Sustainability of the Chemical Manufacturing Industry – Towards a New Paradigm?

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Abstract

This paper describes the current situation of the chemical manufacturing industry, with special reference to Europe and looks to the future sustainability demands on the sector, and the implications of these demands for chemical engineering education. These implications include definitions of sustainability criteria for the sector and the need for transparent reporting under the Triple Bottom Line approach. The response of the education system to the sustainability agenda over the years and a number of strategies to incorporate it into courses are described. The important role of chemical (or more generally, process) engineers in delivering sustainable solutions is emphasised but this also suggests that a new way of thinking about the discipline is required. Indeed, this paper argues that the demand for a sustainable chemical manufacturing sector could bring about the next paradigm shift in the discipline which has been predicted for some time.

1. Introduction

The chemical manufacturing industry (CMI) is a multinational, varied scale sector producing the products which underpin other sectors such as: health; clothing; housing and shelter; food and nutrition; entertainment and leisure; transport and tourism – the very fabric of human life. The products of the chemical industry are derived from inorganic, synthetic organic and biological sources which have been manipulated by a range of process operations. These include classical physico-chemical processes such as synthesis, distillation, precipitation, filtration, solvent extraction and crystallisation techniques which have been supplemented by fermentation, the application of industrial enzymes and the genetic manipulation of microorganisms in modern biotechnology. These technologies have made a myriad of products available to promote social development and economic growth and prosperity. At the same time the chemical industry has been accused of overexploitation of natural resources; air, water and land pollution (such as by oil production in the Niger River delta, copper mining on Bougainville Island and mercury poisoning from fish caught in Minimata Bay, Japan) and creating social problems associated with rapid industrialisation and the invasion of vulnerable societies and environments for commercial gain (witness the toxic release from the Union Carbide plant in Bhopal, India in 1984). Successive, "Industrial Revolutions", have taken place starting from Europe, North America and then into Latin America, Asia and Africa where the ills of industrialisation were ignored initially, as the price to pay for progress although eventually the development of organised labour and government structures have improved the situation in many cases. Whilst accepting this historical context (Coley and Wilmot, 2000) the future development of the CMI must nowadays be viewed in the light of the concept of sustainable development (Garcia-Serna *et al.*, 2007).

This paper will describe the unsustainable nature of the CMI (in Europe as an example) including the criteria by which it is judged and how sustainability is reported by the industry.

It will then investigate the educational needs for chemical engineers in a sustainable CMI and finally go on to discuss whether the sustainable approach will demand a new paradigm for the industry.

The advent of the concept of sustainability can be traced back in modern times to the 1970's but the UN Commission on Environment and Development (the so-called Brundtland Report) in the 1980's was a major point in defining the topic (World Commission on Environment and Development, 1987). Their oft-used report definition of sustainable development is, **"Development which meets the needs of the present without compromising the ability of future generations to meet their needs"**. It should be noted that the Commission was originally instructed to investigate the issues of global inequality, resource distribution and global population impacts and recommend solutions to these issues. The report linked economic development with social and environmental concerns for the first time and a balance of economics, social justice and environmental protection was proposed if sustainable development was to happen. This became known as the Triple Bottom Line (TBL) and has been embraced by business and commerce to legitimise their activities in the eyes of the general public, government and environmental watchdogs. The concept of Corporate Social Responsibility (CSR) has been developed to allow businesses to measure and promote their impact on the three pillars of the TBL. There is of course some scepticism over the sincerity, practicality and even the legitimacy of this approach given the wide spectrum of business scale, operating styles, cultural attitudes and the strength of national governments to monitor and enforce a TBL model. The Brundtland Commission was the starting point for the many UN-sponsored events and initiatives such as the Rio Summit in 1992 on environment and development and the Kyoto Protocol (1997) on greenhouse gas emissions and onwards up to the recent COP 15 meeting in Copenhagen in 2009.

Early implementation of these ideas in industry linked long-term sustainability with competitiveness where obvious links existed between, say, energy efficiency and savings which would benefit the traditional bottom line and the TBL (Florida, 1996, Judge and Douglas, 1998). Other studies have linked sustainability with organisational capability leading to increased competitiveness (Aragon-Correa and Sharma, 2003) and the promotion of sustainability into corporate strategy (McGhee, 1998). More recently there has been the introduction of sustainability considerations at the operational level which would assess the viability of new projects, the introduction of new technology and even overall company structure against the background of sustainability (Labuschange *et al*., 2005).

However, as mentioned above the CMI is a very varied sector covering a range of raw materials and processing operations; different scales and global impact of operation and differing environmental impacts as a consequence of its activities. As a result we should ask ourselves: is there a coherent approach to sustainability in the sector and are the current chemical engineers being educated in sustainability appropriate to the needs of a sustainable industry? Batterham (2006) argued that chemical engineers would be able to play a significant role in achieving sustainability goals. This recognises their understanding of the molecular and micro levels and integration of these levels into macro level systems together with their abilities in systems analysis, modelling and process balances. Furthermore, addressing these different levels would also make process engineering practice assess the sustainability agenda as a whole which could be reflected in a paradigm shift for the sector – chemical engineers must change the way they practice and embrace sustainability concepts and implement them. Garcia-Serna *et al.* (2007) give a broad review of the philosophies, disciplines and technologies which have been brought together to apply sustainability to chemical (process) engineering and which have been labelled, “Green Engineering”. They also recognised that the education of chemical engineers in green engineering was crucial in making the shift to a sustainable future and that sustainability concepts should be included from the very start of courses, rather than being seen as an add-on after other major concepts such as design have been introduced. If green engineering is to be considered at all levels (molecular, micro- and macro-) it should be included from the early stages of the educational programme. Graedel and Allenby (2009) suggest that green engineering is a move towards a more responsible technology but does not ask how the social and environmental aspects of sustainability can be incorporated into the engineering profession – it is thus a subset of sustainable engineering.

2. Sustainability criteria

In order to establish the sustainability of the CMI it is necessary to determine the criteria by which it is judged. These criteria might be the same as for any other sector in most cases but could (or rather should) include those peculiar to the chemical industry. Furthermore it is necessary to apply methodologies which allow measurement of the industry impacts on the environment and the effectiveness of sustainability policies when applied. Such techniques already exist and include Life Cycle Assessment (LCA), Carbon Footprinting (CF) and Supply Chain analysis. In an LCA the conventional Environmental Impact Analysis (EIA) categories are: global warming (expressed as carbon dioxide equivalents); acidification (expressed as sulphur dioxide equivalents); eutrophication (expressed as nitrate equivalents); ozone depletion, land use (expressed in square metres or hectares) and photochemical smog (expressed in ethane equivalents). These categories will work very well for an LCA for the chemical industry as they reflect the importance of emissions and their impact on the environment. However there may be a need to extend the range of EIA categories to reflect better the impact of the industry through human and eco-toxicology for example. Other categories could reflect the social impact of the CMI, either, directly on workers in the industry, on the surrounding community and even (inter)nationally. Such categories might be more difficult to define but will allow the LCA approach to reflect all aspects of the TBL rather than just the environmental (see Table 1). One attempt to achieve such reporting is the Global Reporting Initiative (GRI) which has developed sustainability reporting guidelines to encompass the three areas of the TBL – the current guidelines are the third generation (G3) and still subject to scrutiny and change. Starting from a number of common principles the reporting framework (based on the G3 guidelines) includes specific sector supplements to reflect unique sectoral issues and community impacts. It is also developing supply chain sustainability issues through a Global Action Network (GAN) project (Global Reporting Initiative, 2010).

A fundamental question raised earlier is whether there can be a coherent approach to sustainability in the CMI sector and, if not, is this important? The development of a standardised set of sustainability criteria would have benefits such as:

- making realistic comparisons between companies and different sub-sectors
- ensuring robust methodologies of assessment through application in a variety of settings
- making knowledge transfer from industry-to-industry or academia-to-industry easier
- establishing a common language of sustainability to be used in negotiations and enforcement of (inter)nationally agreed treaties and protocols
- giving legitimacy to CSR and make communication with the lay public more transparent
- reducing the cost of producing LCA through economies of scale and standardisation of inputs with IT-based support.

At the same time the different scale of operation and range of processes and products within the CMI sector militates against a rigid approach and some sub-sectors face specific sustainability issues which must be addressed in a unique manner, as mentioned above in relation to the GRI sector supplements. For example, whilst everyone would agree that all products must comply with health and safety criteria in their use the demands on the pharmaceutical industry are greater than on the consumer goods industry which would be greater than on speciality and base chemicals which are more divorced from the consumer. The industry response to these demands must affect the sustainability of that sub-sector and hence the LCA criteria applied to it should reflect this.

Finally, it should be noted that the concept of the Social Life Cycle Assessment (S-LCA) has been developed recently to complement the (traditional) environmental LCA (E-LCA now?) and life cycle costing and in doing so give a fuller assessment of the sustainability of goods and services (Benoit *et al*,. 2010). Guidelines for the S-LCA of processes and products have been drawn up (Benoit and Mazijn, 2009) putting the process into the context of E-LCA and life cycle costing. It can be anticipated that there will be an explosion of interest in this third sphere of the sustainability relationship which will be applied across all process/product sectors. An important goal for the S-LCA has been proclaimed as the improvement of the social conditions of stakeholders in the process/product covered by the S-LCA (Jorgensen *et al*., 2010). Stakeholders have been defined as: workers, consumers, the local community and society at large and it is obvious that the S-LCA could become a useful tool to promote the activities of the CMI or a stick to beat it. Nevertheless, it will become incumbent on the CMI to get to grips with these new assessments of its activities.

3. Chemical Manufacturing Industry sectors

This section will concentrate on the CMI in the European region, specifically the European Union of 27 countries (EU-27), which serves as a good general model because all the major sub-sectors are represented and the industry is substantial, well regulated, documented and its activities reported upon regularly (CEFIC, 2009). The availability of accurate information is essential to make informed assessments and introducing new impact criteria for inclusion in the LCA. The following data for the EU-27 illustrates some of the issues which the chemical engineers of the future must grapple.

In 2007 the EU-27 countries provided 29.5% of world chemical sales (total value Euro 1820 billion) second only to the Asian contribution (excluding Japan) at 30.4%. The value of the Asian contribution had increased from 17.0% in 1997 which probably reflects the emergence of China and India in particular and suggests that efforts to deliver a sustainable CMI must include these countries sooner rather than later. Within the EU-27, eight countries dominate (88.3% of CMI sales) with Germany the lead at 25.3% followed by France, Italy, GB, Netherlands, Spain, Belgium and Ireland. The twelve newly joined countries of Central Europe contribute little by these criteria at present. The EU dominates world trade in chemicals (54% of exports and 46.9% of imports) which includes a vigorous trade within the EU itself. Table 2 gives a sectoral breakdown of the EU chemicals sales which emphasises the value of the subsectors; however, this does not always reflect volumes of production. Base chemicals tend to be large volume-lower value compared with speciality chemicals which are low volume-higher value. The chemical and pharmaceutical industries also generate the highest value-added per employee of all the manufacturing sectors. Twelve of the top thirty major chemical companies in the world, such as BASF and Shell, are based in the EU; but 96% of CMI enterprises in the EU employ less than 250 employees. The other 4% are large companies which generate 72% of total chemical sales, again emphasising the variety of scale within the sector. This variety might preclude an all-encompassing approach to sustainability initiatives to the sector with a more focussed approach being favoured. Compared with the Asia region in particular the current and projected rate of growth for the CMI in Europe is sluggish and well behind that of Asia and Latin America (but similar to the

North America rate of growth). The effect of a slow growth rate allied to the general world recession on sustainability is unknown but may allow a breathing space in which sustainable practices can be assessed and applied to the benefit of the sector. Research and Investment in the sector is high but is directed at new products and it is not clear how much goes into developing new sustainable processing technologies directly and how much is directed to new process development with a sustainability outcome. A consideration of sustainability when introducing new technology is becoming more prevalent as noted earlier (Labuschange *et al*., 2005) but does not appear to be reported as such in CMI statistics.

The energy profile for the CMI sector could give some clues in this area. The CMI uses oil, gas and renewable sources for fuel and power but also as the raw materials for its processes to a greater or lesser extent; for example the petrochemical industry uses oil mainly as a feedstock (90%). Overall, 60% of energy is locked up in final products which is lost unless recovery is done where possible. This could involve recycling or reuse of the product or conversion to energy by incineration or other energy-generating technology. The contribution of renewable energy sources purely for fuel and power has been very low. Since 1990 the energy intensity of products has decreased by about 4.6% annually, such that in 2006 it was 53% lower than in 1990 which means that as CMI output has increased (however slowly in recent years) the energy input has remained more or less constant. This follows the laws of diminishing returns as each year’s energy savings reduces the savings which can be made in subsequent years (within the context of a given technology platform or paradigm).

A clear measure of CMI sustainability practices is given by greenhouse gas emissions (GHG) for the period 1990-2006. Whilst production has increased (by 67%) and energy consumption has been pretty constant as mentioned above the GHG fell by 32% largely through the adoption of cleaner production technology, waste recycling and the adoption of new processes based on biotechnology catalysts and membrane technology. The GHG per unit of energy consumption or per unit of production follow these trends, down 31% and 60% respectively. These reductions are far better than those achieved in the USA over the same time - GHG per unit of production down 36%. These numbers do not reflect contributions by the CMI sector to cutting GHG through products and processes applied elsewhere by the users of its products. Once again, the application of a supply chain approach (including an LCA) would allow this and other environmental benefits to be recognised more widely. Over 53% of the EU CMI output supplies other industrial sectors such as: agriculture, automotive, construction, paper/printing and textiles/clothing so there should be a hidden but substantial sustainability contribution there which should be measured and celebrated. This brief survey of the CMI in Europe suggests that sustainability is a substantial issue and the ability of the chemical engineer to connect with it also becomes crucial.

4. Sustainability Education for Chemical Engineers

In addition to recognising a range of methods of reporting sustainability in the CMI there is a need to ensure that the new generation of chemical engineers recognises the importance of sustainability in general, to the sector in particular and how to apply such principles in all aspects of process design. Batterham (2006) has already been cited previously as saying that chemical engineers have much to offer in achieving sustainability goals through the very nature of their education, skills and outlook. Garcia-Serna *et al.* (2007) proposed that sustainability should be introduced early on and so permeate all the other major teaching elements which make up a chemical engineering course. However, the typical undergraduate programme in chemical engineering is already full of intellectually-demanding content from the basic sciences such as Mathematics, Physics and Chemistry to core engineering subjects like Thermodynamics, Fluid Mechanics. Reaction Engineering and

Process Control together with electives such as Biotechnology (see Table 3). How should sustainability be incorporated into this curriculum and at what level?

Mitchell (2000) described the concept of sustainability along the traditional lines of the TBL and turned this interpretation into one consistent with an engineering viewpoint as initially proposed by Clift (1998) who introduced micro/macro-thermodynamics, techno-centricity and micro/macro-economics into the three spheres of influence of the TBL (see Table 4). Clift associated micro thermodynamics and micro economics with the techno-centric sphere (familiar to engineers); macro thermodynamics with the eco-centric sphere and macro economics with the social sphere. Mitchell then went on to propose a concentric model of sustainability with the techno-centric aspect surrounded by socio-centric and eco-centric considerations which emphasises the need for engineers to recognise and work within these constraints. Such a view was essential for a sustainable CMI and represented a paradigm shift in engineering and engineering education. Evidence for such a change was provided by various reports and communiqués in the late 1990's and recognition that practicing engineers needed not only technical expertise but also a set of broader social skills. This need was said to be recognised by the Institution of Engineers, Australia (IEAust) and the Accreditation Board of Engineering and Technology (ABET in the USA) but not so, at that time, by the Institution of Chemical Engineers (IChemE) in the UK – as an example of a major European professional group (Mitchell, 2000).

The American Chemistry Society (ACS) delivered a public policy statement on sustainability and the, "chemical enterprise", which consists of all the industry, trade associations and educational and professional organisations underpinning the sector suggesting that they had a role to play in sustainable development (ACS, 2008). The document identified eight areas of importance for a sustainable chemical enterprise:

- green sustainable chemistry
- LCA
- toxicology
- renewable feedstocks
- renewable fuels
- energy intensification of processing
- separation, sequestration and use of carbon dioxide
- sustainability education.

In addition, the non-technical barriers to a sustainable CMI were recognised (Satterfield *et al*., 2009):

- develop working definitions and practical metrics to measure progress towards sustainability
- quantify the true cost of products to promote sustainable options
- promote cross-functional and multi-disciplinary communication
- support continuous improvement through forward thinking, collaborative, goal-orientated, non-technology specific regulations and/or incentives which could be adapted as sustainable technology evolves
- incorporate sustainability principles at all levels of education.

The report then went on to recommend various support tools to achieve these aims. Later work by the Harvard-Yale-ACS-GCI Green chemistry project (Matus *et al*., 2007) delved deeply into the challenges facing green chemistry and recognised the following barriers to implementation:

- economic and financial
- regulatory

- technical
- organisational
- cultural
- definition and metrics.

Each of these barriers covered a range of objections; for example, included under the regulatory barrier was the possible cost of recertification of processes by the US FDA (Food and Drugs Administration) when changes were made to already accepted processes in the name of sustainability. Under cultural barriers were a lack of awareness in both the chemistry community and the general public and common misconceptions that green chemistry products were more expensive, less effective and not based on rigorous science. Some possible solutions to these barriers were mooted, such as: creating incentives for development/implementation of innovation; facilitating linkages and networks to spread the word on green chemistry; increase research activity in green chemistry and to raise the profile of positive environmental/health impacts rather than taking a defensive approach. Finally, there needed to be a national framework for green chemistry policy which should reach out beyond the USA, particularly to the emerging chemical enterprise in China and India. Thus, the chemical enterprise is taking cognisance of green chemistry and it falls to the process engineering fraternity to do likewise and deliver a CMI that reflects the current paradigm shift in the discipline.

Favre *et al* (2008) argued that chemical engineering has always evolved under the twin pressures of science and industry and the introduction of the concepts of unit operations (1915) and transport phenomena (1960) have been accepted as the two previous great paradigm shifts in the discipline. There has also been a change in curriculum from initial descriptive courses to the introduction of hard science, new tools such as computer simulation and new areas of application, for example biotechnology. Chemical engineers are also becoming focussed on product performance (what they do rather than on what they are) under the umbrella title, “product technology”, or, “chemical product engineering”, with an emphasis on speciality chemicals as opposed to commodity (bulk) materials and this has brought a wider range of molecules to their attention (Cussler *et al*., 2002, Hill, 2009). The time taken to teach all the required aspects of chemical engineering has lead to the modern degree with a curriculum as described in Table 3. Other aspects of a university degree have always been prominent in chemical engineering education such as problem solving and the modern chemical engineer with good mathematical ability and literacy, combined with the ability to communicate with those from a range of disciplines, can find employment in areas far removed from the CMI. The issue of how to fit sustainability into this crowded timetable offers a range of options (Favre *et al*., 2008):

- no change in the curriculum as it fits the bill already and has proved to do so despite significant changes in the industry
- overhaul the curriculum to become a, “curriculum for the future”, (Armstrong, 2006)
- adapt the current curriculum to meet the new challenges of sustainability and the needs of green chemistry (McDonough *et al*., 2003).

The most recent exercise to establish how sustainability, in the broadest sense, is being incorporated in to chemical engineering education was conducted in the USA (Allen *et al*., 2009). The study covered 366 engineering colleges and 327 staff active in sustainability teaching who were canvassed on all aspects of their teaching in this area. They described 155 courses covering all the engineering disciplines including civil, environmental, mechanical and systems engineering and also chemical, bio and materials engineering (18 courses).

Four main strategies for incorporating sustainable engineering into engineering curricula were discerned:

- **dedicated** sustainable engineering courses in any of the major disciplines. About 48% of the courses described come under this heading.
- **integrate** sustainable engineering concepts into existing courses to raise awareness of students (23% of courses)
- **focus** on technologies which will be important in sustainable engineering (14% of courses)
- **mixed** teaching strategy and some interdisciplinary courses with non-engineering departments (15% of courses).

Whatever strategy is used sustainable engineering is usually presented as a stand-alone course and offered to high-level students. Some of the issues concerning the chemical product engineering-driven chemical engineering teaching mentioned above also relate to sustainability recognising that a well designed product will be environmentally, economically and socially acceptable. The teaching of sustainability methodologies and tools was determined by the extent of integration of sustainability into a chemical engineering course. For example, Evans *et al*, (2008) described the use of quantitative life cycle analysis in a first year chemical engineering course which built on the traditional skills of material and energy balances and modelling but in doing so introduced sustainability concepts. On the other hand, Harris and Briscoe-Andrews (2008) described an elective in green engineering which was offered to final year students and based on problem solving which also served to introduce the students to engineering in the real world.

Allenby *et al*, (2009) reflected on the conceptual challenge of sustainable engineering and the educational conflict between teaching the topic as a speciality or as a component of other engineering disciplines. They commented on the social dimensions of sustainability which are less quantifiable and more normative and subjective than the typical material taught in engineering courses and which teachers were less comfortable teaching. They concluded that, in the USA, there was a split between those that integrated sustainability into existing courses and those that offered dedicated courses sustainable engineering courses.

The issue with **dedicated** undergraduate sustainable engineering courses is that they might only attract those students for whom the very idea of sustainability is vitally important whilst deterring the generalist student who wants to be an engineer but not follow a specialist course at this level. A standard engineering degree in any subject area, including sustainability elements, followed by specialisation at post-graduate level might be a better way to attract good capable engineers into the area of sustainability. Another argument says that all engineers should be aware of sustainability, hence the need for **integrated** courses but a limited number need to be specialists – hence the need for post-graduate courses in sustainability (with proper **focus**). As mentioned above the current chemical engineering degree course is full of intellectually-demanding material which is taught through a problem solving/design format combined with practical classes and students finding their way through this challenge become well-rounded individuals capable of tackling the wide sustainability agenda at this time. In this case the **mixed** teaching strategy would come to the fore but this leads the education debate into the realms of the disciplinarity of sustainable development.

5. Cross-, multi- or non-disciplinarity?

The by-word for sustainability has been cross- or multidisciplinarity as demonstrated by the TBL or concentric models (Satterfield *et al*., 2009). However, within university academia the, “silo”, mentality still prevails with fierce protection of expertise or specialist knowledge and a resultant lack of understanding between the social, cultural, scientific and economic disciplines and most importantly what can be learned by one discipline from the others. There is also a fear factor in entering into another domain where the academic is not the master and their assumptions and knowledge can be questioned. But technical solutions to sustainability can only work if they have social and cultural acceptance and their economic significance is recognised - the TBL and S-LCA writ large. Academics that move from their own domain into that of others can be deeply mistrusted and treated as dilettantes at best and loose cannons at worst. Yet it is such free thinkers who can draw together the various strands of the sustainability web and recognise the interconnectivity of the subject. Another issue working against the cross- or multidisciplinary approach to sustainability, certainly in the UK education system, is early specialisation which often separates the arts and sciences in the secondary schooling system and leads the science student into ever more esoteric areas as they progress through the university system. This experience does not develop the wide-ranging broad-brush mental flexibility capable of dealing with sustainability and as a result regards it as a, “fuzzy”, or, “elusive” concept, in particular its qualitative aspects. The gulf between the, “two cultures”, of the social and physical sciences described by C P Snow (Snow, 1959) does not seem any narrower today.

The introduction of sustainability into the general educational experience for all students has been considered a major requirement to move it from its hard science confines into the broadest application – in fashion, business and law for example. In this context sustainability could be described as a non-discipline equally applicable to **all** courses in **all** disciplines **at the same time** as other aspects are being taught. This best fits with the integrated approach mentioned above for engineers but being widened to all courses and disciplines. All students need to be aware of sustainability to function as citizens in the future and make informed choices in their personal, professional and political lives and virtually all disciplines can contribute positively to this endeavour. This requires a common knowledge base and language/vocabulary such that a greater understanding of the different object worlds that prevail among disciplines can emerge (Bucciarelli, 2008) and collaborations are made on an equal footing. This is a laudable but necessary intention but simply getting the science community to work collaboratively is difficult enough without bringing in non-science disciplines. Driving the sustainability agenda into schools is a possible route to making students, "sustainability aware", on entry to university with the common language to promote dialogue between disciplines and develop the wide-ranging mentality described above and capable of addressing sustainability concepts.

The silo mentality, which mitigates against a required whole systems approach to tackling complex sustainability issues, is not an academic preserve and can also be observed in industry and government alike (Kemp et al, 2005, Curran, 2008). In industry there are sharp divides between responsibilities and as each section has its own budgetary support and outputs this militates against collaboration. Government is organised along traditional departmental and agency responsibilities and between national, regional and local levels of jurisdiction, again putting up barriers to collaboration. Development of a credo of collaboration between disciplines during their education will help people in all areas to grasp the sustainability nettle, again based on a common vocabulary, shared interest and respect.

6. The next paradigm shift

As mentioned earlier, Favre *et al* (2008) proposed that chemical (process) engineering reacts to the pressure of industry (CMI) and science and evolves accordingly. Chemical engineering education has changed subtly and incrementally over the years in parallel with these pressures and paradigm shifts have been rare and we are still awaiting a third. The advent of product technology (or chemical product engineering), the intrusion of life sciences under the banner of biotechnology and the introduction of computers in many areas of chemical engineering design and operation have not been seen as paradigm shifts but part of the evolution of the subject. Perhaps the concept of a sustainable CMI with its attendant TBL demands will usher in a paradigm shift in the discipline. Because chemical engineers already possess the skills and occupy the professional role necessary to deliver a sustainable society there is a moral and ethical duty on them to play such a role (Byrne and Fitzpatrick, 2009). The term, "paradigm", was introduced by Thomas S Kuhn (1962) in his book, "The Structure of Scientific Revolutions", and used to describe a specific view of scientific reality, and the implications that stem from it, and which is based on the knowledge available to scientists at the time. Likewise, a paradigm shift implies a complete revolution in the mindset of the scientific community based on new realities replacing accepted views.

What sweeping changes in the fundamental model of chemical engineering based on sustainability principles would bring about a situation worthy of the name paradigm shift? Here are some thoughts;

- firstly, the need to recognise that the CMI cannot rely on the traditional fossil sources of basic chemicals for manipulation and transformation into useful products and that the process operations based on these raw materials are not be sustainable.

- instead the CMI will rely on renewable raw materials based on biomass for platform chemicals, transforming them into products (currently focussed on polymers and fuels) which are described as, "bio-based", materials. This will have fundamental implications for sustainable engineering based on renewable carbon accounting leading to a carbon-neutral industry.

- to take the present state of knowledge in biotechnology to another level where engineering and biology are combined to design and synthesise novel functions and systems ranging from enzyme combinations to whole organism analogues – currently promoted under the name of synthetic biology.

- this ability to design and synthesise DNA sequences and synthetic biological systems based on them will bring a completely new view of chemical engineering (the paradigm shift) with governance, intellectual property, safety/security and ethical issues demanding a new type of engineer to deal with them.

- finally, the need to grasp the wider social dimensions of developing processes/products as proposed under the S-LCA banner which demands new skills and view points for chemical engineers.

The interaction between chemical engineering and biology has a long tradition, from the early food fermentations (brewing, wine making, baking and lactic acid fermented milks) through to the industrial processes based on microorganisms and enzyme extracts (modern biotechnology) although total reliance on renewable biological systems is a big step to take. The use of bio-based raw materials will also bring about a new relationship between the CMI and agriculture (including forestry). Agriculture inputs will need to be brought into the LCA (and carbon accounting) for industrial bio-based products to ensure that a sustainable future for them exists and their co-existence with food production must be established.

This interaction will become more intimate as the sustainable, biology-based technologies are applied under whatever name, as described above, and this will bring about the long-awaited third paradigm shift in chemical (process) engineering.

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