution of the use of materials over the ages and an outlook into the future. The world population growth rate and its implications on materials scarcity and energy production are then pointed out and discussed. This offers in turn a very obvious stepping stone into sustainability issues, life cycle assessment and design for the environment. A partitioning of energy consumption of products during several phases of their entire life cycle is then introduced. The phases were described earlier in Figure 9. Depending on which phase is dominant, one can then discuss what actions can be taken to lower the products environmental impact, and what are the repercussions of these actions on the other phases of life.

The results from this new approach have been very encouraging so far. The number of students failing the course decrease from 28% to 12%, the number of students in class in the final weeks of the semester has drastically increased from around 50 to over 100. The faculty team is highly motivated and willing to explore new developments to this design led approach. The team is now getting feedback (some of it negative) from colleagues teaching other courses further downstream about the students wanting to get more broad perspectives on their course’s topics.

The next step would be to get this vision across the entire curriculum. The Grand Challenges can only be tackled in a meaningful and lasting way if a number of courses stress their importance and devote some time to them. It will require some accommodation on existing curricula, but the example given in here shows that it can be done in 2 of the 14 weeks of a typical European Bologna-compliant semester. A first step can be to provide space for a design led approach across the entire curriculum, within the courses that already exist (8). This will then allow the Grand Challenges to be tackled in a second step.

CES Edupack is currently used in more than 850 Universities worldwide, from introductory courses to advanced research modules. The built in levels of data allow its use with varying degrees of detail on the data provided. Fully integrated materials and manufacturing processes data tables allow navigating back and forth. Tools like the Eco-audit and the hybrid synthesizer make rough but meaningful environmental assessment and the study of virtual sandwiches and composites possible. The highly visual appearance of this support tool makes it especially suitable for a growing population of students that are geared towards visual stimuli.CES Edupack is itself further supported by a wealth of other resources available from Granta’s teaching resource website (9), from where a number of powerpoint lectures, exercises, projects and white papers can be downloaded. Contributed resources from Granta’s growing community of academics are also available.

5. CONCLUDING REMARKS

The first half of the 20th century saw metallurgy, ceramics and polymers engineering evolve from arts to sciences. The second half saw the integration of these three disciplines into single programs of Materials Science and Engineering which sit at the hub of engineering, science and design. This means that Materials is well positioned to promote interdisciplinary learning. Materials Systems and Design is a framework providing a foundation of skills needed to be an effective engineer over a long career. This framework will encompass all the implications of and trade-offs in the adoption of materials in innovative design: not just the technical implications like cost, strength or manufacturability, but also issues of environmental impact, social awareness or material scarcity.

To produce effective engineers capable of realising their ideas and adapting to new technologies and future challenges, courses need to help students develop skills as well as knowledge. The Grand Challenges are a nice way of motivating group work and projects that help in this area.

Summarising, to adapt their learning to the needs of the 21st century, students need:

- Expertise in materials science
- To understand the design process
- Life-long learning skills.
- To learn leadership skills in order to make things happen.
- The ability to work across disciplines.
- Broad perspectives that integrate TEES issues in their designs.
- The ability to take advantage of information technology.

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