A THEORITICAL FRAMEWORK FOR TEACHING AND LEARNING OF ENGINEERING DESIGN METHODS AND TOOLS

Guy Prudhomme, Daniel Brissaud, Frédéric Vignat

ABSTRACT
This paper aims to define a framework for the teaching and learning of undergraduate students in mechanical design. Training students in mechanical engineering design involves teaching both design methods and tools, and their usage in projects. Students should then consider and apply these methods and tools in product design projects. The paper is developed as follow. The relevant part of the curriculum of the mechanical engineering and design department of the Technological University of Grenoble (INPG) is first described and particularly the key element, the engineering project, is presented. A theoretical framework based on the instrument concept is then described. This framework is applied to observed design project situations to analyse practices and finally to propose new training situations enabling students to better use taught methods and tools to design efficiently.

Keywords: Engineering design project, Methodological project tools, Training situations

1 THE ENGINEERING DESIGN PROJECT ACTIVITY

The Mechanical Engineering Department of the Technological University of Grenoble (INPG) was created 15 years ago with an ambition of developing product design projects as key elements of engineering students' training. This activity has evolved several times to take place now throughout the 3 years of French engineering training (which follow two years of preparatory classes). Today are undertaken :

- In year 3, a project named the Product Design Project (48 hours). The objective is the expression of a design problem, the discovery and comparison of technical solutions to the problem and finally the development of a solution based on CAD modeling.
- In year 4, the Engineering Project which study is the subject of the paper.
- In year 5, two short projects (24h) allowing focus on two significant topics of new design activities: innovative and global design.

The Engineering Project of year 4 represents an hourly volume of 148 hours, 10 ECTS credits, registered in the timetable of the students, and concerns the whole Mechanical Engineering Department (100 students). Its objectives are two-fold; applying scientific and technological tools taught in other courses on one hand and applying methodological project tools (Functional Analysis and provisional plan) on the other hand. The students are expected to develop and realize a product to meet a customer's demand. The projects are carried out by groups of 5 students and the activity is supervised by 4 teachers and a technician. The teachers simultaneously play two roles:

the customer's initial demand and decision making on one hand, the scientific resource staff and the methodological advisers on the other. The technician advises and supports manufacturing technologies. The main stages of the project are marked out in the following way:

- Short presentation of all the project subjects to all the students,
- Subject allocation to groups of students based on their choices,
- Elaboration of the initial functional requirements and the initial planning of tasks. These two documents are stored in a shared database available for the whole student and teaching team. Throughout the project, these documents are updated according to the progress of the project
- Progress meetings. There are 4 meetings a year per group. Their role is to assess and validate the work already done, to present and discuss the possible alternatives and to plan the future tasks.
- Intermediate audit meeting. The intermediate audit meeting should allow the group to assess the progress of its activity at mid-course. This audit includes a viva and a report that contains:
  - the presentation of the technical and scientific work done,
  - the bibliography, the references to the documentary resources used within the project,
  - the yearly schedule and the forecast task organization,
  - A forward-looking balance assessment for the continuation of the project.
- Final audit meeting. This stage allows assessment of the activity of the group in technical and organizational terms, and storage of the project information collected and generated for possible use in a future project. This audit also includes a viva and a report. All the data (report, CAD files, etc) is then stored on a server for capitalization and use by the following groups.

For the realization of this project, the students have material resources in the form of 800 square meters including:

- a design studio equipped with computers supporting CAD, CAM and simulation software, Internet access, and a room of technical documentation,
- a prototyping room equipped with machines tools, hand equipment, and molding facilities,
- an instrumentation room for experiments and data acquisitions,
- a room for the realization of prototypes in composite materials,
- a professional workshop with numerically controlled machine tools.

The paper addresses a specific project whose objective was the improvement of the Department's casting center. It followed a previous project which started the casting activity within the department.

2 THE THEORETICAL FRAMEWORK

The first assumption is that everybody knows how to design. Due to their everyday experiences, human beings can empirically create stuff to adapt their environment to their tasks. These creations deal with physical or intellectual things. To carry out a design task, either individually or collectively, people perform a technique. In this sense, a technique is seen as a way to apply a set of personal procedures to obtain a determined result. A technique can thus be empirical, built from experience. Reflection on its effects [1], in the course of or after the action, and on the domain of validity and limits, makes people improve the technique and adapt it to their working conditions and the targeted results. If technology is a rational discussion on the technique brought after this reflection, it can be said that the experts build themselves an empirical technology to gain in effectiveness when applying it.

Task Technique Technology

Figure 1 : An empirical approach : from task to technology

Design tools and methods taught in universities and engineering schools are at a scientific technology level. They arise from thought and scientific discourse about how to improve techniques and make them more effective. They are the products of institutions connected to research or development services. The implicit objective of teaching design methods and tools is that students will apply them to perform design tasks. Indeed the technique of task solving should be supported by the knowledge taught.

Task Technique Technology

Figure 2 : A scientific approach : from technology to task

But even when students apply them, this does not mean that they have considered the taught knowledge as an effective means to perform the task. Rabardel [2] and Vérillon [3] spoke about instruments and instrumented activity. An instrument is any object that a person associates with his action in order to carry out a task. Indeed an instrument is composed of an artefact and schemes. The artefact is a physical object (or a natural object) if the instrumented action aims at pragmatic transformations as for example a hammer to drive in a nail. It may be a semiotic one if the instrumented action aims at altering another subject's state of information as for example a mechanical drawing to inform another person about how it has been done. Schemes are the complex set of representations, mental operations and motor skills that are brought into play by the user of the artefact during action. So : Instrument = Artefact + Schemes

In this study, the design methods and tools taught are the artefacts. How does each student integrate them within his cognitive reasoning? Have they been instrumented for a specific design task?

It can be thought that simple teaching of the design methods and tools, and their in-use rules is not sufficient to lead students to their own construction of schemes. A scheme is a psychological entity built by a person when acting. The question is then that of the education situation choice to allow this instrumentation. The implemented traditional situation is a design project activity. A project activity seems to give a pedagogic situation in which students should implement their initial techniques of problem solving. It is assumed that the techniques have been empirically reconstructed from preliminary trainings before the project starts, and that it would not be sufficient and economic to solve the problem under study. The students should then associate a personal sense to tools and methods taught to perform and improve their own technique.

But applying generic methods and tools to perform a singular task in specific conditions, leads to the adaptation of methods and tools to the task conditions, and to get use from the recommended usage. Verillon said that the artefact has to be appropriated to the outside context. Specific ends and functional properties, which are not necessarily intended by the designers of the artefact, are attributed by the user.

Adjustments to the artefact itself or its rules of usage are made to account for goals and operating conditions. Rabardel and Verillon call this step instrumentalization.

3 TOOLS AND METHODS TO BE INSTRUMENTED IN A DESIGN PROJECT ACTIVITY

Basically the instruction at the start of the project is to implement two types of tools or methods:

- Functional analysis tools, which have to support the expression of the functional specification,
- A provisional plan, which has to lead designers to the anticipation, the organization and the realization of the various tasks for the project to be achieved.

3.1 Functional specification list

The functional specification list is a document [4] whose main function is to formalize:

- The statement of needs expressed by the customer and the description of the industrial and economic environment, and the market in which needs must be satisfied. In our case after having been clarified by the students, this expression was to optimise the casting process device to obtain a safe, fast, efficient realization of the cast parts. The parts must be metallurgically and dimensionally correct.
- The problem the designers have to answer. This problem must be expressed by functions to be realized and by constraints to be respected by the product [5]. The characterization of the functions leads to the definition of assessment criteria with associated levels describing the performances to be achieved. A flexibility index points out the potential for negotiation about these levels.

Designers are responsible for the expression of the functional specification. The customer's expectations are appropriated by the designers through a collective formulation process. This stage is generally computer-aided.

3.2 Provisional plan

Along with the definition of the functional specification list, the teachers recommend that students plan a provisional plan. This aims at planning for:

- Defining the various tasks to achieve the objective of the project,
- Anticipating the duration and deadline for each task in respect to the time allocated to the project,
- Distributing tasks and responsibilities among the group of students.

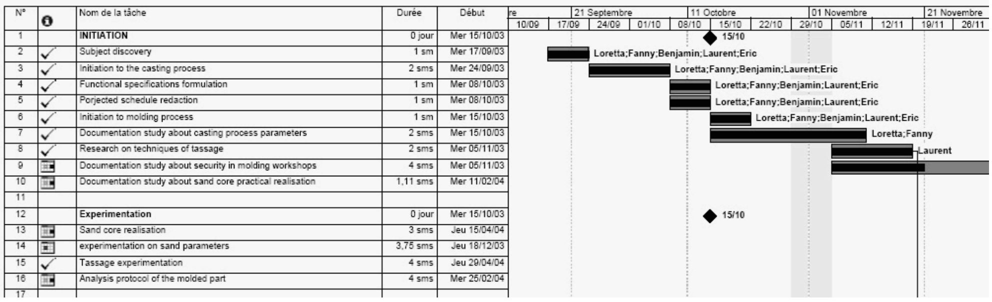

Figure 3 : a part of the projected schedule on this project

The construction and monitoring of the plan is computer-aided. It is supposed to be evolutionary. It must enable students to have a global and shared view on all the tasks to be realized within the allotted time, but its quality of provisional leaves it open to evolutions throughout the project.

4 OBSERVATION AND ANALYSIS

Students projects were observed once a month during progress meetings or intermediate audits, but not continuously. These meetings gave an opportunity to question students on the instrumentation for design of both the functional specification list and the provisional plan.

4.1 Concerning the provisional plan

From the first meeting in November, the provisional plan is the key for the project progress presentation by students. For students, the root notion of the plan construction is the task. The notion of task supports the definition of the action as led, leading or "will be led". Example of an argumentation :

The work which we led was at first to understand the objective to reach, which is to improve the moulding. Then, from there, we tried to define the various tasks to reach this objective.

Here is a short abstract of the observation which explains well why it is profitable to study the instrumentation of the provisional plan.

Students: We have already made a project in year one ... It is a bad memory ... We did not reach our objective of designing the product. We divided the work. We worked separately, and when we collected together our various results nothing worked ...

Observer: What are your conclusions?

Students: That it is necessary to plan more finely, and that systematically we have to work together from the beginning of a session on what we have to make, and at the end of a session on what we have made.

It is thus from the reflexive analysis initiated by students themselves and relative to their previous personal practices in the year 1 project that the relevance of the provisional plan and the rules of its use were built. These schemes in use, collectively accepted by the current group, made the conditions good for the provisional plan to be really instrumented for actual design activities.

The first tasks of the provisional plan were easily defined, notably because they were well directed by the teachers (subject discovery, introduction to casting practices, drafting of the provisional plan, joint discussion of the functional specification list, and visit to the company). It was more difficult to develop the following ones. Two main reasons for this: their objectives are initially vague and their duration associated difficult to determine. However, after their first school practice on casting activity and a visit to a professional foundry, the tasks are more easily built from the parameters of the process that the students considered needed to be improved. The initial labels of the tasks were parameter-name-oriented. It is considered that these parameters (shape of the casting holes, temperature of casting, pressure and mode of sand compression, mode of assistance) appeared from their own practice and from their discussions with the experts of the visited foundry. It is confirmed by their discussion:

The schedule is for us an organizing element of our work. From our foundry experience, we know what it is necessary to improve. Thus we can define the tasks to be realized. On the other hand the duration is not easy to define. For example, today we foresaw four hours to do research about information on the casting parameters, we haven't had enough time. What are we going to do now?

What is shown in this transcript is that the definition of the tasks includes, and relies on, the parameters that should be varied to optimise the casting processes. The intermediate audit showed that the different parameters associated with the experimentation and optimisation tasks were really coherent and relevant. But the existence of the parameters (and consequently of the tasks) was legitimised by both the professionals when visited and the teachers who accepted the proposed tasks, and not by an analysis and a deployment of the problem. So the students used the provisional plan for the definition of the relevant tasks to be realized according to the problem and the parameters associated with, which was not in the initial and pre-defined usability of the provisional plan. It can be said that the provisional plan was instrumentalised for the definition of tasks and parameters.

Actors (Loretta, Fanny, Benjamin, Laurent, Eric) were associated with each task. A task was given to the one who knew best how to do it.

> *You give the task to the one who knows best how to make it. It is as in companies … Anyway, as we have constraints of duration, we have no choice! … And then we meet in the beginning of session and we define together what we have to do. We finish every session by a debriefing to see what has been done, to share the result of our actions.*

The work was divided. This first raises the problem of the school role: learning the knowledge for the one who does not know or using the skills of the one who knows. But the most important is that, on one hand when the tasks are divided the responsibilities are divided (meaning without collective negotiation on dominant parameters) and that on the other hand the argument about available time becomes the only driver.

For example concerning the adequacy of the designed device with regard to the standards:

> *Some tasks were abandoned, notably those concerning the search of the standards, because we did not find information on the subject, and because we have to manage on time.*

This transcript emphasizes the problem of the instrumentation of the provisional plan. Schemes or rules in use, associated with the plan and disconnected to the conditions that saw them being established, were built as global rules based on limited experience. The division of the tasks responsibility split decision-making as well. Time became the first element of negotiation to define parameters to be considered. There was no consideration of the level of parameters as a whole for the best device performances. Time was considered as the key driver of the negotiation for the problem evolution. The students so attributed a new functionality to the provisional plan, being the negotiator of the expected performances of the designed device. The provisional plan was instrumentalised thus in a second way.

4.2 Concerning the tools of the functional analysis

The functional specification list was drafted using the supplied software. But the students saw this as an extra task. The first version was very light, only defining very briefly the overall needs of the customer, and the technical and economic environments. Functions were generally defined but not characterized (just a few criteria, no level nor flexibility were associated with). The following versions did not evolve really and the students did not refer to this document at any time. When we asked them about this, they told that:

> *Functional specification are of use for nothing … It is moreover not our role to express the problem, but that of the customer …*

Then in the intermediate report, it can be read:

The role of the specifications seems to us very vague. Indeed our relation with the teachers is very different from the relation customer / supplier … It is us who fixed tasks and objectives..

The functional specification list was not instrumented for the design activities. It was seen as a training institution exercise, but not as a good support to design activities. But when the students were asked for the reason why they studied the influence of a process parameter (for example the sand compression pressure) and considered it as important with regard to the problem, they were unable to justify explicitly and locally. Their references were the experts or the literature, not the relation to the posed problem.

4.3 Conclusion of this observation

Confronted with a casting process optimisation problem in a singular environment, students approached difficulties from personal practical experience. Then they referred to documents and experts to extract influential parameters. Tasks were planned to check the influence of these parameters. From our point of view it was what created favourable conditions to the instrumentation of the provisional plan (the notion of tasks was considered as an adapted support for designing). These tasks were built to test the influence of parameters that had a legitimacy outside the context of the design problem. This left students to instrument the provisional plan to express the tasks to be performed from the parameters to be analysed. Teachers validated the relation of influence between these generic parameters and the design problem by their more or less explicit acceptance of the proposed tasks. But they involved students neither to characterize the specific problem, nor to validate the links between process parameters and problem properties. These links should have appeared when using the functional analysis tools. They should enable students to pass from an argumentation based on expert discussion to an argumentation that is personally and technologically structured. The general performance of the device under design would then be explored, and not the aggregation of local and optimal performances.

Even if generalization should be made with caution, it can be considered that the provisional plan was instrumented and instrumentalised in the same way by all the groups of students and the functional specification list was instrumented by nobody. That is why a new organisation of design projects should be proposed.

5 CONCLUSION AND PERSPECTIVES

The concepts of instrumentation and instrumentalization gave a theoretical framework for the analysis of the way people appropriate design tools and methods and adapt them to the design activity. The analyses of the observations led us to define a new training situation to facilitate the instrumentation of design tools and methods. This new situation is built around the following recommendations:

- First of all, let the students implement their own techniques to design, for example asking them for a provisional plan and a functional specification list. Basically this should lead students to instrument the provisional plan but not the functional specification list.
- Create then a situation to enable the instrumentation of the functional specification list, but not the instrumentalisation of the provisional plan, with a new roles for teachers. These were continuously both knowledge resources and customers in the observed projects. It is suggested to split out these roles between different persons:
    - o Technical resources (teachers, manufacturers, technicians). The teacher having this role must be present at every session,

- Customer representatives are needed only to present and to negotiate the needs. They will be effectively present only at the launch of the project and at the various audits but should be easily available for urgent and key decision making.

And to add a role, That of the companion-guide. He is the specialist on design methods. His role is not to say how to do, but to question the students about why they do or they intend to do the tasks. This guides the students' instrumentation of the provisional plan and the functional specification list by forcing a rational connection of the work carried out during the time (plan) to the defined objectives (functional specification list). This result should be reached if the companion-guide's questions enable students to structure the problem (link between tasks, the parameters characterizing them and the elements of the problem description) and if the negotiation necessary for the consideration of needs and constraints builds itself dynamically (flexibilities associated to the criteria).

Throughout the project, a logbook would formalize the activities and the planned results, those achieved, the progress of the problem and the solutions under study. At the end of the project, a debriefing will be organized for each group through a reflective analysis of the design process [6, 7], to bring to the foreground the effective design process and the roles held by the schedule and the functional specification list in the actual design process.

In future work, this new organization of the design formation will be tested in the next academic year. We intend to observe in particular the relevance of the new organization of the frame team, the skills built to assume these new roles, and the coordination of the teaching staff.

REFERENCES

[1] Schon D.A, *The reflective practitioner : how professionals think in action,* Ashgate Publishing, Aldershot, 1991

[2] Rabardel, *Les hommes et les technologies, Approche cognitive des instruments contemporains*, Armand Colin Editions, Paris, 1995

[3] Verillon P., Instruments and cognition : Piaget and Vigotsky revisited in search of a learning model for technology education*, The Journal of Technologies Studies*, n°26 (1), p 3-10, 2000

[4] Norme Européenne EN 1325-1, Vocabulaire du management de la valeur, de l'analyse de la valeur et de l'analyse fonctionnelle, *AFNOR*, 1996

[5] Prudhomme G., Zwolinski P., Brissaud D., Integrating into the design process the needs of those involved in the product life-cycle, *Journal of Engineering Design*, vol 14, n°3, pp 333-353, 2003

[6] Prudhomme G., Boujut J-F., Brissaud D., Toward reflective practice in engineering design education, *The International Journal of Engineering Education*, n°19 (2), p 328-337, Dublin, 2003

[7] Adams R., Turns J., Atman C., The role of reflective pratice, *Design studies*, vol 24, n°3, pp 275-294, 2003

Contact information:
Guy Prudhomme, Laboratoire 3S, DU,
BP 53, 38041 Grenoble Cedex, France
Phone : +33 04 76 82 70 11,
Email : guy.prudhomme@hmg.inpg.fr

Co-author Information:
Pr Daniel Brissaud, Frédéric Vignat
Laboratoire 3S, Grenoble, France