Teaching Methods for Concept Design and Prototyping

F. De Crescenzio (a), M. Fantini (a), F. Lucchi (a)

(a) Second Faculty of Engineering, University of Bologna

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Corresponding author:
Francesca De Crescenzio
Tel.: +39 0543 374447
Fax.: +39 0543 374444
e-mail: francesca.decrescenzo@unibo.it
Address: Università di Bologna,
Seconda Facoltà di Ingegneria,
via Fontanelle 40, 47121 Forlì (FC)

Abstract

In a product development process, the definition of an adequate design methodology allows to reduce the Time to Market (TTM) and to create new products meeting user's requirements. The design of industrial products starts from the Mission Statement, which gives a brief description of the product and its goals, underling target market and stakeholders, assumptions and constrains that guide product development. Hence, in the early steps of the development process, alternative concepts of new products are generated, evaluated and then selected for further development and testing. In this phase, the first activities consist in identifying customer needs and establishing target specifications. Following actions regard concepts generation and selection. In this context, new technologies, such as knowledge based engineering and rapid prototyping have a significant impact on the reduction of the time and costs needed to verify the technical and functional aspects of the project. This paper reports the teaching experience carried out in the course of “Project Methodologies for Industrial Engineering” of the MSc in Mechanical Engineering at the Second Faculty of Engineering at the University of Bologna. The aim of this course is to supply students with design methodologies and all the related activities that are at the basis of concept development and prototyping. Therefore, students are directly involved, through a design experience, in the creation of a new product from some defined topics and issues. In addition to the conceptual design methods and the Computer Aided Industrial Design tools, students experience the Rapid Prototyping of the designed shape by means of a FDM (Fused Deposition Modelling) technique. In 2008, students, working in groups up to 4 persons, were requested to design a helmet, with an advanced level of customization. Following the phases of the design process, their ideas evolved into new products, which addressed latent needs defined in accordance with the typology and functions of the helmet chosen by each team and compared to similar existing products. Therefore, each project resulted in significant different products concerning several markets in spite of the few same guiding indications and workflow. By this teaching approach, it is possible to transmit course's contents through students' direct experience and applying product design concepts and innovative technologies on a specific case study. In this way, the final step of the paper is to compare the different projects, and underline in each of them the workflow of each product design and how each team developed the ideas of future engineers.

1 Introduction

The use of project works for graduate classes is successfully implemented in technical universities in order to improve the student’s skills in finding solutions inside the workgroup [1][2]. This helps students to think at a system level and reflects a major requirement for people seeking to work in innovative companies. In this context, techniques and technologies to create aesthetic or functional prototypes play a very important role as means to visibly integrate ideas and solutions to discuss about or to communicate out of the group [3].

Therefore, the course of “Project Methodologies for Industrial Engineering” of the second degree course (MSc) in Mechanical Engineering was established in the Second Faculty of Engineering of Bologna University with the aim to go through early design methods for industrial products, prototyping technologies and participation in design teams [4].

Early design methods here concern the phases from product planning to concept prototyping. Prototyping technologies are 3D virtual modelling and visualization and Rapid Prototyping techniques [5].

From this kind of activities, and in particular from the elaboration of a design project working in groups, students can achieve many abilities, instruments and methodologies useful in design processes and in product development activities. Moreover, this gives them awareness of how different instruments, based on computational graphics, are connected into a design process, which tends to be always more collaborative.

Such teaching activity also intends to highlight the real connections between different technical subjects that students encounter during their courses, and the integration of different acquired knowledge. Though a specific problem and a real case study, students have to test solutions and verify their ideas in accordance with all the different subjects and interdisciplinary practice, trying their abilities working in groups, arranging and planning activities, in order to achieve a common goal.

At the end of the course period, the final evaluation is based on project’s submission at a defined deadline. All groups introduce their work to all members of the examiner committee and to all the other students. The
presentation is followed by a brief discussion in which students have to reply and answer to commission observations, giving reasons for their choices. Students have also to elaborate a short report about their work, describing their project and the design methodology used, and finally to give the 3D model produced, using a 3D surface modeller, and the mesh (file .stl) for the Rapid Prototyping application. The exam finishes with an oral examination about all program’s subjects (also in another exam session).

In this paper are collected and analyzed the different projects presented by the 2008 class.

2 Project guidelines

An initial set of guidelines is provided to students. It aims to make student capable of applying the appropriate tools and methods to the first phase of product development in a realistic context and in a practical case in which they have to create their own project’s prototype. Student’s work starts with an idea, which they have to develop during a conceptual design phase, and to produce an analytical and physical prototype.

Students are also provided by many instruments to use during their activities: particular attention is turned to industrial geometrical modelling, from mathematical representation of free form curves and surfaces, to their usability in surface modeller. Moreover, Reverse Engineering and Rapid Prototyping techniques are shown and used during the prototypes generation.

All groups have to focus on a particular product typology, exposing it clearly on a mission statement. The general product definition in which they have to focus their new concept is fixed by examiner committee, which proposed the “helmet” as common theme. The presence of a common product typology helps to evaluate projects, giving the possibility to compare achieved results, and to better verify student’s ideas and issues. Even if the object’s typology that all groups have to design is the same, a good project planning can make all projects completely different to each other.

Helmets are a good product example to implement tools and methods presented in lectures. Moreover, this product is appropriate for a 3 or 4 persons group to produce a project with a good precision at a system level. More elaborate systems would require more students in each group, and this could give groups less homogeneity, causing an imbalance of working load between group’s components. The time required to complete the project work is 9 weeks.

3 Mission Statement

In the mission statement, students from each group must declare their ideas and what they intend to design, specifying a brief description of main object’s features, constrains and purposes, identifying also the primary market and stakeholders.

Even if one could expect that the choice of the “helmet”, as design object, would lead to similar projects, all groups diversify them, taking in exam a lot of helmet’s typologies and different application fields in which it is used. In the totally of 16 projects, students take in exam 6 different helmets’ types: for cycling, for car racing, for snowboard, for motor racing, for American football and the work safety helmet. In particular, in fig. 1 depicts the percentage of the markets that students decided to focus on.

<table>
<thead>
<tr>
<th>Project</th>
<th>Project’s name</th>
<th>Main design objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project A</td>
<td>Air plus</td>
<td>Improve ventilation system, in order to improve comfort conditions.</td>
</tr>
<tr>
<td>Project B</td>
<td>Full-face sportive helmet</td>
<td>Racing helmet with internal parts in shape memory polymer materials, in order to maximize wearing comfort and absorption crashes.</td>
</tr>
<tr>
<td>Project C</td>
<td>Interchangeable chin rest helmet</td>
<td>Motor helmet with an interchangeable chin rest, in order to be adaptable to all climatic conditions, combining comfort to safety.</td>
</tr>
<tr>
<td>Project D</td>
<td>Ergonomically adaptable helmet</td>
<td>Guarantee a maximum cohesion helmet-face, conformably to European rules, improving lightness and aerodynamics properties.</td>
</tr>
<tr>
<td>Project E</td>
<td>Entry-level full-face helmet</td>
<td>Economic helmet, for mass-production.</td>
</tr>
<tr>
<td>Project F</td>
<td>Motocross helmet</td>
<td>High protection level, in order to reduce the presence of hitting objects (such as mud or powders), which reduce visibility.</td>
</tr>
<tr>
<td>Project G</td>
<td>Racing helmet</td>
<td>With high protection performances, this helmet has a safety air bag, maintaining weights contained.</td>
</tr>
<tr>
<td>Project H</td>
<td>ICE helmet</td>
<td>Increase visibility, improving aerodynamics and with customized interior.</td>
</tr>
<tr>
<td>Project I</td>
<td>City and tourist routes</td>
<td>With an anti-rainy integrated system.</td>
</tr>
</tbody>
</table>

Fig. 1 Percentage distribution of chosen markets

Looking at the 16 mission statements, purposes and ideas that come out are very different in accordance with helmet’s functions, and students try to find innovations and issues in existing products, paying attention to market competitiveness, throw a clear competitors’ analysis and constrains from standard regulations. For example, principal features in snowboard helmet consist in improving technology and materials in order to make the helmet nicer, more customized and with a high protection level. Regarding car racing helmet, idea concern product architecture and usability, in particular there are analyses on internal settings (such as removable insides), electronics components and their usability, or aerodynamics features.

Regarding the most frequent helmet type, which is the motorcycle helmet, several innovations and design objectives are reported in tab. 1.
4 Conceptual Design

Usually, the conceptual design phase starts with an analysis of customer needs, which determine products aesthetic and technical features. From each collected requirement, students define a target specification that correctly satisfies it. In this phase students try to define actual needs connected to the type of helmet that they intend to design: some groups suppose what issues are related to the project they are working on, and from this define customer needs. Other groups prepare an evaluation questionnaire to be submitted to frequent users: a nice example is the experience reported by a group that designs a cycling helmet for bicycle-track racings. In order to identify latent needs in specific markets, they contact a cycling team, proposing them some questions in order to define their needs and then concentrate their design or key elements that improve their product.

From this customer needs’ analysis, groups can establish their project’s target and how to achieve them, giving priorities and identifying equivalent measuring values.

During this phase, students should try to deploy needs and problems into many components, in order to study all possible solutions, combinations and trade-offs to each sub-problem, and then combine them in the final project, being sure to find the best solution to fit all initial requirements. Useful instruments, provided to groups during theoretical lessons, consist in the Quality Function Deployment (QFD) and the concept screening and scoring arrays. QFD represents the connection between needs and the corresponding measuring value, and all the possible associations and influences between them, giving the possibility to detect which changes will cause variations in other aspects too, and symbols or symbolic values identify the connection level. In the final part of this table there are target values corresponding to all sizes.

Concept generation and the final choice phases are supported by concept screening and concept scoring arrays. The first one is used for a qualitative comparison between different alternatives: a concept is chosen as reference and the others are evaluated comparing if some features improve or not the concept in exam in respect to the reference one. This technique is particularly useful for a first concept’s selection, identifying what projects are interesting to develop in the concept-scoring array. In this second array, the previous features are quantitatively evaluated in the chosen concepts, using scores and weights for each feature. The concept with the higher score will be developed in the design phase.

Concepts selection is based on selection criteria that the students identified for their projects and that derive from customer requirements and selected project goals: students use such selection criteria as key performance indicators in concept screening and scoring arrays. In the following fig. 2, all indicators are presented in a graph that indicates the percentages of projects based on that criteria; instead, in fig. 3, the same project’s characteristics are presented in function of the importance rate that groups give to them.

Some groups verify the choice of the final concept to realize also at the basis of aerodynamics analysis: from CFD simulation a concept is verified from its external shell shape and if the integration of spoiler has or not positive effects, an example is proposed in fig. 4.

The described selection work flow, that almost all groups conducted in concept design phase, is performed analyzing object functionality, usability and product architecture. Many groups approach to concept generation analyzing all components and parts that compose the helmet, and how this different parts are connected together and the interfaces between each other. Another approach consists in a study of the possible using sequence that a common customer would follow in product employ (tab. 2).
Once groups have defined their project’s features and morphological attributes through conceptual design, they can start the design phase, where they create a helmet 3D model. To perform this complex phase, groups are addressed to the use of superficial modelling software. In particular, Rhinoceros 4.0 is the tool that examining commission indicates as adequate for this project and that students are urged to learn. This choice is in function of the opportunity to use a particularly indicated tool for freeform modelling. A surface modeller allows creating NURBS curves and surfaces, with no limits on complexity or surface degree. Many tutorials and laboratory lectures are conducted, in order to give students all necessary notions and practices about how modelling with a superficial CAD, and about Rhino commands and its use. Parallel to Rhino, students can also use parametrical modelling software, based on geometrical primitives, such as SolidWorks: in this case the second tool is used for those components not freeform, but with a regular and geometrically defined form (such as screws or the lacing system). Groups verify then a compatible file format for the placement of models in the same virtual environment.

Since helmets are products with a high possibility of customization, not only aesthetic objectives, but also through ergonomic considerations are declared in the mission statements. For this reason, the model of the head of a hypothetic user is provided to students in order to realize a product conformal to a hypothesis of customer. Groups elaborate their projects, generating all necessary surfaces to describe it and to realize all chosen details. Finally, they provide the model with textures, in order to give it an appropriate appearance. Selected final results are depicted in fig. 6.

This phase of project’s elaboration and modelling lasts about 7 weeks, during them many classes and laboratory lessons are conducted, also verifying project’s processing and student’s work, helping groups to solve their doubts, giving them some input and verifying their models.

The elaboration phase ends with the deliver to assessment committee of the final file, which will be used in the final examination. The principal evaluation criteria consists in the check of the model’s correction: in B-Rep modeller, final surfaces have to be closed, connected, limited, not self-intersecting and with the same surface’s orientation: by these considerations, models have to be closed and connected surfaces, without open edges and all different components, parts and details that composed the final project have to be separate and without crossing faces.

5 Virtual Prototyping

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6 Rapid Prototyping

Finally, to enhance the work of the students giving them back a physical object of their projects, it was
planned to build a scaled prototype of each designed
helmet by means of the Rapid Prototyping machine of the
Lab. The use of this technology in educational programs
is reported to be very useful to enhance the comprehension of features in technical design projects
[6][7].

Therefore, each group was requested to provide a
specific model suitable for Rapid Prototyping, since it is
difficult to expect that a model generated for
representation purpose would properly work as input for
RP machines.

Actually, to obtain a physical object by means of RP
machines, it is important to prepare the digital model
correctly since a fully closed, water-tight model is required
for this kind of additive manufacturing process. The digital
model is first virtually sliced into very thin layers and then
the physical object is built layer by layer. Usually, CAD
solid modellers are preferred for providing model data for
RP processes since are capable of automatically
producing water-tight models. On the other hand, CAD
surface modellers (such as Rhinoceros) usually require
diagnosing and repairing operations to produce model
data meeting RP requirements.

The link between CAD modellers and RP machines is
the STL format. This file format consists in a list of x, y
and z coordinate triplets describing a connected set of
triangular facets with the direction of the normal vector
for each triangle, which should point outward the model. CAD
modellers with an STL translator are able to perform an
automatic surface tessellation obtaining a triangular mesh
and then save the data to either a binary or ASCII STL
file. Binary STL format is much smaller in size and usually
preferred for working with huge data, but ASCII STL
format permits to view and edit the content of the file so
that can be chosen for an educational approach.

Rhinoceros 4.0, in addition to the possibility of
importing and exporting the STL file format, comprises a
new suite of tools which allows to manage mesh data,
repair holes, identify and remove non-legal geometry
(such as overlapping surfaces, intersecting triangles,
dangling edges or isolated vertices). When generating an
STL file for rapid prototyping, the CheckMesh command
provides detailed information to be used as a checklist for
repairing the mesh and obtaining the final "closed
manifold" model suitable for RP machines.

For each group, the quality of the generated mesh was
one of the criteria for the evaluation of the whole project.

The physical models (scale 1:2) of each designed
helmet were built by means of Stratasys Dimension SST
(Soluble Support Technology) that is a Rapid Prototyping
machine based on FDM (Fused Deposition Modelling)
with layer thickness of 0.254 mm and maximum build size
of 203 x 203 x 305 mm (height). It deposits ABS plastic
material (Acrylonitrile Butadiene Styrene) and soluble
support material to sustain the prototype under
construction.

Both filaments (ABS and support) are fed through a
heating head in a semi-molten state and then extruded
through a nozzle to be deposited onto the partially
constructed model. During the cooling process in the
working room, the semi-molten filaments sticks to the
preceding layer already deposited. The extrusion
temperature of ABS is usually 270°C while the envelope
temperature (the temperature of the air in the working
room around the model) is 70°C. Finally, an automated
support removal process for hands-free model completion
is also provided by an agitation system of hot water and
soap bath (at 70°C) that automatically wash away the
support structures.

The Dimension SST is also provided with pre-
processing software (Catalyst) that makes it possible to
import the STL file, orient and slice the model, generate
any needed support structures and calculate the head’s
path to build up the part.

This RP machine allows two different fill options: solid
and sparse. In the first case, each cross-section through
the model is filled with ABS material. In the second one,
the interior part of the model is not filled solid. The model
is built up with thin inner and outer walls while the interior
part is replaced with a kind of honeycomb structure. Since
the sparse interior structure results entirely enclosed
when the model is completed, there is no visible
difference in a prototype built with these two different options. As a result of these two different approaches, solid fills are stronger and heavier while sparse fills are weaker and lighter. Moreover, the sparse fill option saves on material and therefore speeds up the construction process. All the STL models of the helmets were processed by Catalyst choosing sparse fill option.

In fig. 9 and fig. 10 are presented some of the final helmet physical models, opportune scaled, as ending output student's projects.

Finally, group's approach to project's design show an appropriate process to solution and arrangement of ideas to solve the case study in exam and to find technical solutions to defined functional problems.

### References


### 7 Conclusion

The teaching method described in this paper places students in a real case study. Such and educational approach provides students with the ability of analyzing the system problem. Very much importance it is also given to the ability that students proof working in groups and their attitudes in a collaborative approach to the other members.

One of the first notions acquired during this course consists in the design project's methodology and the process of develop of the new product. Moreover students can test technologies, like Rapid Prototyping, that are in support to a common design process. For engineering students, the use of different modeling software, like surface modellers and solid modellers, the choice of which one to use and its integration is an important step for their studies.