International Journal of Engineering Education Vol. 27, No. 2, pp. 354–363, 2011
Printed in Great Britain

0949-149X/91 $3.00+0.00

Thermodynamic Approach in Chemical Plant Design: Teaching Chemical Engineering in the First Year*

P. ORTIZ
GDPP. Grupo de Diseño de Productos y Procesos, Department of Chemical Engineering, University of Los Andes, Carrera 1E Nº 19A-40. Of 778. Edifico Mario Laserna. Bogotá, Colombia. E-mail: portiz@uniandes.edu.co

J. MONTOYA, C. HERNÁNDEZ and A. MANRIQUE
CIFE. Center for Research and Teaching on Education, University of Los Andes, Calle 18A Nº0-19 Este, Casita Rosada, 2do Piso, Bogotá, Colombia.

W. NIETO
GDPP. Grupo de Diseño de Procesos y Productos. Department of Chemical Engineering, University of Los Andes, Carrera 1E Nº 19A-40. Of 778. Edifico Mario Laserna. Bogotá, Colombia

This work describes and discusses an educational experience developed in a first year course of a chemical engineering program. Student teams are guided through the ideal design of a chemical plant from basic thermodynamic concepts, so that they can identify the differences between their designs and real processes and to establish relationships between what they have done and specific areas of chemical engineering knowledge. The design project had an integration curriculum approach and involved the assisted use of process simulation software and some specialized bibliographic resources. The learning process was assessed by surveys and interviews, and by a rubric-guided analysis of students' reports. The project and its methodology are intended to be a mechanism to promote a wider vision of the curriculum from the early years and to foster students' motivation.

Keywords: chemical engineering education; curriculum integration; learning cycles

1. Introduction

The Universidad de los Andes (hereinafter Uniandes) is a Colombian private university promoting a learner centered environment guided by the maxim 'learning how to learn.' In recent years, the Engineering Faculty at Uniandes has been implementing a renovation project that includes a process of curricular reform, the renewal of classroom practice, and detailed design of the physical infrastructure and laboratory equipment [1–3].

This process of renovation takes into account international recommendations about the reduction of the number of hours the students spend in classrooms in undergraduate programs and the articulation of these with postgraduate courses. Other recommendations include education for lifelong learning, learning in context, interdisciplinary and simultaneous links between courses, integration between theory and practice, and the development of transversal and integrative projects, to cite only a few examples. The educational project discussed in this article is a way of attempting to materialize these commitments in the area of chemical engineering and is specifically aimed at developing the spirit of the proposal formulated by the US National Academy of Engineering (hereinafter NAE):

> Whatever other creative approaches are taken in the four-year engineering curriculum, the essence of engineering—the iterative process of designing, predicting performance, building, and testing—should be taught from the earliest stages of the curriculum, including the first year. Curricular approaches that engage students in team exercises, in team design courses, and as noted above, in courses that connect engineering design and solutions to real-world problems so that the social relevance of engineering is apparent appear to be successful in retaining students [4].

The chemical engineering curriculum at Uniandes is divided into three cycles of formation that stretch over a period of four years. The first cycle provides the basic tools of general engineering, knowledge of basic sciences, thermodynamics and mass and energy balances. The second cycle establishes the basis with respect to transport phenomena and kinetic theory. The third cycle introduces aspects of design and ends with the course 'Plant Design', as this is a subject that clearly integrates the knowledge acquired in the other courses.

Three mandatory research projects are developed throughout the curriculum, which helps to complement and strengthen the knowledge acquired in the courses. The first two play an important role in that they allow the student to become familiar with spheres of action and applications of chemical engineering, by means of a creative process. In the final

* Accepted 11 December 2010.

year, students have to develop a formal research project on a particular topic or technology. However, these projects need to be complemented with shorter, more academically-focused activities that are curriculum embedded and allow students to establish strong links with the content of the different courses, so that they are able to understand the meaning and the usefulness of the curriculum that they are studying. This is particularly important in the first stage of studies, as the NAE document recognizes.

The study that we present here evaluated the impact on students' learning of a project involving the design of a chemical process in the 'Fundamentals of Industrial Processes' course. In this course the students systematically carry out mass and energy balances as well as calculations and numerical analysis on data associated with processes and units that are considered 'black boxes'. Thermodynamics, kinetics and design analysis are excluded and the student is expected to cope with a large amount of information and use this correctly, even though he or she does not know where this comes from. In this sense the proposed project must provide an important opportunity to develop a global acquaintance with the curriculum and the tools that this offers, in a short space of time.

2. Plant design project

In the last decades, Problem-Based and Project-Based Learning (hereinafter PBL) have been promoted in Higher Education curricula as a way of creating learning-centered environments to support students' contextual learning and they have been proved to be effective for the promotion of curriculum integration [5], knowledge application [6], the development of cognitive, social and practical skills [7], motivation and acquaintance with the profession [8].

With regard to Engineering Education, it has been argued that PBL is more effective than traditional education in producing engineers who are better suited for the task of solving real life engineering problems [9]. Compared with traditional education, the evaluations of Project-Led Education in Engineering have proven to help students achieve stronger articulation between theory and practice, improved learning and motivation, and to develop transversal competencies such as project management, problem solving, communication and team work [10–12].

Projects involving the design of chemical processes have been shown to be an efficient alternative in the teaching of chemical engineering, due to their complexity and their multidisciplinary nature [13]. Bailie and Shaeiwitz [14–16] created long-term projects during the sophomore and junior years by means of which students gradually improve the design of a specific chemical process while they continue to learn. This type of experience brings home to the students the existence of a structured and coherent curriculum. Clark et al. [17] have maintained that traditional teaching contexts make it difficult for students to retain a high level of content knowledge and, consequently, this leads to a loss of motivation. As a way of increasing curriculum integration, these authors propose the concept of a 'spiral curriculum' and the development of projects that involve a permanent process of revision of the basic topics in chemical engineering, at the same time as there is an increase in the degree of detail and sophistication in the design of a specific chemical process. On the other hand, in the advanced (senior) courses the carrying out of design projects involving relatively complex processes is common, as well as the incorporation of technical challenges that allow for the strengthening of the concepts of responsibility and lifelong learning [18].

Our project incorporates some of the elements used in the experiences mentioned above, but establishes a novel approach based on the thermodynamic design of chemical processes. Starting with an ideal analysis, arising from knowledge of the basic cycle, results are obtained, which are later compared with actual processes. This allows students to identify and have a preliminary discussion on the big differences that very often exist between real and ideal processes without having to wait until they receive formal and intense education on advanced topics. The task is proposed as an integration exercise: the required critical analysis of their solution against real world conditions directly establishes bridges between different knowledge areas of the curriculum. In addition, this comparative study is an innovation that allows projects to overcome the limitation posed by the need to balance educational objectives and complex design requirements. That tension is usually resolved solely by a simplification of the design task. The proposed methodology here includes the analysis of actual processes.

The main aim of the project consisted in making the preliminary design of an industrial plant that produces a specific chemical product (Appendix A). The project is structured in three stages and three reports that are carried out by work teams of four students for a period of thirteen weeks (Fig. 1). The project guidelines are as follows.

- In the first stage each work group studied the importance of the product that was assigned and the members had to describe the technical and economic characteristics that are associated with each product. A preliminary economic study of

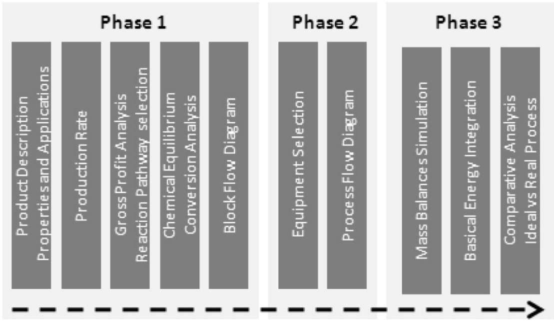

Fig. 1. Design process structure.

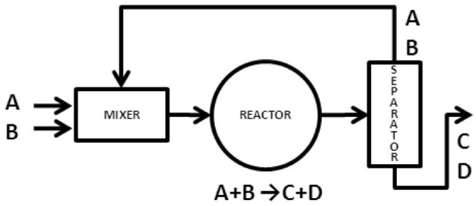

Fig. 2. Generic chemical process.

two or three possible production pathways was also carried out, assuming 100% conversion in the reactor and selecting the pathway to apply in the rest of the project. Then, the group evaluated the equilibrium conversion of the selected pathway through the use of specialized software. In order to do this, a study of the influence of the variables of pressure and temperature in the reactor was carried out and the final conditions of operation were set up. Finally, a generic block diagram process was developed (Fig. 2).

- In the intermediate stage of the project, the group took decisions about the type of separation units that could be used. To do this, they worked from physical properties of reagents and products, or they supported their decisions with reference to bibliographical sources. There was an advance in the representation by means of a PFD (Process Flow Diagram), in which stream energetic variables were obtained through the use of specialized software as a properties 'calculator'.
- The third stage requires the programming of mass balances in the designed process through the use of datasheet software. This phase also requires a preliminary work of heat integration. The final but relevant requirement is the comparative study between the design obtained by the group and the industrial processes described in the bibliography.

Project implementation was articulated from a simple instruction setting out each phase and reporting contents. Assessment rubrics helped students to understand clearly what was expected from them in terms of results and analysis. Each stage of the design had different valid alternatives, therefore, the rubrics emphasized the importance of arguing for the solutions and the decisions set out in each of the three reports. To illustrate this, Appendix B shows assessment criteria for the first report. The rubric evidences the focus on writing/argumentation skills at a simple level: management of data and sources to justify technical decisions. The other reports were graded following similar criteria and, in the last phase, attention was paid to critical thinking and solid explanations about the comparative study.

As regards the pedagogical design, it may be said that classes took place as usual: students were supposed to do the reading and perform application exercises in advance. At the beginning of each session, there was a short presentation of the basics of each topic, based on the material that had previously been prepared. The rest of the class was taken up with discussion of the doubts and difficulties related to the problems that had been assigned. The project was not just a parallel activity to the classes as various strategies were used to integrate it to the course. Every two weeks the professor provided a short general feedback session about the process, using class time to talk about relevant aspects of the projects, trying to identify the main obstacles and helping the groups to formulate their results and their queries. In a similar fashion, in the first stage of the project there was a recitation session focus on the use of specialized software to simulate chemical processes. In addition, each group was able to be in constant contact with the professor in order to solve particular doubts they had about the project.

3. Research

In order to be able to evaluate how far the proposed aims had been achieved in the project, information was collected while the project was being carried out, with the informed consent of the students. The grades from the rubrics awarded for the different stages of the project and the final assessment included a series of interviews with the participating groups, in order to decide on the fundamental issues of the technical and creative process developed. There was also an assessment of the feedback session with the professor in the project.

In addition, written questionnaires were completed by the whole group at the beginning and end of the semester in order to establish the base line and to assess progress in relation to the knowledge of the chemical engineering core courses, the use of specialized software and different bibliographical resources as well as industrial and commercial data. The general description of each survey is presented in Appendix C. Professors and students were also interviewed to find out about their perceptions of the development of the project as a pedagogical process.

The grades from the rubrics and the statistical aspects of the questionnaires were analyzed quantitatively and the resulting information was triangulated. In other words, what the different participants presented and the various types of information on a particular aspect were compared in order to establish similarities, differences and tensions. It was this analysis that helped to structure the results.

In sum, this evaluation study uses different sources of information in an attempt to grasp the complexity of the learning taking place in this environment. Given that the project pursued multiple learning goals and most of them were oriented to the development of complex skills that are not traceable using a single pre-test pos-test design (for example, their ability to carry out the whole project as a team), we made use of surveys, observations and interviews to understand better the students' development and learning throughout the course. We also had to pay attention to subtle qualitative differences between, for example, the way a student describes a chemical industrial process at the beginning and the way he or she describe it at the end of the course or the quality of the argumentation he or she displays in the final presentation of the project.

4. Results and experiences

The first aspects evaluated were the characteristics and the composition of the course itself. Of a total of 36 students, 64% were between second semester first year and first semester second year and the majority had already taken basic thermodynamics. Only 7% of the students were simultaneously taking the 'Phase and Chemical Equilibrium' course. Therefore, basic mathematics is part of the students' skills and aspects such as energy balances begin to be integrated into their knowledge naturally. Physical Chemistry and Reaction Engineering elements are not yet part of the spectrum of knowledge of the group and the project may act as a link with the learning challenges of the second and third cycles. The most relevant results are discussed below.

4.1 First report and methodology

The analysis of the first project report helped to identify one of the most important deficiencies on the part of the students in the implementation of the project and became an opportunity to establish solid rules of play. Although the instructions provided for the project clearly asked for argumentation and technical or bibliographical support for all the information or decisions given, the students found it difficult to modulate the level of detail required. The class discussions clarified the type of data that should be supported and how to do that. The message was 'a design decision during the first stage of the project may finally lead to a difficult or a simple process, which may be expensive, cheap, successful or not, but this will be valid if its presentation has been solidly argued.'

The report was reformulated by the majority of the groups and the results and the progress made helped the students to value the logic and the importance of supporting sources. The change of grades between the first version and second version of the report was substantial and some of the groups realized that their grades could be doubled just by correctly presenting the information collected. The appropriate use of bibliographical material was also maintained in the following reports.

In the first stage, the students were confronted with certain basic elements characteristic of an open problem, such as the design of a chemical process:

- Various possible production pathways with very different economic balances
- Products of interest with a wide range of possible degrees of purity, all of potential commercial interest
- Purity of reagents and products, conversion values of simulated reactions, never reaching 100%
- Different types of bibliographical sources.

The experiences were varied but, in general, the groups proved the connection between high purity products and special applications, as well as products of intermediate quality and industrial applications. In all of these there was evidence of coherence between the use of sources of prices, production and sale volume and product quality. In this way, 50% of the groups were able to relate the factors mentioned above coherently, 25% selected purity adequately in relation to application and production, but did not define prices adequately according to sales volume. The bibliography used included quotations from industrial and laboratory suppliers.

4.2 Thermodynamic equilibrium

One of the central elements of the project was the approximation to thermodynamic equilibrium by means of the use of specialized software. The analysis required a definition of the conditions of the process and the conversion in the reactor. The use of simulation resources during the first years has in fact been discouraged by some teachers. Others maintain that these resources can and should be incorporated into the curriculum right from the beginning, provided that the learning approach is adequate [19]. The only support they received was some supervision about the architecture of a specific type of software (Aspen Plus) and some basic tutorials. In general, the groups were very efficient in the use of existing software tools and they evaluated different conditions of pressure and temperature by means of different analyses of sensitivity. It should be noted here that the products defined by the teacher were generally produced by means of reversible reactions (i.e. esterification), which allowed for different process conditions in equilibrium analysis. The result was interesting in that by working to improve and selected the conditions/ conversion of the reactor, the groups were helped to make 'correct actions' and 'mistakes', which were later discussed in class, leading to some of the most attractive aspects of the experience. We discuss some of these now.

- The majority of the groups that specified high quality products optimized the reactor by obtaining the highest conversion simplifying the following separation stages.
- Some groups that decided to sacrifice conversion for moderate conditions of operation, including environmental issues, complemented the process by separation operations that were more or less demanding.
- Some of the groups adjusted the conversion in order to avoid recirculation operations and they defended this decision by balancing in a qualitative manner reactor operating costs versus the pumping of unreacted species.
- One group used heuristics to determine the conversion limit from which it is economically more advantageous to separate the effluents from the reactor and avoid recirculation.
- At the end of the first phase, some groups obtained a process consisting of just a reactor with no need for separation units or raw materials pretreatments.

The success of the equilibrium analysis could be seen in the assessment of the report that showed that 73% of the groups carried out a complete balance analysis (sensitivity analysis and defended decisions), while only 27% showed some deficiency either in the use of the software or in the processing of the results obtained. The use of the software showed positive results that were then confirmed in the second report (Phase 2) when the students evaluated the stream energetic variables using Aspen Plus. It may be concluded that the use of software in the form of a 'calculator' (reaction conversion calculator, stream enthalpies calculations) is a useful alternative in education, provided that it is introduced within a clear context and that students are told that the way calculations are done will be discussed in later courses.

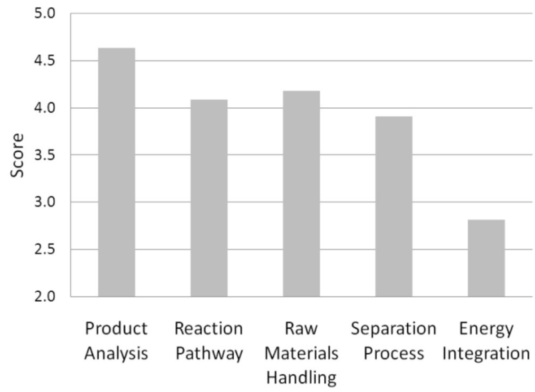

Fig. 3. Students' performances in comparative analysis. Grades. 5 excellent; 4 satisfactory; 3 need improvement; 2 unsatisfactory.

4.3 Comparative study: actual and ideal processes

The comparative analysis of the process obtained and the industrial process had special weight in the assessment of the third report. The reports were assessed in relation to different aspects on which differences had to be identified (Fig. 3). The most relevant results are given here.

- The aspects related to the product were well analyzed and the students showed evidence that the bibliographical search carried out in the first phase was adequate. The production pathway led to some interesting discussions, but it was not always possible to obtain written explanations in the cases in which the pathway chosen by the group did not coincide with the commercial pathway.

  We can clearly see the difference in the process designed by us and the process described above. With regards to purity we can see that in both processes methyl benzoate is obtained at 99%. The production pathway that we used is a simple esterification using benzoic acid and methanol meanwhile the industrial pathway separates methyl benzoate as reaction sub-product between methyl-p-toluate and xilene.

- There was frequent evidence of deviations due to the existence of secondary reactions:

  We can see that the difference in the number and type of process units is due to the sequence in which the reaction was carried out. In the industrial process, acetone was produced in a second reaction stage . . . given the reaction system, in the industrial process more equipment (basically separators) was necessary than in the process designed in this project.

- Reaction conversion in the main reactor was fairly well discussed and aspects such as process conditions versus the use of catalysts and equilibrium conversion constituted part of the analysis. The comparison of the stages involving the adaptation and separation of reagents and products led to interesting discussion in some cases. When the industrial separation differed completely from that chosen by the group, the participants were able to identify errors in the taking of decisions. In other cases, the two alternatives were shown to be possible and this was understood in the light of differences generated by the conversion of the reactor.

The main reaction is reversible, exothermic and limited by the equilibrium. In industry the equilibrium of the main reaction is only taken to 80% and the presence of methane and toluene in the reactor exit stream modifies process conditions.

On the other hand, the reactor used in industry is different to that proposed in the plant simulation. In that simulation an adiabatic equilibrium reactor was used and catalysis of the reaction was not taken into account. In contrast the industrial reactor is an isothermal catalytic bed which accelerates reaction kinetics, but as well it helps to reduce the formation of the collateral reaction, increasing the selectivity of the reactor.

- The energy analysis was not tackled very well, not so much in terms of results as argumentation. It is possible that the reason for this is a lack of skill in the reading and analysis of process flow diagrams, which is a type of representation that the students had not previously studied in the course.

The above elements and the discussion about ideal approach and deviations from this were also evaluated through interviews. The reason is that in the reports the students had to identify some facts and give a precise explanation of them. The general analysis, however, requires a certain perspective that is difficult to capture in writing. One example is the following: even though some groups were able to identify that the use of the catalyst allowed the process at less demanding temperatures, while maintaining high conversions, no group directly noted that the conversion predicted by the equilibrium might not have been reached in the industrial process, even with the corresponding pressure and temperature conditions, because the industrial reactor was continuous.

In synthesis, an additional discussion is necessary to try to capture the scope of the project in terms of the understanding acquired by the students of a problem like the one analyzed. The interviews, carried out with the groups by the professor reflected a particular type of argumentation characteristic of the students who were involved in the process. The topics associated with the comparison of actual and ideal process helped the groups to notice the existing differences between the thermodynamic approach and the complexity of involving time related issues. This was one of the results that were expected in the project in so far as it helped in the process of students' maturity and gave them a perspective on the next learning cycles. Considering the discussions, however, it must be said that although the project was able to raise questions, there was no evidence that the students developed solid criteria in all cases. In the future, it is recommended that there should be an additional session to help students to organize the information and clarify accumulated doubts.

4.4 Surveys results

Comparative analysis of individual surveys performed at the beginning and the end of the course is now discussed. With regard to the use of engineering resources during the project some expected results were obtained: besides the strong support on the Internet, there was a generalized use of encyclopedias, requested bids, and price guides as was confirmed by the analysis of reference sections in the reports. Regarding the use of specialized software, process simulators were introduced for the first time in their program. The project required the preliminary use of some specialized tools and the degree of success was assessed through the reports and rubrics as already mentioned.

Curriculum knowledge and curriculum integration were also analyzed through the reports and student interviews but surveys offer a direct result: whereas the first questionnaire indicates that in nearly all the cases the description of core courses of next cycles simply corresponded to a direct translation of the course title, in the second survey courses were described very frequently as a means of improving the industrial processes. Even if this simplification somehow limited the wide field of applications of some courses, there is great progress in the fact that the project helps students to change their abstract perception of the curriculum. As an interesting exception, Transport Phenomena courses seem to remain out of the sphere of understanding and here there is an important opportunity to improve in further curriculum integration studies.

Chemical process definitions also indicated an important effect of the project. If in the first survey, 75% of answers were limited to a correct but simplified description in terms of 'a process that transforms materials into products with higher values', in the second survey, over 60% of the students systematically included aspects related to time, efficiency, operation units, and design. Students' answers revealed some difficulties in describing in an orderly way what is now a complex process but at the same time evidenced a valuable approximation to the chemical process structure.

4.5 The pedagogical process and learning by the teacher

In many cases, processes of educational research are focused on observing and measuring the products of student learning and the achievement of the proposed pedagogical objectives. The collaboration carried out during this research by the Center for Research and Teaching on Education (CIFE) allowed for teacher development, which is very important for the university in the light of its renovation process. In particular, relevant aspects were noted in the interview carried out with the professor at the end of the data collection. This showed that by means of a process of permanent reflection on the pedagogical issues of the course, two different aspects related to teaching roles were identified. This will now be described.

First, there is the role of the teacher as designer and evaluator of his or her course. In this sense the professor noted that, due to the University proposal, there are many courses that include projects, but one of the characteristics of this project is that throughout this research student response to the course and the project, as well as the personal perception and the pedagogical learning that has been appropriated was identified. This, in turn, leads to change, to the proposing and implementing of different proposals relating to course projects. The aim is to produce a course that, as far as possible, is more efficient that a traditional class based on theory and application exercises. This can be seen as a much more active and critical approach to the professor's own teaching role.

The second aspect to discuss is the role of the teacher as guide, leading to a permanent process of working together with the students in the project, not only through the process of learning assessment but also in the feedback in class at certain times. This helped the students to see the project as an integral part of the course. It also enabled the teacher to identify the need to have an extra phase in the project. This led to a closure that was richer in that the feedback provided helped to solve doubts, discuss the general results and bring the process to a better conclusion.

Finally, we consider that this wider vision of the teacher's role helps to give rise to new pedagogical practices that transform institutions and help them to achieve the aims of change and renewal proposed in many curricular reforms.

5. Conclusions

Design projects have been recognized as powerful curriculum integration tools and therefore they are usually developed in the last years of traditional educational programs. The work presented here described a methodology to achieve some progress in curriculum integration right from the first year by an approach that lies in the coherent identification of issues belonging to the following learning cycles of the chemical engineering program. Students' reports and interviews analysis indicated that the proposed plant design project helped the students to become coherently involved with a large number of topics and resources that would commonly be reserved for sophomore or senior levels.

The general perception of the students was positive and the questionnaires completed at the beginning and end of the project reflected progress in the four aspects evaluated: use of bibliographical sources, use of specialized software or programming resources, curriculum knowledge and the defining of a chemical process. One of the most important achievements was the advance in the topic of chemical equilibrium and the use of simulation resources as a calculator. The discussion about thermodynamics and kinetics at times touched on the direct consequences in the architecture of a chemical process.

The partnership established between professors of engineering and specialists in education from CIFE was particularly profitable, in carrying out the follow up to the student learning processes as well as being present throughout the teacher's reflexive process, which resulted in new possibilities for improving the teaching and the curriculum in the Engineering Faculty.

Finally, we recommend integrating this type of project into basic courses, particularly emphasizing the possibility of relating different topics and understanding the impact that these may have in the efficient development of a design task.

References

1. Universidad de Los Andes, http://www.uniandes.edu.co, Accessed 2 November 2009.
2. Universidad de Los Andes, http://renovacioningenieria.uniandes.edu.co/cms/home, Accessed 2 November 2009.
3. A. Gauthier and R. Gómez, *Estructuración del plan curricular: una experiencia*, Universidad de los Andes, 2006.
4. National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, The National Academies Press, Washington, 2005.
5. H. Hubball and H. Burt, An integrated approach to developing and implementing learning-centred curricula, *International Journal for Academic Development*, **9**(1), 2004, pp. 51–65.
6. D. Gijbels, F. Dochy, P.V. den Bossche and M. Segers, Effects of problem-based learning: A meta-analysis from the angle of assessment, *Review of Educational Research*, **75**(1), 2005, pp. 27–61.
7. G. C. Koh, H. E. Khoo, M. L. Wong and D. Koh. The effects of problem-based learning during medical school on physician competency: A systematic review. *Canadian Medical Association Journal*, **178**(1), 2008, pp. 34–41.
8. C. K. Tanner, J. L. Keedy and S. A. Galis, Problem-based

learning: Relating the 'real world' to principalship preparation, *The Clearing House*, **68**(3), 1995, pp. 154–157.
9. L. B. Henriksen, *Research on PBL Practice in Engineering Education*, Sense Publishers, Rotterdam, 2009, pp. 23–34.
10. D. R. Woods, R. M. Felder, A. Rugarcia and J. E. Stice, The future of engineering education III: Developing critical skills, *Chemical Engineering Education*, **34**(2), 2000, pp 108–117.
11. M. Frenay, B. Galand, E. Milgrom and B. Raucent, *Management of Change: Implementation of Problem-Based and Project-Based Learning in Engineering,* Sense Publishers, Rotterdam, 2007, pp. 93–108.
12. S. Fernandes, M. A. Flores and R. M. Lima, *Research on PBL Practice in Engineering Education*, Sense Publishers, Rotterdam, 2009, pp. 45–55.
13. R. Turton and J. A. Shaeiwitz, Educating chemical engineers in product design*, International Journal of Engineering Education*, **19**(1), 2003, pp. 153–157.
14. R. C. Bailie and R. Turton, Chemical engineering design: Problem-Solving Strategy, *Chemical Engineering Education*, **26**(1), 1992, pp. 44–49.
15. R. C. Bailieand J. A. Shaeiwitz, An integrated design sequence: sophomore and junior years, *Chemical Engineering Education*, **28**(1), 1994, pp. 52,57
16. J. A. Shaeiwitz, Teaching design by integration throughout the curriculum and assessing the curriculum using design projects, *International Journal of Engineering Education*, **17**(4–5), 2001, p p. 479–482.
17. W. M. Clark , D. DiBiasio and A. G. Dixon, A project-based, spiral curriculum for chemical engineering?, *Chemical Engineering Education*, **36**(3), 2002, pp. 222–233.
18. J. A. Shaeiwitz, A large-group design experience: teaching responsibility and life-long learning, *Chemical Engineering Education*, **26**(1),1992, pp. 70–75.
19. K. D. Dahm, R. P. Hesketh and M. J. Savelski, Is process simulation used effectively in ChE courses*? Chemical Engineering Education*, **36**(3), 2002, pp. 192–198.

Appendix A: Project description and methodology

You need to carry out the preliminary design of an ethyl acetate production plant. For this you must follow the next methodology:

1. Product and Block Diagram Flow (1st report)

1.1 Product: Describe the main physical and chemical characteristics of ethyl acetate, its industrial importance, commercial characteristics and market prices.

1.2 Production: Define the production rate.

1.3 Synthesis pathway: Analyze two chemical reactions industrially used for ethyl acetate production and select one according to price benefits on the basis of 100% conversion. Once selected, find the equilibrium conversion through simulation software selecting the most convenient conditions (pressure and temperature).

1.4 Block diagram: Present the preliminary design of the plant describing the generic necessary operations. Flow compositions must be defined following team decisions and not calculations.

2. Operation Units and Process Flow Diagram PFD (2nd report)

2.1 Separation and treatment units: Detail the specific units selected.
2.2 Flow tables: Present flow tables that include: flow, composition, pressure and temperature.
2.3 PFD diagram.

3. Process Simulation and Comparative Study (3rd report)

3.1 Build up the mass and energy balances equations for the process in datasheet software. Use software (i.e. Aspen Plus) for calculating energy properties.

3.2 Energy integration: Carry out the energy balances for each unit, perform a preliminary energy integration and calculate energy costs.

3.3 New PFD: Present a new PFD diagram that reflects preliminary energy integration.

3.4 Comparative analysis: Compare and analyze the obtained design with real process.

Appendix B: Rubric for the first report

PHASE 1	% of the report grade	ASSESSMENT CRITERION
1. Product	15%	a. The project team uses bibliographic sources to determine the relevant physical/chemical properties of selected product. b. The project team establishes the product purity according a specific market (commodity or specialty chemicals) and a specific product pack size. c. The project team uses relevant sources to determine the product price for the selected market.
2. Rate of production	15%	The project team defines the production rate according to the national/international market.
3. Production pathway	35%	a. The project team defines at least two possible industrial pathways for industrial production. b. The project team uses adequate sources for price determination of products, sub-products and reagents. c. The project team performs preliminary cost/benefit analysis for each proposed pathway and selects the most favorable. d. The project team uses a process simulator to determine the most favorable process conditions on the basis of equilibrium conversion.
4. Block diagram	35%	a. The block diagram is clear with regard to the main stages needed to separate reactor effluents. b. The project team analyses the need for recirculation on the basis of equilibrium conversion. c. Flow compositions are defined.

Appendix C: Surveys description

1. **Survey about Curriculum Knowledge**
   Please give a short description (max. 30 words) of each of the chemical engineering core courses (i.e. phase and chemical equilibrium, transport phenomena, reaction engineering, separation processes, simulation/optimization, plant design).
2. **Survey about Engineering Data Resources:**
   Which of the following resources have you used during your career; in what courses (textbooks, encyclopedias of chemical technology, handbooks, price guides, databases, Internet, others)?
3. **Survey about Software Resources:**
   Which of the following software/programming resources have you used during your career; in what courses (datasheets, process simulators, Matlab, C++, Java, Design Expert, others)?
4. **Survey about Chemical Process Definition**
   Please give a short description (max. 50 words) of a Chemical Process.

Pablo Ortiz is Assistant Professor at the Chemical Engineering Department, University of los Andes, Bogotá. He received his master degree in materials science from Ecole National Supérieure de Chimie, Toulouse and his Ph.D. in metallurgy science from Universidad de Navarra–Spain. He has taught the following courses in the basic cycle of the chemical engineering program: Introduction to Chemical Engineering, Fundamentals of Industrial Processes and Phases and Chemical Equilibrium. As Master Program Coordinator he participates in academic committees for undergraduate and graduate curriculum design.

Juny Montoya gained her Ph.D. in Education from the University of Illinois, and is Associate Professor and Head of the Center for Research and Teaching on Education (CIFE) at University of Los Andes. She teaches graduate courses in Curriculum and Pedagogy, Qualitative Research Methods, and Program Evaluation. She is a member of the American Evaluation Association. Current research interests are Problem Based Learning, Active Learning, Participatory Evaluation, and Education for Democracy.

Carola Hernández holds a Bachelor in Physics from the University of Los Andes in Bogotá, Colombia, and has two - master degrees, one in Physics and one in Education, from the same university. She also has a minor in Economics. Her research experience is in biophysics, science education, ICT and education. She worked at the University of Los Andes for 4 years in the Center for Research and Teaching on Education (CIFE). She is currently associated as a Ph.D. student at the Institute of Education, Learning and Philosophy at Aalborg University. Her research is centered in Problem Based Learning (PBL)—Projects Organized Learning (POL) in science education at university level.

Adry Liliana Manrique is a chemistry teacher at the Universidad Distrital Francisco Jose de Caldas, Colombia, and holds a Master's in education from the University of Los Andes. She has research experience in education and development of community projects.

Wilson Nieto obtained his undergraduate diploma in Chemical Engineering at the University of Los Andes. He developed his last year of research work in chemical engineering education as assistant for the course Fundamentals of Industrial Processes.