Reengineering Chemical Engineering Education for the Future

Pedro M. Saraiva, Lino O. Santos, Rosa M. Quinta-Ferreira
Department of Chemical Engineering, University of Coimbra – Pólo II, 3030-790 Coimbra, Portugal
pas@eq.uc.pt, lino@eq.uc.pt, rosa@eq.uc.pt

Abstract - **The recent reformulation of the Chemical Engineering curriculum at the Faculty of Science and Technology of the University of Coimbra, according to the paradigms of the Bologna process, created an unique opportunity to implement substantial changes, in line with the new emerging paradigms of Chemical Engineering. The curriculum reformulation process involved a broad discussion among the faculty members over the new avenues of Chemical Engineering Education. The new curriculum was outlined in line with the future directions of chemical engineering education reported by recent literature in the field of chemical engineering. It integrates subjects in the line of the new organizing principles for chemical engineering education: molecular transformations, multi-scale analysis, and a systems approach. The importance of subjects in the domain of life sciences is also emphasized. These curriculum changes aim for a new breed of chemical engineers, with an education and skills to succed in increasingly competitive and global markets, with highly integrated and complex technological, economical, environmental, and social challenges.**

Index Terms – Future of Chemical Engineering, Chemical Engineering Education, Bologna Process, Curriculum reformulation.

INTRODUCTION

The adaptation of the Chemical Engineering curriculum at the Faculty of Science and Technology of the University of Coimbra to the Bologna system created the opportunity for an exciting discussion among the faculty members on what is chemical engineering, the new challenges chemical engineers are faced with, and the way chemical engineering education is delivered. As a result, proposals to introduce changes in the existing curriculum were outlined over several faculty members meetings.

Several authors report the need for changes in the chemical engineering curriculum to cope with the new challenges chemical engineers are faced with (for instance, see [1,5,6,8,14,15,18,19]). The increasingly global and competitive market the process industries are faced with, demands for chemical engineers with varied and versatile skills to tackle a wide range of problems. During the last decades new areas of application for chemical engineering have emerged. For instance, it has become apparent that the skills of chemical engineers and the methodology of chemical engineering find application in many new areas in the field of biology, such as biochemistry and biomedicine, but also in the areas of nanotechnology, materials and information technology [9]. Also, it is noteworthy to mention that the chemical engineering research community nowadays embraces a wide variety of problems in many different fields. For instance, the late programs of the American Institute of Chemical Engineers (AIChE) annual meetings [20,21] are demonstrative of the large scope and interdisciplinary nature of the problems, technologies and applications tackled with chemical engineering approaches. Thus the chemical engineering community in general has become apprehensive about the way new generations of chemical engineers are being trained to handle a large diversity of problems, with an increasingly higher degree of integration and complexity [1,6,7,8,14,18,19].

Some important issues have been identified as key factors to the education of a new breed of chemical engineers, such as the need for integrating biology as a fundamental science in the chemical engineering curriculum, in addition to mathematics, chemistry and physics. Chemical Engineering has evolved over the last decades from being an engineering discipline rooted in the concept of unit operations to one based on engineering science and mathematics with increasing ties to the natural sciences [15,17]. The increasing presence of subjects in the area of biological systems in the chemical engineering curricula in universities around the world is a clear indicator of its importance for the education of chemical engineers. Another important point is the perception that the nature of the problems chemical engineers are faced with, do span across several (space and time) scales and complexity levels, from a nano-scale (molecular processes, active sites) up to a mega-scale (environment, atmosphere, oceans, soils, global market) [7,14,15,16]. In between these two scales, problems are addressed at a micro-scale (bubbles, drops, particles, eddies, etc), meso-scale (reactors, columns, exchangers, pumps, compressors, etc), and macro-scale (production, plants, local market). In line with this multi-scale perspective, from product design at the molecular level to the consumer at the end of the processing line, chemical engineers have to integrate from the very beginning concerns about environment and sustainability in their research, modeling, design, optimization and control, and management activities [4]. Reference [8] identifies three major trends to cope with the required update in the scientific sphere of chemical engineering, and with consequences on the way chemical engineering education is delivered:

a) broadening of the body of knowledge associated with the discipline;
b) adoption of a multifaceted approach to products and processes;
c) emergence of chemical product engineering as a well-established teaching and research field.

A large percentage of chemical engineers is nowadays engaged in making various specialty products (formulated products). While chemical engineers still need much of the traditional chemical engineering skills, there is now a need to include some knowledge of "product engineering" in the common core [10]. There is demand for much more versatile chemical engineers to create products and processes, manipulating complex systems, and managing technical operations in industries increasingly reliant on molecular understanding and manipulation [1,13]. Therefore, all these factors motivate a dramatic shift in chemical engineering education established on a new set of organizing principles [1,13]: molecular transformations, multi-scale analysis, and a systems approach. In line with the emergence of these organizing principles, careful attention must me paid to the way education is delivered. Here it is of paramount importance the chemical engineering curricula be organized to ensure that students are able to make the relevant connections between the different subjects [10].

The methodology to reformulate the Chemical Engineering curriculum to comply with the Bologna system, and to integrate the new paradigms in chemical engineering education to tackle the new emerging areas, involved the creation of a Bologna process team with some of the faculty members of the Chemical Engineering Department. This same team worked as the interface between the department and the Faculty of Science and Technology Bologna process coordination team. Progress in the Chemical Engineering curriculum reformulation was carried out in an iterative manner, through over more than thirty full department faculty staff brainstorm meetings during 2006. These debates were fundamental to develop the perception and awareness among all faculty members with respect to the new directions chemical engineering activities are leading to, and their consequences to chemical engineering education. The discussion was supported by diverse literature and several online web resources available on this topic.

The paper is organized as follows. First of all, the next section summarizes the main features and underlying principles of the new five years Masters Degree in Chemical Engineering (MchemE) program. Then a brief discussion is given concerning the new paradigms of chemical engineering education, the molecular transformations and the systems multi-scale perspectives. The importance of subjects in the domain of life sciences is also emphasized. The 3rd section provides a detailed description of the MchemE curriculum, emphasizing some of its assets. The 4th section presents the assessment methodology and the principles it is based on. Finally, concluding remarks are given in the last section.

THE NEW MASTERS DEGREE IN CHEMICAL ENGINEERING

The development of the new five year Masters Degree in Chemical Engineering (MChemE) involved an evaluation of current and best practices in Chemical Engineering education in Portugal, Europe, and all over the world. The new paradigms of Chemical Engineering Education, also known as the "New Frontiers in Chemical Engineering Education" [1,13], were also taken into consideration. In line with this, the curriculum reformulation process was initiated taking the following actions:

d) the adoption of multi-scale perspectives as key integrating tools;
e) the consideration of molecular phenomena as key supporting pillars;
f) the adoption of systems thinking as central to an overall understanding of processes and products;
g) the move from a process orientation to an integrated chemical product/process view;
h) the need to reinforce issues such as sustainability, energy, biological systems, and nanotechnologies as critical ones.

As a result, some of the following changes in the chemical engineering curriculum were introduced:

a) subjects in the area of biological systems were reinforced and their scope enlarged;
b) cellular and molecular basis of chemical engineering are introduced in the first year;
c) the first three years of the MChemE were designed to enhance the integrated and multi-scale perspectives for the analysis and design of chemical and biological processes/products, mostly supported by molecular transformations;
d) the integrated nature of the information and complexity of chemical systems, and the associated tools to analyze, model, optimize, design and control them, are handled through a variety of projects along a set of disciplines denominated Integrated ChemE Problems (IChemEP).

In the fourth year of the MChemE new subjects are introduced, to address issues related to sustainability, safety, energy, and chemical product design. Here, it is noteworthy to point out the existence of a product design discipline. In their fifth and final year, students can select one out of two main areas: a) Process, Energy and Environment, or b) Biosystems.

Evaluation methodologies were also updated, relying much less in traditional examinations and much more on integrated and project based learning.

NEW AVENUES OF CHEMICAL ENGINEERING EDUCATION

I. The emerging trio: Molecules, Product, and Process

During the first periods of the 20th century chemical engineering education was delivered on the ground of a process systems classification based on the concept of unit operation. From the paradigm of the unit operation concept, the teaching of chemical engineering evolved to a more integrated view of the way processes operate and behave, using rigorous mathematical modeling approaches to describe and analyze the underlying physicochemical and transport phenomena mechanisms.

More recently, the emergence of a third paradigm, that stems from the molecular basis of knowledge to analyze, design, optimize and control new products and their processes, is taking place. This stands as a main driving-force to change the way chemical engineering education is delivered, and it requires a multi-scale vision to analyze and understand process systems, from the molecular scale up to the scales of the process unit, the plant, the market and the environment (for instance, see [2]). Moreover, recent available hardware and software for predicting the behavior of systems and processes based on molecular-scale properties, presents chemical engineering educators the opportunity for better integration of the fundamental molecular processes of chemical physics into chemical engineering [3].

In line with this multi-scale perspective [1,5,14,15,16], from product design at the molecular level to the consumer at the end of the processing line, structural and stabilization processes assume an increasingly larger importance to preserve the chemical, microbiological, and enzymatic stability of the newly developed products. These are crucial steps in the final stages of product processing to achieve high standards of quality and safety, and definitely have a high impact in industrial sectors such as fine chemicals, pharmaceutical, food, hygiene and cosmetics industrial sectors.

Thus, special attention must be paid to these emerging trends and to their inclusion in the curriculum of a chemical engineering degree. The classic processing sequence "separation-transformation-separation" must now be extended to integrate the final processing stages related to structure and stability of chemical product engineering [8].

II. The Sciences of Life

Since the first entire genome sequencing of a free-living organism in 1995 [12], one have been assisting to new developments in the domain of biological systems at a very fast pace. In recent years chemical engineers have also started to play a central role in developing novel cell factories through the use of the so-called metabolic engineering [17]. Cellular and Molecular Biology, Metabolic Engineering, Proteomics, and Genomics are creating new opportunities to the design of new molecules, to devise the production of new pharmaceutical products, or products with specific functionalities. Knowledge of basic concepts in the domain of biological systems is a leading edge for the new generation of chemical engineers of the 21st century, to be prepared for versatile and multifaceted careers. This trend is being observed in the Chemical Engineering curricula over the world, where Molecular and Cellular Biology assumes the same status as those of Mathematics, Physics and Chemistry, as a fundamental science for Chemical Engineering.

THE MCHEME LAYOUT

The configuration of the layout of the new Masters Degree in Chemical Engineering at the University of Coimbra is described through tables I to IV. In the next paragraphs are highlighted some of its main components and strategic options.

I. The Integrated Chemical Engineering Problems

The main core of Chemical Engineering is addressed in the first three years of the MChemE degree program (Table I), where the fundamentals in Mathematics, Physics, Chemistry, and Biology are introduced. The areas of Chemical Engineering Science are also included through a set of disciplines in the areas of Chemical Thermodynamics and Transport Phenomena.

There are various interconnected sets of disciplines that can be identified. For instance, a set of disciplines in the area of Process Systems Engineering, that includes Chemical and Biological Systems Analysis, Transfer and Separation, Transformation, Structuration and Stabilization Processes, and Supervision of Processes. Related to the area of Molecular Process Engineering there are the disciplines of Molecular and Cellular Biology and Chemical Engineering of Molecular and Cellular Basis. Issues related to Materials Engineering are addressed in the discipline of Materials and Interfacial Phenomena, and the contents of Industrial Effluents and Residues address environmental issues. There is also a set of disciplines addressing mathematical tools for Simulation, Modeling and Decision making. Complementary skills are also provided through the disciplines of Informatics, Instrumental Analysis Methods, and Management and Entrepreneurship.

TABLE I
FIRST THREE YEARS PROGRAM OF THE MASTERS DEGREE IN CHEMICAL ENGINEERING

Year/ Semester	Discipline	ECTU
1 / 1st	Mathematical Analysis I	6
	Linear Algebra and Analytical Geometry	6
	Physics I	6
	Chemistry I	6
	Informatics	3
	Integrated Chemical Engineering Problems I	3
1 / 2nd	Mathematical Analysis II	6
	Physics II	6
	Chemistry II	6
	Molecular and Cellular Biology	4
	Modeling, Simulation and Decision I	5
	Integrated Chemical Engineering Problems II	3
2 / 1st	Mathematical Analysis III	6
	Organic Chemistry and Synthesis	5
	Chemical Thermodynamics I	5
	Transport Phenomena I	5
	Biological and Chemical Systems Analysis	4
	Integrated Chemical Engineering Problems III	5
2 / 2nd	Chemical Thermodynamics II	5
	Transport Phenomena II	6
	Materials and Interfacial Phenomena	4
	Transfer and Separation Processes I	5
	Modeling, Simulation and Decision II	5
	Integrated Chemical Engineering Problems IV	5
3 / 1st	Transformation Processes I	5
	Transfer and Separation Processes II	6
	Structuration and Stabilization Processes	5
	Instrumental Analysis Methods	4
	Management and Entrepreneurship I	4
	Integrated Chemical Engineering Problems V	6
3 / 2nd	Transformation Processes II	5
	Industrial Effluents and Residues	5
	Supervision of Processes	5
	Chemical Engineering of Molecular and Cellular Basis	5
	Management and Entrepreneurship II	4
	Integrated Chemical Engineering Problems VI	6
	Total ECTU	*180*

The Integrated Chemical Engineering Problems (IChemEP) cover a set of six disciplines in the first three years of the MChemE degree program. These disciplines play a role of paramount importance to the integration of knowledge acquired in the other disciplines of each semester. The contents covered at the various disciplines are applied here to solve practical problems, to analyze, design, optimize and control systems of various complexity and dimensions. This set of disciplines lies at the corner stone of the idea of developing an integrated perspective of the problems in chemical process engineering systems. The underlying goal is to provide to the students the *big picture*, how to integrate the various tools and methods to solve and analyze problems from a systems engineering perspective. This is also essential to increase their confidence to manage the information and the interplay between the core contents of the various disciplines they attend during each semester [10].

The organization of these three years of the MChemE degree program is presented in Table I. In the left column ECTU stands for European Credit Transfer Unit. It is a common European credit unit under the European Credit Transfer System (ECTS), aimed to make easier students mobility across Europe. These ECTU values are a measure of the student workload. That is, it measures the total effort spent by the student attending classes, doing homeworks, studying and performing assessment evaluations. Following the Bologna system European recommendations on that matter, the first three years account for a total of 180 ECTU, with 30 ECTU in each semester (Table I).

II. The major milestone

The first three years of the MChemE degree program deliver to the students a solid background in the main core of chemical engineering. At the same time the new perspectives based on molecular approaches and on the multi-scale analysis are introduced along that curriculum. This preparation leads the students to the two final years of the MChemE degree program (Table II, III and IV).

The 4th year program (Table II) involves a set of disciplines to reinforce the background in advanced chemical engineering tools and methodologies such as Planning and Operations Management, Industrial Facilities and Equipment, Nonconventional Separation Processes, and Advanced Modeling and Simulation Techniques.

Sustainable and environmentally conscious chemical process engineering developments are also of particular concern, addressed through disciplines such as Sustainability of Chemical and Biological Processes, Industrial Safety and Risk Assessment, Energy and Biofuels, Quality, Environment, Safety, and Industrial Licensing. These are essential to develop students knowledge and ability to implement pollution prevention technologies, to minimize the environmental impact of biological and chemical manufacturing processes [4]. It is noteworthy to mention the relevance of Product Design in the MChemE curriculum, which accounts for a total workload of 9 ECTU. In the line of the objectives of the previous set of IChemEP disciplines, Product Design can be viewed as an integrating knowledge agent of the 4th year program.

The 4th year program is a major milestone in the students trajectory through the MChemE degree program. Here the students can experience new topics from a given selection of optional disciplines (Table II). Besides the contribution to open new avenues on the application of chemical engineering methodologies, this will help students to make their decision regarding which branch to follow in the final year program of the MChemE degree: Area 1 - Process, Energy and Environment (Table III); Area 2 - Biosystems (Table IV). Both areas comprise Process Design with a workload of 12 ECTU and, in the 2nd semester, the Masters thesis in Chemical Engineering, which accounts for a workload of 30 ECTU.

TABLE II
4TH YEAR PROGRAM OF THE MASTERS DEGREE IN CHEMICAL ENGINEERING

Year/ Semester	Discipline	ECTU
4 / 1st	Sustainability of Chemical and Biological Processes	6
	Planning and Operations Management	6
	Industrial Facilities and Equipment	5
	Industrial Safety and Risk Assessment	4
	Nonconventional Separation Processes	5
	- Select one of the following disciplines:	
	Image and Signal Treatment and Analysis	4
	Biosensors and Biomedical Signals	4
	Interfacial Phenomena	4
4 / 2nd	Product Design	9
	Energy and Biofuels	5
	Advanced Modeling and Simulation Techniques	6
	Quality, Environment, Safety, and Industrial Licensing	6
	- Select one of the following disciplines:	
	Pharmaceutical Processes	4
	Biosystems and Metabolic Engineering	4
	Nanotechnology	4
	Total ECTU	*60*

TABLE III
5TH YEAR PROGRAM, AREA 1 - PROCESS, ENERGY AND ENVIRONMENT

Year/ Semester	Discipline	ECTU
5 / 1st	Process Design	12
	Process Intensification and Integration	6
	Industrial Ecology and Life Cycle Assessment	4
	Industrial Pollution Control Technology	4
	- Select one of the following disciplines:	
	Nontechnical discipline to be chosen by the student	4
	Pulp and Paper Science and Technology	4
	Transformation and Separation Processes in Biological Systems	4
5 / 2nd	Masters Thesis in Chemical Engineering	30
	Total ECTU	*60*

TABLE IV
5TH YEAR PROGRAM, AREA 2 - BIOSYSTEMS

Year/ Semester	Discipline	ECTU
5 / 1st	Process Design	12
	Transformation and Separation Processes in Biological Systems	6
	Biomaterials	4
	Development of New Pharmaceuticals	4
	- Select one of the following disciplines:	
	Nontechnical discipline to be chosen by the student	4
	Synthetic Biology	4
	Tissue Engineering	4
	Bioinformatics	4
	Biomechanics	4
5 / 2nd	Masters Thesis in Chemical Engineering	30
	Total ECTU	*60*

III. Process, Energy and Environment

The impact of chemical engineering activities in the society and the environment is of significant importance, as they play a central role in the society to develop and manufacture new materials and products to improve the quality of life. However, this development needs to be achieved in a sustainable way, investigating optimal and safe products and processes, with the best performance and environment friendly solutions, preventing pollution, minimizing energy consumption, and looking for alternative renewable sources of energy. These very often conflicting objectives add substantial complexity to the problems which chemical engineers are faced with. In the line of these important aspects, Area 1 in the final year program (Table III) offers a set of disciplines comprising Process Intensification and Integration, Industrial Ecology and Life Cycle Assessment, and Industrial Pollution Control Technology. The students have also the possibility to select one optional discipline, which can be a non-technical discipline to attend outside the department, which has to be selected in agreement with the course coordinator.

IV. Biosystems

As described previously, in recent years chemical engineering started to play a central role in developing novel solutions and products in the context of biological systems, including biomedical systems. These are domains where considerable market grow is expected to take place. This motivated the introduction in the final year of the MChemE degree program of an area focused on biosystems (Area 2 in Table IV). It is noteworthy to mention in this regard the existence of a favorable environment in the university campus to the definition of Area 2. One can refer for instance to the closeness to the Hospitals of the University of Coimbra (HUC) and the Center for Neuroscience and Cell Biology (CNC). Also, there is nearby Coimbra a quite recent and the first Portuguese technology park dedicated to biotechnology, located in Cantanhede (BIOCANT Park), which is an applied research and development center in Life Sciences for the creation of innovative biotechnology services and products.

The set of disciplines in Area 2 will provide additional multidisciplinary skills to the chemical engineering students, in various subjects such as: Transformation and Separation Processes in Biological Systems, Biomaterials, and Development of New Pharmaceuticals. Also, a set of optional disciplines is available to the students: Synthetic Biology, Tissue Engineering, Bioinformatics, and Biomechanics. As in Area 1, the students have the possibility to select a nontechnical discipline to attend outside the department, to be defined in agreement with the course coordinator.

V. The Masters Thesis

The last semester of the MChemE degree program is fully dedicated to the masters thesis (Table III and IV), with a total workload of 30 ECTU. The two last years account for a total workload of 120 ECTU, which makes a total workload of 300 ECTU for the five year program.

Although the MCHemE degree program is a five year integrated program, special attention was also paid to the recommendations of the European Federation of Chemical Engineering (EFCE) for chemical engineering education in a Bologna two cycle degree system [10]. This includes recommended indicators for the relative contribution in terms of required workload (number of ECTU) assigned to main streams of the core curriculum: science and mathematics, chemical engineering, non-technical topics, and thesis and chemical engineering project. The new MCHemE degree program satisfies well above the minimum indicators reported in [10].

STUDENTS ASSESSMENT METHODOLOGY

The student's assessment methodology is set on the grounds of the new Bologna system paradigms that propose an educational model learning process where the student participation is more active than in the previous classical model. To converge to these objectives, the education delivery process is organized as follows:

a) In each year of the MChemE degree program, the students are organized in teams, with one of the students being the team representative;
b) For each semester, there is a faculty member leading the student teams, advising and monitoring their performance;
c) The same faculty member leads meetings every two weeks with the student teams representatives and all the teachers involved in the disciplines those students are attending in that semester;
d) The same faculty member is also responsible for the IChemEP discipline of that semester;
e) A file is constituted for each Chemical Engineering course (that is, for each batch of students entering the department) that gathers all information about the contents of the set of IChemEP disciplines (IChemEP I - VI), held over the first three years of the MChemE degree program;
f) During the last two years, the integrating nature of the previous set of IChemEP disciplines is ensured by the Product Design and Process Design disciplines;
g) The new reformulation considers the possibility of teaching either in English or in Portuguese the disciplines of the last two years of the MChemE degree program;
h) A single examination will be made at the end of each semester, covering the contents from all the different disciplines.

In addition to this, all student teams will organize one monthly oral presentation in each discipline. Also, the faculty member adviser of the student teams promotes in each semester a social event involving all the students. The assessment of the students at all the disciplines is based on continuous evaluation processes, involving tests, homework, oral presentations, etc., including an important component associated to the performance of the student teams.

The faculty members also identified the following most relevant interpersonal competences and skills to be developed in the new breed of chemical engineers:

a) Teamwork;
b) Capacity of initiative;
c) Oral and written communication;
d) Capacity to integrate knowledge;
e) Personal organization to work in a regular basis;
f) Honesty, ethics and deontology.

CONCLUDING REMARKS

The new five year Masters Degree in Chemical Engineering at the University of Coimbra was designed in compliance with the Bologna Process paradigms, and taking into consideration several factors, such as the emerging paradigms in chemical engineering education, the importance of molecular transformations, and of the life sciences. The program was devised taking into consideration recommendations from the European Federation of Chemical Engineering (EFCE) [10] and of the European Federation of National Engineering Associations (FEANI) [11].

The new curriculum is to be launched in September 2007. It is also a challenge for all faculty members, since careful coordination among the different subjects in each semester is needed, with a tight and coordinated supervision at the level of each Integrated Chemical Engineering Problems (IchemEP) discipline. In all, this will require certain cultural changes from both students and faculty members as well. With this course organization the Chemical Engineering Department aim for a new breed of chemical engineers, more versatile and capable to tackle increasingly complex problems across several time and space scales. This is achieved with the integration and reinforcement of ties to the natural sciences, the means to develop the perception of the multi-scale nature of the problems to be addressed, and broadening the body of knowledge associated with the discipline of Chemical Engineering. There will be a necessary period of adaptation to proceed with the change from the previous curriculum to the new MChemE degree program. This will be made in accordance to the transition plans established together with the Faculty of Science and Technology of the University of Coimbra.

REFERENCES

[1] Armstrong, R. C.., "Frontiers in Chemical Engineering Education", *9th International Chemical Engineering Conference, Coimbra, Portugal,* September 21-23, 2005.

[2] Babic, D., A. Pfennig, "Direct Modeling of Unit Operations on Molecular Level", 1*6th European Symposium on Computer Aided Process Engineering and 9th International Symposium on Process Systems Engineering, W. Marquardt, C. Pantelides (Ed.), Elsevier B. V.*, 2006, 359-364.

[3] Baldwin, R. M., J. F. Ely, J. D. Way, S. R. Daniel, "Incorporating molecular modeling in the ChE curriculum", *Chemical Engineering Education*, Spring 2000, 162-167.

[4] Brennecke, J. F., M. A. Stadtherr, "A course in environmentally conscious chemical process engineering", *Computers and Chemical Engineering*, 26, 2002, 307-318.

[5] Charpentier, J.-C., "The triplet, “molecular processes-product-process” engineering: the future of chemical engineering ?", *Chemical Engineering Science*, 57, 2002, 4667-4690.

[6] Charpentier, J.-C., T. F. McKenna, "Managing complex systems: some trends for the future of chemical and process engineering", *Chemical Engineering Science*, 59, 2004, 1617-1640.

[7] Charpentier, J.-C., P. Trambouze, "Process engineering and problems encountered by chemical and related industries in the near future. Revolution or continuity?", *Chemical Engineering and Processing,* 37, 1998, 559-565.

[8] Costa, R.., G. D. Moggridge, P. M. Saraiva, "Chemical Product Engineering: An Emerging Paradigm within Chemical Engineering", *AIChE Journal,* 52(6), 2006, 1976-1986.

[9] Evans, T. J., "Establishing a better appreciation of chemical engineering as an essential contributor to the quality of life and to achieving a sustainable future - A role for National Societies and the European Federation of Chemical Engineering?", 9*th International Chemical Engineering Conference, Coimbra, Portugal,* September 21-23, 2005.

[10] European Federation of Chemical Engineering (EFCE) Recommendations for Chemical Engineering Education in a Bologna Two Cycle Degree System *(as of September 2005), EFCE Statements on Bologna Process.* http://www.efce.info, April 2007.

[11] FEANI (Fédération Européenne d'Associations Nationales d'Ingénieurs) Position Paper on Bologna and Prague Declarations, September 2003, http://www.feani.org, April 2007.

[12] Fleischmann, R., M. Adams, O. White, R. Clayton, E. Kirkness, A. Kerlavage, C. Bult, J. Tomb, B. Dougherty, J. Merrick, "Whole-genome random sequencing and assembly of Haemophilus influenzae Rd", *Science,* 269 (5223), 1995, 496-512.

[13] Frontiers in Chemical Engineering Education. A discipline-wide initiative to advance the undergraduate chemical engineering curriculum. Statements/papers and records of meetings in 2002-2005 available at http://web.mit.edu/che-curriculum/, April 2007

[14] Grossmann, I. E., "Challenges in the new millennium: product discovery and design, enterprise and supply chain optimization, global life cycle assessment", *Proceedings of the 8th International Symposium on Process Systems Engineering,* 2003, 28-47.

[15] Grossmann, I. E., A. W. Westerberg, "Research Challenges in Process Systems Engineering", *AIChE Journal*, 46(9), 2000, 1700-1703.

[16] Krieger, J. H., "Chemical Engineering redefines itself in era of global change", *Chemical & Engineering News, American Chemical Society*, August 19, 1996.

[17] Nielsen, J., "The role of Chemical Engineering in Modern Biotechnology", *9th International Chemical Engineering Conference, Coimbra, Portugal,* September 21-23, 2005.

[18] Villermaux, J., "Future challenges in chemical engineering research", *Trans IchemE* – Part A, 73, 1995, 105-109.

[19] Wintermantel, K., "Process and product engineering – achievements, present and future challenges", *Chemical Engineering Science,* 54, 1999, 1601-1620.

[20] 2*005 AIChE Annual Meeting Preliminary Program, Cincinnati, OH.* http://aiche.confex.com/aiche/2005/preliminaryprogram/index.html, April 2007.

[21] *2006 AIChE Annual Meeting Preliminary Prog., San Francisco, CA,* http://aiche.confex.com/aiche/2006/preliminaryprogram/index.html, April 2007.