Plenary Lecture – CHEMPOR'01 – 8th Int. Chem. Engng. Conference, p. 107-120, Aveiro, Portugal, 12-14 September 2001

Which Education of Chemical Engineers in 2020?

Sebastião Feyo de Azevedo

Department of Chemical Engineering & Institute for Systems and Robotics

Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto , Portugal, E-mail: sfeyo@fe.up.pt

1. Introduction - historical overview

Prospective words, I was asked to write. In Science, they say, *the Truth Today is quite often simply a lie queuing patiently for its time*. Prospective analysis is of course Science, though not on the sense we, Chemical Engineers, usually practice, consequently I leave this idea of *reasonable doubt* in my words about the future.

History plays obviously a major role in any forecasting attempt. Guedes de Carvalho (1998) with the concise wisdom of the Wise describes, in his book about the history of chemical engineering education at the University of Porto, the evolution, the milestones, the paradigms in the chemical engineering profession and in Chemical Engineering Education. The works of Hougen (1977), of James Wei (1996), of Landau (1997), of Gillett (2000, 2001), of Edgard (2000a, 2000b) of Silverberg and Ondrey (2000) and that of Drinkenburg (2001), indeed are best quality *food for thought*, complementing the work of Guedes de Carvalho in this thinking of the future.

As John Gillett (2001) so well puts it "the knowledge and experience gained during an individual lifetime affects the individual perception and interpretation of events in the world. The individual thus develops a *World-view (Weltanschauung)* or *Mindset* that affects his or her thinking processes, values, beliefs and emotions. A change in mindset, sometimes referred to as a *Paradigm shift*, is very creative or enlightening and usually affects the emotions. Childhood education and experiences develop the mindset so that it can evolve in later life. Holistic thinking in chemical engineering, possibly the key word for the near future depends on the mindset".

It is clear that mentioning this concept of *mindset/paradigm* in relation to areas of knowledge such as chemical engineering means to say that we are recognising and identifying firm theoretical foundations for these areas, with successful application and matching to (and with) empirical observations, supported by textbooks and handbooks, by professional societies and specialised journals, subjects and concepts that are taught to beginners (Wei, 1996).

So, how was it with the evolution of chemical engineering?

1.1 First paradigm

The first paradigm of chemical engineering should be identified by the key words *Unit Operations*. The equipment, its design and form of operation, were the object. Physics was the scientific basis. According to James Wei (1996) it was Arthur D. Little who first proposed this structure of teaching of chemical engineering. The first textbook organised in line with this mindset was that of Walker, Lewis and McAdams (1923). Many others followed. The Series by Coulson and Richardson (*Chemical Engineering,* now in its 6th volume) first published in 1954**,** the textbook of Foust et al. (1960), the three volumes of Hougen and Watson, the third one with Ragatz, under the title *Chemical Process Principles,* the originals dating back to 1943, and the text by Shreve and Brink (1st Ed., 1956) represent references of this paradigm.

In the decades up to the Fifties and Sixties, thus covering the frenetic period of production of World War II and of post-war, chemical engineering achieved a state of maturity, particularly in the oil and petrochemical industries. Continuous processes were scaled up to capacities of millions of tons per year. This was a period characterised by the search for improvement of the design and operation of industrial processes by bringing into the practice fundamental concepts of physical-chemistry, thermodynamics and kinetics.

1.2 Second paradigm

A shift (not a discontinuity!) in chemical engineering R&D and education can be observed as having started somewhere in the transition from the Fifties to the Sixties. The reference is of course the book by Bird, Stewart and Lightfoot (1960) *Transport Phenomena*.

The concept of unit operations was extended or enhanced through this increased attention paid to transport phenomena. As an important consequence, just as example, this knowledge was incorporated in reactor technology thereby lifting this discipline to the level of science.

In parallel with developments in chemical engineering (chemical engineering in *strictus sensus)* the sixties also witnessed the rising of what is today a major discipline, with which chemical engineering has very close affinity, that is *process systems engineering*. The book by Rudd and Watson 1968) *Strategy of Process Engineering* can be considered a reference on this shift to include optimisation at the level of both process design and operation. Process control, already in the practice since the forties, was intensified. First, it was process control mainly with stand-alone instruments; then on the seventies and the eighties, process computers brought in distributed and supervisory control; systems theory received a major impulse with this perspective of availability of means (computers) to bring the theory into the practice of process operation; now and for the foreseeable future the theme is computer-aided process operation, including on-line optimising control and knowledge engineering approaches (Peres et al., 2001) .

With R&D being valued in the more developed countries as *the obvious source for progress,* hence with a material driving-force behind, this was a natural evolution having as main actors those who wanted to learn and understand basic mechanisms and fundamental phenomena. That beginning of the availability of computers, with the related increased capability of dealing with mathematical modelling, further led to the development of this new pattern of learning and teaching chemical engineering. The goal to achieve was *À Priori Design*.

This is the *Era of Chemical Engineering Science*. Wilhelm (1962) with his seminal work *Progress Towards the A Priori Design of Chemical Reactors* has described the goal, possibly better than anyone else. It should be mentioned that *À priori design* is still to be reached…

Concerning chemical engineering education, curricula in this period were re-structured in line with this second paradigm. They were adapted to accommodate topics and contents that approached teaching from research. The percentage of disciplines related to chemical engineering sciences increased significantly (transport phenomena, reaction engineering, separation processes).

1.3 Third paradigm?

Are we already on the age of a third paradigm? Not entirely, not everybody, some are already in. The contours are not completely defined, but the general shape is taking form.

Before engaging in this discussion, once again the question should be raised that we are witnessing and being actors of a shift, a change of trajectory, not of a discontinuity. The *Chemical Engineering Science* paradigm has obviously not erased or even overshadowed the *Unit Operations* paradigm. Similarly, the new evolution we are witnessing will for sure make use of all knowledge available. Equally it will not overshadow the methods and concepts of the recent past, even when, and that will happen, some unit operations may become obsolete.

So, where to are we heading off?

Quite clearly, shifts in mindset have not solely to do with human effort to increase knowledge, on the candid sense of the word. They have also, and significantly, to do with dominant driving forces in the societies, in each historical moment or age. They have to do with the pressure to fulfil societal needs and demands, directions that often Intellectuals find hard to accept.

So, let us review a number of factors, of different nature, that today influence decisions for the future:

- Economy and market forces represent at present the driving forces of societies.
- The tremendous growth in technological development spanned by the developments in digital technology, particularly the evolution in methods of work related to developments in communications, is changing dramatically concepts of time and space, not only from a technical point of view but also in terms of working procedures.
- Globalisation, which is by no means exempt of serious disadvantages, is conditioning and setting the patterns of development.
- Distance plays today a minor role both in competition and co-operation. Both the job market and the potential for joint ventures are wider than ever before.
- At individual level, the concept of managing a career has also been changing significantly. This of course influences strongly individual behaviour.
- Standards and quality references have sharply increased. Protectionist barriers have fallen down. For the European Space, standards are those of Europe.
- Process and product development times came down sharply, by factors of 3 to 5. Risk management is becoming the standard practice.
- The winds of history brought in new concerns on environment and in general on the need to educate on sustainability.
- New paradigms of Unit Operations are open for discussion. Active search is in progress for micro-systems (Jensen, 2001; Cefai, 2000); process intensification is transforming chemical engineering, being possible that some types of equipment may become obsolete (Stankiewicz and Moulijn, 2000).
- There has been a sharp increase in the production of performance products, like specialties, food and personal care products and many others. These products are not sold

on their chemical properties, but on their performance characteristics. Product technology, product engineering or formulation engineering represent an area to bring into CE education.

- Management has acquired a new relevance. Many of our alumni will spend a relatively large part of their career in managerial jobs, most often on the development side (technology management). The same basically applies to consultant work in areas as wide as IT, management, finance, commerce, technology etc..
- Free societies generate a demand of education opportunities (resulting from people exercising the right to education - *Education for All*). In parallel, the need of a balanced distribution of skills (coming as pressure from the society to fulfil society demands) leads naturally to the need of establishing different levels and profiles of education. Higher education institutions must manage their offer in such a way that they that they satisfy both demand of opportunities for education and the societal needs.

So, it is within these realities and constraints that the evolution of chemical engineering and of chemical engineering education should be discussed.

Let us for the moment leave the question of the third paradigm open…

2. Chemical Engineering identity and new directions for Education

The first comment is indeed a tribute to the second paradigm.

As far as chemical engineering is of concern a shift, which for sure is related to the birth of the third paradigm, started in fact back in the late seventies, when new options were developed and offered to the young generations - environment, biomedical sciences, materials (polymers), food, biotechnology in a wider sense.

That represented the first clear signal of the recognition that chemical engineering concepts and methodologies could and should provide major contributions to the needs of humanity in a space of disciplines wider than those of chemical engineering understood in *strictus sensus.* Much through these applications the original domains of chemical engineering were clearly enlarged. Indeed chemical engineering, now in a *latus sensus*, encompasses a wide set of disciplines from biotechnology to cybernetics, including industrial chemistry, process systems engineering, biochemical engineering, material sciences and the classical process engineering (Silverberg and Ondrey, 2000). This means a new identity for chemical engineering.

This enlargement of the potential role of chemical engineers, together with new demands and requirements from the society, with the changing time- and space-scale of technical developments, the change in working practices and together with the dominant economic factors affecting company organisation, raises major questions concerning the need for new directions of chemical engineering education (CEE).

In practical terms, the objective of the exercise is to finally choose (decide) the (appropriate) answers to two main questions:

- What role and distinction of education at the tertiary stage (University education)?
- What should be the structure and the core content of chemical engineering curricula for a first degree? What, what depth, when, how…

No easy answers available, depending as they are on deciding about so many other sensitive questions, viz. –

- Which skills and competencies should be promoted, thinking of both the needs of industry and the individual right of managing a career?
- What is the role of cultural interchanges and how to use international co-operation for promoting such interchanges?
- Assuming as a fact its relevance, how to induce holistic thinking and concepts of integrated development?
- To what extent should CEE approach (or combine with) industrial practice?
- Should CEE rather be research oriented?
- Should CEE be oriented towards societal needs such as environmental protection, and sustainability?
- Should we bring in disciplines from life sciences?
- Should CEE include new disciplines such as industrial informatics, information technology, process intensification and miniaturisation technology?
- Should we shift from process design to product development?
- Which new methods and tools for teaching and how to induce self-learning?

These are of course inter-related subjects, to be discussed keeping such inter-relations in mind.

2.1 Education at the tertiary stage

These words are written on a moment where it seems that indeed a number of changes are occurring (or about to occur) at European level with relation to the application of the so-called Bologna Declaration.

In practical terms, the Declaration is about comparability of the level of qualifications and consistent use of qualification titles. All of the other objectives rest, to a greater or lesser extent, on the establishment of that common currency of qualifications.

What is clear is that it is fostering discussion and promoting curricula adaptations at European level, this in itself a condition for progress.

Promoting some of the changes already suggested or hinted above in this text, bringing in new subjects, can only be done by taking out enough material from the old curriculum. We all know the difficulty of such exercise. All current topics are individually self-classified as essential, if anything is to be done is to extend them, this without exception…! Practical hurdles that have to be overcome.

Cutting some subjects to the fundamental concepts is the solution, together with clearly making students and company managers feel that lifelong learning is the only key for progress and for filling in gaps that appear with practice.

Many curricula following the second paradigm represented a close match between education and research. It is delicate to say that this will have to change, because concepts and attitude of innovation and research should be in the tissue of education of young generations.

There should be no doubt of the role of innovation (more than R&D) at national and international level for the progress of Humanity. Governments-Academia-Industry constitute the key triangle for such development.

But some change is inevitable. It is not a binary 'on/off' or '0/1' problem. The questions are 'How much?' and 'To what depth?'

What this means is that the first university degree, though strong in fundamentals and depositing the seeds for research, will have to be directed to the more basic and practical requirements of industry and of the society, leaving to the second degree the effort for growing and developing new concepts, with formal courses, with compulsory and elective subjects, for a longer research oriented horizon, as in a crystallisation process where crystals grow from the seeds supplied at the moment of the right supersaturation.

One (or two) of the questions that should be addressed by those who have the responsibility of (re-)designing a course in chemical engineering is –

- What is it that the young engineer is going to find in the practice and what skills and competencies does the practice expect from a young engineer?

At this point I would like to re-visit two thoughts written with about 40 years of distance between each other:

- The words of A.B. Newman, in 1938, President of AIChE at the time who commented in one of his published speeches that theoretical descriptions should be limited to illustrate the engineering fundamentals, because a manager does not hire a young engineer just because he is able to describe how a product is produced. This was in 1938.
- The words of Ralph Landau (1977) from Stanford University who wrote 'I believe chemical engineering's third paradigm, if there is one, is to return the discipline closer to the practices in industry.

It is thoughts like those that make clear to me that *Human History is really a sine wave.*

2.2 International co-operation, cultural interchanges

These all are inter-related subjects. At the present moment European programmes and very active discussion groups are undoubtedly catalysing discussion on Education and promoting interchanging of both students and staff.

Besides well known exchange programmes such as ERASMUS/SOCRATES, the activity of the Working Party on Education (WPE) of the European Federation of Chemical Engineering (EFCE) deserves special mention.

The WPE has been devoting efforts over the past 10 years to develop ideas and proposals concerning as relevant subjects as curriculum survey, programmes of work of biochemical engineering education, chemical engineering teaching and learning, sustainable technology and continuing education. The essential of such effort is summarised in a recent paper by John Gillett (2001) Chairman of the WP up to June 2001.

The potential of using web-site technology for the purpose of disseminating and interchanging information has not been forgotten. It can be announced that on the European conference that took place in Nuremberg, on June 225, 2001, the Web-site of the Working Party on Education in Chemical Engineering was formally declared opened, with the URL:

http://www.dechema.de/efce/education/eduframe.htm

This homepage has been designed to become a link between everybody who is interested in education in chemical engineering in Europe or who wants to get latest information on the topic. It is offering a lot of useful information (studies, surveys, papers, useful links) as well as links to education homepages of all the 21 countries participating (at the moment) in the WPE.

Portugal is in this group of Countries, represented through delegates nominated by the Institution of Engineers and linked to this web-site through a national node coordinated at executive level by Dr. Eugenio Ferreira (U. Minho), Dr. Jaime Villate (FEUP), together with the author of these lines. The main objective is to develop in the near future fruitful exchange of information and teaching tools. All departments responsible for chemical engineering education were invited to join this node.

The other initiative deserving mention is the attempt currently in progress of forming an European Chemical Engineering Network, including at present 26 founder members (including the Faculty of Engineering, Porto), which aims mainly at establishing an interactive forum between Industry and Academia concerning training needs, staff exchanges, student internships in industry, all actions directed to increase student exchange or better saying training periods in industry, in the European space.

This type of actions and efforts will significantly influence and model, if successful, the teaching of chemical engineering for the years to come, beyond 2020…

Just to mention the world dimension of this line of international co-operation: Shallcross et al. (2000) describe a most interesting experiment carried out by Melbourne University within the UNIVERSITAS group (18 Universities) where students get their degrees after studying for two periods of one year in two other countries. Cultural interchanges (together with learning not teaching) represent the essential or the core of the 3rd paradigm for these authors.

The World is indeed becoming smaller and smaller.

2.3 Skills, personal career development and lifelong learning

These are major questions to be answered for suitable developments for the next decades.

It should be clear to a young engineer, and he/she should be trained accordingly, that at the end of the day it is up to each individual to manage his/her career by careful planning, with the advice that they find desirable, which expectedly should be available. Advice that can take the form of specialisation courses and more and more aids for self-learning.

Contractors and employers do not so much at present provide opportunity for specialist training, expecting that the young engineer they hire will have technical sufficient background. This happens a bit all over Europe. What distinguishes the Countries and Companies is the intensity of the phenomena…the consequence is that some are richer and more developed, some are less rich and less developed…

Companies value nowadays competencies and skills that are not limited to the technical areas. Indeed, Companies more easily provide opportunities for developing those other skills and competencies that are of the short-term benefit of their organisations.

The question of skills and career planning is best understood with a possible model of the functional structure of company in the process industries (Table 1). The unfortunate comment about the contents of this Table is that companies today are in such a process of thinning, that some of the functions described are ideal functions waiting for better days.

In close relation with the structure and based on the pharmaceutical industry Gillett (2001) has identified a global picture of skills and competencies valued by the industry. The author believes that such picture (Table 2) fits well to the process industries as a whole.

Table 1 – Functional structure of a Company, on the form of levels of internal contributions (adapted from Gillett, 2000)

Strategic perspective	**Functional contents**	**Position in the structure**
Decides future directions	Company strategy	Director/General Director
Links sectors of the global business	Business management	Departmental Director
Anticipates and manages required changes	***Innovation, R&D, liaison to process***	I&D or production group leader
Develops and makes improvements. Optimise activities	Adapts, improves process	Senior engineer or process director
Designs, performs commissioning and operates	Does.	Junior engineer

Table 2 – Some typical skills and competencies valued by industry (adapted from Gillett, 2001)

Job related skills	**Competencies (How tasks are done)**	**Technical knowledge**
Teamwork	Holistic thinking	Chemical engineering, batch processing, particle technology, SHE...
Communication	Influencing	Organic chemistry, biotechnology, microbiology...
Leadership	Self-management, people management	Systems engineering, production engineering, process control..
	Achievement of objectives	

Lifelong learning is the key for ensuring progress, not only, as it will be discussed below, because it is clear that 1st degrees for sure do not cover all relevant technical topics, but also because it is the only way to avoid obsolescence.

This reality is generally accepted in words by many, but only very slowly put into practice (and by few). What is clear is that this is the way towards the future and the number of organisations offering different forms of part-time education is clearly growing. This is even a case where offer comes before and is larger than the real demand (just as a remark because this is not the place for such discussion, we are not far from the day where accreditation of such offer will have to be a fact).

Formal courses, workshops, seminars, 'hands-on' and 'on-the-job' training are well established offer in many countries, but all over, not only in Portugal, employers are reluctant to educate staff, particularly now that employers themselves promote short-term jobs and forced mobility. Again, this is the *sine wave of history…*

No need to emphasize the revolution that also in this particular the Internet is bringing about, with distance and interactive courses, together with the increased capacity of remote control. An example of the potential of this explosive increase in communications is the paper presented in this conference by Paiva et al. (2001) on a case-study of running a lab experiment from home.

Using once again Gillett's summary paper (2001) of the work of the WPE, an overview of such offer, the providers, the potential customers, forms and models, is presented in Table 3.

Table 3 – Examples of different forms of continuing education (adapted from Gillett, 2001)

Delivery method	**Providers**	**Customers**	**Comments**
Formal courses (full-time)	Universities	Engineers between jobs Engineers in employment	e.g.: M.Sc., diplomas etc.
Formal courses (part-time)	Universities	Engineers in employment	e.g.: M.Sc., diplomas, etc.
Conferences and seminars	Professional organizations	Engineers in employment	Technology updating, etc.
Workshops	Professional organizations	Engineers between jobs Engineers in employment	Technology updating, etc.
Distance learning	Universities and Professional organizations	Engineers between jobs Engineers in employment	Technology updating, etc.
Computer-based learning	Specialist training agents		Task-oriented
In-house courses	Industrial employers	Engineers in employment	Personal skills and competencies
On-the-job training	Industrial employers	Engineers in employment	Task-oriented
Private study	Professional organizations	All engineers	Personal careers plans

2.4 Teaching chemical engineering – what, what depth, when, how, what teaching aids

So, we come now to a conclusion. Not all topics will be answered. Namely*, when* is to a large extent a matter of experience?

The work of the Working Party Education surveying and analysing different European curricula deserves attention (full report is available on the WPE web-site).

It was confined to higher education engineering studies (i.e. those whose diplomas give access to the preparation of a Doctorate), but went beyond the different profiles, teaching methods, and historical development of the chemical engineering schools surveyed.

A major (expected) observation was the diversity of the curricula surveyed, which led (and leads) to think that attempts should not be made to draw accurate objective figures on the scope of courses according to their content.

Independently of questions of European accreditation, which may be eventually raised in our rapidly expanding European Space, the fact is that it seems clear that no core curriculum should be imposed (by what authority?) on existing programmes, but guidelines coming out of a consensus should serve for countries seeking to develop their training programmes.

The following general guidelines seem to deserve consensus:

- A reasonable degree of diversity in chemical education is desirable. *To take advantage of this diversity, student and educational staff exchanges between countries and cultures should be encouraged.*

- It is important that sufficient practical experience, both in the laboratory, pilot plant and industry should be included in the core curriculum
- It is important to keep a database, at European level, that provide (to Industry) coherent and regularly updated information on the extremely wide range of curricula available.

2.4.1 A general structure for a curriculum

It is not for this work to detail numbers and percentages, just general lines.

As a basis of work, curricula can be divided into four major parts, not in the usual three:

- Basic Science
- Engineering Core
- Complementary disciplines (compulsory or electives)
- External training

The basic science part is a pre-requisite for the engineering core topics, but will also have a content of a general nature as well as topics needed for further studies. It should naturally include Mathematics, Informatics, Chemistry and Physics, with 'hands-on' laboratory experience on all of them, using without complex computer tools as aids to mathematics.

The engineering core comprises the topics that should be common to all chemical engineers, and thereby be a major part of their professional distinction: Thermodynamics/Physical chemistry; Fluid Mechanics/Transport Phenomena; Chemical Reaction Engineering and Separation Processes; concepts of Unit Operations; Plant Design *(including Safety, Health and Environment, Economics, Law, etc.)*; Equipment/Materials; Process Dynamics and Control; Computer-aided process operation; Chemical Engineering Laboratory.

Complementary subjects either are related to a well defined direction of studies, which a department may wish to implement, decided for whatever strategic reason, in which case disciplines are compulsory, **or** they just represent an offer of more in-depth studies in specialty fields, in which case disciplines are elective. Most advisable is that, compulsory or elective, all include a thorough application of mathematics and scientific principles to engineering problems. And, as topics come to the end of the first degree, increasingly quality and ethics should be embedded in the teaching.

One discipline of the final semester should or could be devoted to topics representing the future. Novelties like trends in process design (Keller and Bryan, 2000), process intensification (Stankiewicz and Moulijn, 2000), micro-reaction engineering (Jensen, 2001), miniaturization (Cefai, 2000) or process information (Edgar, 2000b).

The list of complementary subjects is immense, but possibly five of them can be picked up for a brief comment. They are product engineering, process systems engineering, biochemical engineering (aspects of), environment engineering (aspects of) and finally production and technology management. These represent major trends and/or also major human concerns of civilization and consequently courses should accommodate or offer compulsory or elective profiles.

Much has already been said about the period of **external training**, be it company work in an European or American country or research in a reputed laboratory, of the expectations of gains in exchanging cultural views on many aspects of life, including methods of work.

2.4.2 Sustainability and holistic thinking

I would like to think that in general terms there is now a true and deep global concern, both in the scientific and the industrial society, for the environment and for the problems of overpopulation and industrialisation. So, this need for developing sustainable technology and for sustainability as an attitude has now become an active premise of work for chemical engineers.

The contribution of chemical engineers towards this problem, beyond their contribution as citizens, is essentially in using their knowledge, in using chemical engineering science to provide comprehensive solutions.

Holistic thinking and holistic approach to problem solving, specifically to design, is not just important for sustainability, but such attitude more than anything else comes as the contribution of chemical engineers and consequently should be considered as a very distinct characteristic to be embedded in the teaching and learning of this area.

Further to this line of thinking, sustainability can also be taught and learned indirectly through increasing knowledge on environmental problems, on biochemistry, on life cycle analysis and as well on economics, just to mention a few subjects. For the same purpose case studies can be offered within formal disciplines.

2.4.3 Integrating knowledge, strengthening horizontal issues, practical training, teaching aids

It all comes to the same, to bring students nearer to the practice of chemical engineering, to promote integrated approaches, to exchange cultures.

Starting by the end, the availability of teaching aids, namely computer-based is now impressive. The Internet and this Human quality or characteristic of wishing that one's work is useful and recognised, together with the business-motivated initiatives, lead to this extraordinary number of aids available, several free of charge, for basically all topics and disciplines.

Also, at laboratory level, the number of small pilot-rigs with high level of educational features, makes it possible to increase engineering practice.

Much can be done through the appropriate choice of case studies and of practical pilot plant work. Two or three illustrative comments:

- Providing case studies to integrate knowledge

  The operation of complex process units (in steady-state) can be optimised through methods of process systems engineering (strategy of process operation), leading students to learn of constraints and inter-relations between units within a production sector.

- Strength horizontal subjects

  Case studies involving batch or fed-batch process operation, allow discussing again inter-relations, now together with process control and safety procedures.

- Pilot cases related to the practice

Co-operation programmes with industry would allow the construction and operation of suitable pilot units related to real industrial problems with all the advantages of experimental work.

3. Conclusion

Third paradigm?

Yes, clearly I think so. There are not yet enough documents to make this shift of mindset completely clear or as clear as what we have discussed about Unit Operations and Chemical Engineering Science. For sure that in 2020 things will be quite transparent.

Fuzzy as the shape may still be we recognize a number of major lines of reference:

Our individual and local universe is larger and larger.

Time and space concepts and dimensions have changed dramatically.

The reference of whatever (quality, competition, etc.) is now Europe and the World, not our City or our Country.

Standards must be high, inflexibly high, attitude holistic, mind flexible.

The Chemical Engineering discipline on its own merits, much due to life during the 2^{nd} paradigm, has enlarged significantly its universe of influence.

The need is clear for international recognition of standards in chemical engineering education. A core group of disciplines, concerning basics and engineering, and of skills and competencies, should be recognized by consensus and implemented. It will happen long before 2020.

External training, more practical 'hands-on' training is required for first-degree level. If possible in another Country. There must be an understanding that it is essential that Academia and Industry, in the European Space, co-operate offering each other aided-value, by accepting students for training (the Industry), by jointly designing pilot case studies, by providing theoretical background through courses (the Academia).

New subject areas must be made available for chemical engineering education, be it as electives or in post-degree education. Systems engineering, biochemical and environment engineering represent major requirements or demand from Society. Management is a need that young engineers will feel they will need to fill in their education.

Lifelong learning through the Internet (or whatever substitutes it in 2020…) is the key concept to have the edge.

Acknowledgment

This paper is dedicated to Professor Rodrigo Guedes de Carvalho for what he taught me of chemical engineering, of quality, of organisation and of discipline of work. The first section of the paper is significantly inspired on his remarkable contribution to the History of Chemical Engineering Education at the University of Porto (1998).

Also, the author would like to acknowledge the brilliant work developed by Dr. John Gillett, Chairman of the WPE of the European Federation of Chemical Engineering, mainly through his personal views and through his many summary reports and papers, which so important were for the present work.

Notation

CEE – Chemical Engineering Education

CES – Chemical Engineering Science

EFCE – European Federation of Chemical Engineering

WPE – Working Party on Education

References

Bird, R.B., W.E. Stewart and E.N. Lightfoot (1960), *Transport Phenomena*, J. Wiley, N.Y USA.

Cefai, J. (2000), *Complexity and Miniaturization – taking chemical analysis*, LC•GC Europe, October 2000, 752-764.

Coulson, J.M. and J.F. Richardson (1st. Edition, 1954) *Chemical Engineering* (6 volumes), Pergamon Press, Oxford, U.K.

Drinkenburg, B. (2001), *New Ways to Educate our Chemical Engineers*, Proc. of ECCE-3, 3rd European Congress of Chemical Engineering, paper 4.4 (CD-ROM), Nuremberg, 26-28 June.

Edgar, T.F. (2000a), *Chemical Engineering Education and the Three C's: Computing, Communication and Collaboration*, AIChE Annual Meeting, , Los Angeles, 12-17 November, (in www.che.utexas.edu/cache/newsletters/fall2000_chemengedu.pdf)

Edgar, T.F. (2000b), *Process Information: Achieving a Unified View*, Chem. Eng. Progress. Jan. 51-57.

Foust, A.S., L.A. Wenzel, C.W. Clump, L. Maus and L.B. Andersen (1960), *Principles of Unit Operations*, Wiley Int. Ed., N.Y., USA

Gillett, J.E. (2000), *The Education of Chemical Engineers in the Third Millennium*, Plenary Lecture, Paper A5.0, CHISA 2000, Prague 27 July -3 August.

Gillett, J.E. (2001), *Chemical Engineering Education in the Next Century*, Chem. Eng. Tech. 24(6) 561-570.

Guedes de Carvalho, R. (1998) História do Ensino da Engenharia Química na Universidade do Porto (1762-1995), FEUP^Edições, Porto, Portugal

Hougen, O.A. (1977), *Seven Decades of Chemical Engineering*, Chem. Eng. Progress 73 (1), 89-104.

Jensen, K.L. (2001), Microreaction Engineering – is small better?, Chem Eng Sci 56 293-303.

Keller, G.E. and P.F. Bryan, (2000) *Process Engineering: moving in new directions*, Chem. Eng. Progress, 96 (1), 41-50.

Landau, R. (1997) *Education: moving from Chemistry to Chemical Engineering*, Chem. Eng. Progress, 93 (1), 52-65

Paiva, P., S. Feyo de Azevedo, A. Mendes and F.D. Magalhães (2001) *Running a Lab Experiment from Home: remote liquid level feedback control,* in CHEMPOR 2001, Aveiro, Portugal, 12-14 September.

Peres, J., R. Oliveira, S. Feyo de Azevedo (2001) Knowledge based modular networks for process modelling and control, Computers & Chemical Engineering, 25, 783-791.

Rudd, D.F. and C.C. Watson (1968) Strategy of Process Engineering, J. Wiley & Sons, N.Y., USA

Silverberg, P. and G. Ondrey (2000), *Chemical Engineering Seeks a New Identity,* Chem. Engineering, 33-37, August.

Shallcross, D.C., J.L. Gravina and D.G. Wood (2000) Chemical Engineering Education – can a 10-year old experiment provide the real paradigm shift for the future), CHISA 2000, 27-31 August 2000, Praha, paper in CD-ROM.

Shreve, R.N. and J.A. Brink Jr. (1956, 1977) Chemical process Industries, McGraw-Hill, N.Y., USA.

Stankiewicz, A. and J.A. Mouljíjn (2000) *Process Intensification: transforming Chemical Engineering*, Chem. Eng. Progress, 96 (1), 22-34.

Walker, W.H., W.K. Lewis and W.H. McAdams (1923) *Principles of Chemical Engineering*, McGraw-Hill, N.Y., USA.

Wei, J. (1996), *A Century of Changing Paradigms in Chemical Engineering*, ChemTech 26 (5), 16-18.

Wilhelm, R.H. (1962) *Progress Towards the A Priori Design of Chemical Reactors*, J. Pure Appl. Chem., 5 403