Evolving aspects of sustainability in a chemical engineering capstone design project

John J. Fitzpatrick, Edmond P. Byrne, Denis Ring, Aisling O'Riordan, Kate O'Sullivan and Jorge Oliveira

Department of Process & Chemical Engineering, University College Cork, Cork, Ireland.

j.fitzpatrick@ucc.ie

Abstract

The design project is a capstone activity in chemical engineering degree programmes. This is where students apply much of their prior learning to develop as a group exercise an integrated conceptual design of a processing plant. In doing this, students are required to demonstrate their ability not only in core engineering activities but to also to consider the broader implications of their designs in terms of ethical considerations, safety, health, environmental protection and more recently in the area of sustainability. For example, the latest iteration of the Institution of Chemical Engineers' (IChemE) accreditation guidelines (2012) has added that *'It is expected that modules throughout a programme include, illustrate and reinforce aspects of sustainability, safety, health, environment and, where possible ethics'*. Such evolving requirements are informed by a context which allows for increasing recognition of the criticality of sustainability and other broader societal aspects in (chemical) engineering practice as evidenced for example, by the IChemE's 'Roadmap for 21st Century Chemical Engineering' (2006).

This paper describes an exercise carried out on the four year Bachelor of Process & Chemical Engineering degree at University College Cork (UCC), Ireland which reflected on current and possible future roles of sustainability in the final year design project. Two final year student research projects were undertaken to assess the sustainability input into the current design project in UCC and to investigate how this could be progressed. Two lecturers involved in teaching the design project were surveyed to ascertain current sustainability content in the design project and their views in relation to future developments. Another two lecturers who teach modules on sustainability and environmental protection helped in survey preparation and interpretation. This led to all four lecturers coming together and sharing their ideas on embedding sustainability within the design project. The student research projects incorporated a review of two previous design projects in terms of sustainability content and made recommendations on how sustainability could be more usefully incorporated into these design projects. This paper describes the ideas and approaches that culminated from the lecturer and student activities. This included the concept of embedding sustainability thinking and activities right throughout the design project and not just as some bolt-on activity at the end.

1 Introduction

It is the responsibility of engineering educators to provide students with the knowledge and expertise necessary to make "*sustainable choices in the way products are made, both from an environmental and social point of view."* (Thakker, 2012) Educators and academies must construct a platform for students to apply their knowledge of sustainability to the chemical

industry. The chemical engineering design project is an ideal opportunity for chemical engineering students to demonstrate their knowledge of sustainability and apply this to a reality based process. The students should be exposed to various different perspectives on sustainability to help them obtain a better informed understanding of sustainability. The framing of the design brief should enable students to be innovative and consider the impact of wider process activities such as utility production, raw material extraction and transportation on the overall sustainability of the design project. The upcoming generation of chemical engineers must be educated to *"recognize and understand these interdependencies in order to design with them in mind."* (Thakker, 2012). The main challenge to overcome is how best to embed sustainability within the design project. Improvements must be made to the design project brief and content as it is essential that *"engineering education moves into the twenty first century charged with an environmental agenda."* (Hasna, 2010). Ultimately the aim of enhancing sustainability within the design project is to adequately prepare the students for challenges awaiting them in their future careers.

University College Cork (UCC) has been offering a four-year bachelor of engineering degree in Process & Chemical Engineering since 2001. In fourth year students undertake a 10 credit (ECTS) module entitled "Design Project". This is a capstone project, similar to what is taken in other chemical engineering programmes, where a group of about 5 students apply their previously gained knowledge to the design of a processing plant. One of the authors is the co-ordinator of this module and another teaches a 5 credit module entitled "Process Design and Feasibility Analysis" whose content is extensively used in the design project. Two other authors teach a third year 5 credit module entitled "Sustainability in Process Engineering", which was recently introduced three years ago and one of these authors also teaches two half 5 credit modules in Environmental Protection in third and fourth years. Both these authors have little involvement in the design project, except one who instructs the students in conducting a preliminary environmental impact assessment (EIA) and preparation of an environmental statement report for their design projects. Overall, the students receive a good grounding in sustainability and environmental protection, however it was felt that an important aspect of trying to embed sustainability within the degree programme would be to strongly embed it within the capstone design project, and consequently, this is the driving motivation behind this work and this paper. In order to explore the embedding of sustainability in the design project, the fourth year "Research Project" module was used as a vehicle to investigate this. Two final year students, who are also authors, undertook projects in this area with the overall aims of:

- Assessing the current state of sustainability incorporated within the design project at UCC.
- Making recommendations for how sustainability can be better embedded into the design project.

Two of the major steps undertaken to achieve the overall aims were to survey the two lecturers who are involved in the design project and to review two previous design projects. The outcomes from these two steps are summarised in the next two sections.

2 Lecturer Survey

The survey was conducted on the two lecturers involved in the design project module. The aim of the survey was to gain their feedback on the current incorporation of sustainability within the

project, identify possible areas for improvement and utilise their suggestions and ideas to make recommendations for improving the overall incorporation of sustainability. A questionnaire was prepared by one of the students and was then forwarded to the lecturers. The student then arranged respective meetings with the two lecturers individually in their offices and conducted the survey orally while recording their answers to each of the questions. The student later prepared a detailed summary of the recordings from each of these two meetings. The questions and a summary of the replies from the two lecturers are presented below.

What is the current content of sustainability in the U.C.C capstone design project?

The major current sustainability related content includes an economic feasibility assessment [which could be considered as micro-economic sustainability]; detailed safety analysis [which could be considered as an important aspect of social sustainability]; and a preliminary environmental impact assessment of the processing facility which is in-part assessing the environmental sustainability of the processing plant itself. Over the last two years, a new sustainability related section was introduced and this is presented in Figure 1, although it was suggested that this is not well defined and needs improvement. Furthermore, in reviewing the latest manual for the design project module given to the students by the co-ordinator, it was noted that there was an emphasis on exploring and optimising energy use, which is very important in the context of environmental and economic sustainability. The above represents the sustainability related activities that students have to implement. However, some projects were more orientated or suitable to sustainability and it was left up to each group to consider and explore additional sustainability content if they wanted to.

7. Perform sustainability analysis	
a. Identify which aspects should be improved and how to achieve an optimal sustainable design.	
b. Analyse costs and benefits of the sustainable alternatives.	
At the end of this task you should be able to state how your design could be made fully sustainable and what are the financial implications.	

Figure 1: Sustainability analysis section in design project manual.

One important comment made was that sustainability per se, other than the activities stated above, is not really compulsory; it is up to the students to include it or not. It is not mandatory, not like the way safety is. Thus, providing direction in sustainability up to a similar level of direction as in safety could more strongly embed sustainability within the design project, however it was also stated that it was important not to be overly prescriptive as students must be encouraged to use their own ingenuity and explore aspects that they have an interest in.

Has there been a significant increase in the level of sustainability in the design project in recent years?

Yes, there has been a significant increase, especially over the last two years. In terms of specific projects – projects that are more amenable to sustainability have been included in recent years. Last year was the first time that the new sustainability related section [Figure 1] was introduced,

where students need to look at the elements of sustainability in the final design, why some elements do not conform to sustainability and are there reasons for this?

Is there a good balance between the different aspects of sustainability - environmental, social and economic in the design project?

No, not really as historically economic feasibility assessment is given a high priority, because in practice, a crucial feature of any design is that it should be economically feasible. The other element which is also crucial is that of safety. Safety implications are important not only for the workers but also for the surrounding community and this is an important aspect of social sustainability. Social concerns also come into play when looking at the plant location. The environment is considered in terms of the preliminary EIA. It was also suggested that the students require greater direction in the design manual to encourage them to consider other aspects of sustainability, without being overly prescriptive.

In your opinion, is the level of sustainability included in the design project sufficient or are there any deficiencies?

This could be looked at in two different ways. It could be argued that the level is sufficient because sustainability is really not of major relevance to industry right now at the moment, thus we can't be too radical in the design project as the main purpose of the degree programme is to teach chemical engineering. However on the other hand, the future points in the direction of developing sustainability; companies will embrace sustainability more strongly over time. More and more of current graduates are going to find they are working developing greener processes. Thus we should be looking at the design of chemical processes that are sustainable. Consequently, it is almost incumbent upon us to improve the level of sustainability within the design project as our graduates will be practicing engineers over the next 40 years.
The best way to improve any deficiencies within the projects' sustainability content involves restructuring the module manual or emphasis on sustainability within the project as the current content of sustainability could be considered as somewhat low key and informal. The incorporation of sustainability can be enhanced by introducing a structured approach to sustainability within the design and seeking guidance from other lecturers who are sufficiently skilled in sustainability matters. By incorporating more outlooks on sustainability from a range of relevant people this could bring different attributes to the project and make it more diverse and comprehensive.

What is your opinion on grouping together students from different departments within the college together with chemical engineers to implement the design project?(e.g. sociology and economics students)

Both lecturers agreed that this was impractical. The content of core chemical engineering required in the design project makes this trans-disciplinary grouping impractical because the overall aim of the project is that everyone in the project gets the opportunity to apply their knowledge of chemical engineering.

What is your opinion on setting up internet conferencing between students here in U.C.C and across the world working on similar design projects in order to compare and contrast their views on the project?

The internet conferencing suggestion received positive feedback from both lecturers. There is potential to join a group of students at UCC with students in other parts of the world to discuss their projects. For this to be effective, the students should be doing the same or similar design projects. The international discussion between design project students is a practical approach to teaching the students' sustainability as it is teaching by student interaction and there is a lot to learn from different cultures about the importance of sustainability. This should also benefit other aspects of the design project and the skill of internet conferencing will benefit students in their later careers.

By broadening the design specification could students focus on an innovative design to a problem rather than a design for specific process to make a specific substance?

Both lecturers agree that the specification is broad already maybe even too broad. The topics and structure of the current design projects are sufficiently broad as they offer the necessary scope to increase the innovation shown by the students without forcing them in particular direction. Broadness can be problematic as a broad innovative design might have a serious lack of concrete information. Students must develop a design that is sufficiently real that they can believe if this design became a reality it would work.

Have you any final thoughts / ideas on how to incorporate sustainability in the capstone design project?

Some of the final thoughts / ideas were:

- Perform sustainability assessment of the design project. This would include both quantitative and qualitative assessment to highlight the sustainabilities and unsustainabilities of the design project; to explore the root causes of unsustainabilities, can they be overcome and what are the barriers to overcome them.
- Include others with knowledge in sustainability to help guide the students in looking at the various sustainability aspects of their design projects.
- Bring people in from industry to present to the students about how they address sustainability in practice. This could provide a source of realistic ideas and practical motivation to the students.
- Include the use of metrics to help quantitatively assess some key aspects of sustainability.

3 Review of Previous Final Year Design Projects

Two previous design projects were reviewed to assess their sustainability content and explore how to apply sustainability knowledge to improving the sustainability of the designs.

3.1 Production of Sodium Diclofenac

In the review of this design project, specific sustainability aspects were investigated, that is, energy and carbon footprint analysis. These are very important sustainability topics in terms of greenhouse gases and global warming, natural resource utilisation and cost, and usually represent a very significant proportion of a product's ecological footprint.

3.1.1 Energy analysis

In the design there was some detailed energy analysis and optimisation carried out, in particular:

- Estimation of energy requirements: This was performed throughout the process in terms of electricity requirements for pumps, stirrers, fans, compressors etc. and the cooling water requirement for a number of cooling jobs.
- Pinch analysis: This was undertaken to develop a heat exchanger network that greatly reduced the cooling and heating utility loads. In fact, it eliminated the need for heating utility requirement altogether, in part due to the use of cooling water to remove heat from reactors with exothermic reactions.

This was then further investigated in the research project from a sustainability perspective. The major outcomes from this were:

- Identification of energy hotspots: One of the unit operations was a particular hotspot, thus it was recommended that this operation or an alternative should be investigated to explore if the energy requirement could be significantly reduced.
- Efficiency and sensitivity analysis: The energy efficiencies assumed should be investigated in more detail and sensitivity analysis should be performed on these to investigate how changes in their values might affect the energy analysis.
- Primary sources of energy: These should be investigated to evaluate if less unsustainable sources of primary energy could be utilised, e.g. on-site wind turbine.

3.1.2 Carbon footprinting

No carbon footprinting was carried out in this design project, thus this was undertaken in the research project to investigate how this might influence the sustainability of the design. In carbon footprinting, the boundary of the footprint is very important. In this study, the greenhouse gas emissions inside the factory boundary were negligible because all of its energy was sourced off-site, including electricity from the grid and even the cooling water was purchased from a neighbouring facility. Thus, these were included inside the footprint boundary as well as transport of materials and employees to and from the factory. The design project had sufficient data, e.g. energy data, transport distances and number of employees, to estimate the $CO_{2\,eq}$ emissions associated with these activities. The carbon footprint analysis showed that the carbon footprints of transportation of both materials and employees was very significant and was much greater than that of grid electricity. It also included some values for refrigerant leakage and showed that this could also be a significant contributor.

From an environmental sustainability perspective, an estimate of the product carbon footprint should be undertaken, as it is the carbon footprint of the whole life cycle is what really counts. This was not undertaken in this analysis, however the analysis does show that major parts of the carbon footprint are often outside the factory boundary even when grid electricity is included. Consequently, product carbon footprint information has the potential for influencing design decisions if a major goal of the design is to minimise unsustainabilities associated with greenhouse gas emissions.

3.2 Production of Ibuprofen

In this design project, sustainability appears to have been a primary consideration in process-route selection as there were a number of alternative chemical synthesis routes available. The synthesis route selected was the one with the highest atom efficiency. However from then on,

sustainability does not appear to be considered in any detail and the design is mainly developed based on traditional economic and technical criteria. In the research project, the sustainability investigation focused on two aspects, the first being unsustainabilities, in particular the product carbon footprint and secondly an alternative sustainability focus for the design project as outlined next.

3.2.1 Product carbon footprint

The carbon footprinting CCalC software package (developed at the University of Manchester) was used to provide an approximation of the life cycle carbon footprint for the production of Ibuprofen. The dominant area in the carbon footprint of this process was the raw materials production, comprising nearly 96% of the overall carbon footprint. Moreover, the waste produced in the previous design project was incinerated and any potential for recycling was not considered. The largest waste stream consisted of 94% acetic anhydride which was an unreacted reactant. According to the data provided in the CCalC tool, acetic anhydride production has a high carbon footprint. Therefore, if a recycle loop was added to recover this acetic-anhydride stream, this could have significantly reduced the carbon footprint of the life cycle. This is an example of where sustainability assessment in the form of product carbon footprinting may have altered the process design.

3.2.2 Alternative sustainability focus for the design project

From reviewing the design brief, design manual and the design project, it appears that the current design project focuses primarily on aspects of sustainability assessment rather than sustainable design. This appears to be an issue across chemical engineering capstone design projects, even ones which promote sustainability aspects. For example, in relation to the IChemE's 2012 McNab-Lacey Student Design Award (awarded annually for the student design project that best shows how chemical engineering practice can contribute to a more sustainable world) *"the judges felt sustainability criteria were being applied as a test of the chosen design rather than being used to assess alternatives at the conceptual design stage."* (IChemE, 2013). UCC nominated a project for this competition and it received similar bespoke feedback. UCC's design project is split into seven sections and sustainability comprises the last and smallest of these sections. The sustainability assessment is a requirement of the project, yet sustainable design is left to the discretion of the design team. In view of the fact that this project provides an opportunity to 'design from scratch', this philosophy seems to be somewhat "upside down". Sustainable design should be a primary consideration and sustainable assessment should be used as a tool to facilitate enhanced sustainable design and assess the degree of sustainability actually achieved. Sustainable assessment should not just be a "bolt-on" activity that is implemented towards the end of the project when the process design is near completion. It should be implemented throughout the design process and the information obtained from it, whether this be quantitative or qualitative, should be considered in terms of how this might influence the process design and its sustainability. To implement this approach, its needs to be worked out what is involved in conducting a sustainability assessment, the methods used, the type of information obtained from it and how it could potentially be applied by students to influence their design decisions. For example, this could include the application of carbon footprinting and life cycle thinking. These methods could be applied alongside current methods such as economic feasibility assessment and safety analysis and likewise this information could be used in influencing the design decisions as the design is being developed.

4 Conclusions and Recommendations

One of the major benefits of this exercise was that it brought together staff who are involved in the teaching of process design with those involved in teaching sustainability to share their thoughts and consider the concept of embedding sustainability within the design project. It was recognised that this is an important area and there is scope for future improvement within the UCC design project. This is particularly pertinent in the context that UCC is educating mainly young chemical engineers whose careers will potentially span over the next 40 years, when there will most likely be an increasing need for skills in sustainability and sustainable design.

Some of the key recommendations from this study are:

- Sustainability should not just be a "bolt-on" activity towards the end of the design project in terms of an assessment. Sustainability assessment should be performed throughout the project so that it can influence design decisions in effort to move towards truly sustainable designs.
- There is a need to explore and determine what exactly is involved in conducting a sustainability assessment and how the information obtained could potentially influence the design. The assessment could involve a number of different methods which could take place at different times throughout the design project.
- Develop and update the design manual that reflects these developments and makes it clear to students what is expected, while allowing them scope to use their own ingenuity.
- Involve others in the design project's development and implementation, for example, those with expertise in sustainability; a presentation from a relevant industry person; and internet conferencing to gain input from other design groups from abroad.

References

Hasna, A. 2010. Embedding Sustainability in Capstone Engineering. *IEEE EDUCON Educational Engineering.*

Institution of Chemical Engineers. 2013. *Sustainable Times. The Newsletter of the Institution of Chemical Engineers' Sustainability Special Interest Group.* (10), March 2013. Rugby, England.

Institution of Chemical Engineers. 2012. *Accreditation of chemical engineering degrees*, Rugby, England.

Institution of Chemical Engineers. 2006. *A Roadmap for 21st Century Chemical Engineering*, Rugby, England.

Thakker, K. 2012. *Start with Sustainability: making sustainability the meta-objective for design,* s.l.: Carnegie Mellon University Research Showcase.