# Product Engineering in Chemical Engineering Curriculum

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**Abstract**

Product design is a relatively new field within Chemical Engineering. More than half of the Chemical Engineering graduates in the US and elsewhere are now entering product-oriented companies. This is a significant increase in recent times. The traditional oil and chemical companies are undergoing major changes and a significant number of companies are shifting into manufacturing value-added specialty chemicals. The switch from process focus to chemical products heralds a corresponding change in pedagogical content of our conventional curriculum. Thus, attention needs to span from molecules to marketable products and a paradigm shift is indicated in education that will help expand the traditional process engineering problem-solving skills. Educational changes need to focus beyond large volume commodity chemicals to small volume specialty chemicals and to expand our courses to include product design. This work focuses on the importance of product design, the incorporation of product design in the curriculum and a case study to demonstrate its implementation. We examine product design framework in the context of an actual market scenario, including the screening of candidate products, development of new industrial products, followed by process design, plant commissioning, manufacture of products and introduction into the marketplace.

**Introduction**

The discipline of Chemical Engineering (ChE) has been traditionally process-oriented. Recent trends within the industrial sector have prompted changes in direction. In particular, Cussler et al. [2001] recently made a strong argument for including product design in the curriculum, following their study, which showed that more than half of the chemical engineering graduates in the US are entering product-oriented companies, a significant increase over the past. The traditional oil and chemical companies are undergoing major changes and commodity chemicals are no longer monopolised by a few. Thus, several chemical companies have moved into value-added chemical manufacture such as specialty chemicals. Other engineering disciplines have for some time emphasized product design [Pugh, 1990], while in Chemical Engineering product design is gradually being introduced as a new subject and it is effectively expanding the traditional engineering problem-solving skills.

The switch from chemical processes to products implies a corresponding change in the focus of research and teaching. Interests need to expand beyond concern with only molecules or processes to a focus on structure-property relations and values that will depend on macroscopic functions. These may in turn depend on the material micro- and nano-structures. Thus, educational delivery must focus beyond large volume commodities and scaling-up procedures to small volume specialty chemicals in multi-scale formats. In addition, time and space must be found within the curriculum to include product design.

## What Is Different

In a typical ChE curriculum, a plethora of bulk products (petroleum, nitrogen, acids, alcohols, etc) are specified for large-scale manufacture. Traditional process design focuses on the process type (batch/continuous), reactors, separations, process integration and optimisation. In contrast, product design aims at identifying customer needs, generating ideas to meet the needs, screening ideas and finally manufacturing and marketing of product. A significant focus is on the interaction with customers and the functionality of the product, which may have a limited life span or acceptability. Thus customer preference and time-scales are the main factors for product design, in addition to the underpinning scales of economy.

To conduct product design in an academic setting, the challenges are as follows: (a) the marketing data may not be realistic; (b) the product design may only be a laboratory curiosity or a simulation at best; (c) an actual product and the corresponding process may not be implemented, (d) the product acceptability in the market is unlikely to be tested. Such gaps may handicap the learning process and lead to an incomplete understanding of the subject.

This work aims to examine product design in a real market scenario, including both the development of new industrial products, process design, plant commissioning, manufacture of products and their introduction into the marketplace with the help of a company. Product design broadens the skill set obtainable by a chemical engineer by looking at both the 'before' and 'after' the process design. Initially a market must be determined and followed by product development to meet the market needs. The direction is determined by the marketing of the product and the economic outcomes that occur.

A goal in product design is to meet customer needs. Practitioners must establish the product attributes and decide how to invent alternative products capable of delivering this need. The producer must decide how to evaluate the product. Thus, products are different from chemical processes in the following key ways:

- Products typically have a short life (few months). Only if it can be protected by a comprehensive patent can a company hope to ensure its longevity.
- The company usually has a distinct advantage by being the first to market the product. Thus the design effort may stress significantly short time-frames and the imperative to launch the product over creating the most economic solution.
- Chemical product design requires a mixture of diverse talents, including those from business, fine arts, social science, related science as well as broad-based engineering, including Chemical Engineering.

Marketing, management and economic issues prove to be extremely important. However, not all engineering students are exposed to Management, Marketing and Economics. Prior to product design, it is important to know what the customers want. Thus marketing research is essential for understanding the needs and preferences of customers. Businesses need to analyse their supply and value chains in order to better understand their customers' needs and reduce overall costs. These will likely help specify standards, modify strategies and meet customer expectations. The business decisions on material, manpower and fiscal management are crucial to the company's prosperity [Goldenberg et al, 2002].

Aesthetic aspects of the product are important to the customer, therefore, neglect in this area may risk product failure. Products must appeal to consumers in terms of its trade-name, look and feel. Engineers risk failure when they design technical programs, including the user interface, without using the services of people who know which colors and shapes suggest technical competence. Sociology, anthropology, psychology, linguistics and history of technology provide a rich set of methods to enhance the understanding and execution of product design. These fields provide methods that contribute to identifying customer needs, for qualitative methods for decision making and for evaluation of the design process through such instruments as questionnaires, interviews, focus studies and historical analysis. Engineers need to appreciate the multi-disciplinary nature of product design to understand consequences and effects of processes on decision making and prioritising [Legge, 1999].

**Product Design Steps**

The first step in product design is determining the goals for the design, i.e., what it must deliver for the stakeholders [Dym & Little, 2000; Ulrich & Eppinger 2000]. Stakeholders may include designers, manufacturers, distributors and customers. For example, attributes desired by customers for paints are that it must stick to surfaces, provide protection and present aesthetic satisfaction. One would also consider ease of manufacturing and safety. Customers may also want it to be available in a certain form. To facilitate the design, it is desirable to construct an object tree that organizes the desired objectives in a hierarchy, where one may include certain attributes (eg, safety) as a high priority. The goals are then further subdivided into objectives and constraints.

Various strategies are adopted to elicit the needs of all the shareholders, including brainstorming and questionnaires. When the goals are listed, the relative importance of each is scaled using a weighting scheme applied to the objective tree.
Figure 1 shows typical steps in product design in a sequential representation, although concept development is an iterative approach for problem solving. To estimate the desired levels of performance, the designer must consider each goal and establish the limits that one expects for it, including product testing and validation protocols. The developed protocol must allow one to choose a design alternative and assess the extent to which it meets the stated goals. A systematic approach to product design is as follows:

1. Initial screening to decide whether to go ahead with the project.
2. Preliminary market assessment for a glimpse into the marketplace to assess market acceptance and competition.
3. Preliminary technical assessment to find if the product is feasible.
4. Detailed market study to investigate and interview relevant stakeholders, to perform concept tests, positioning studies.
5. Predevelopment business and financial analysis for risk analysis, examining market potential and competitive advantage.
6. Product development to make prototypes in actual physical form.
7. In-house product testing to test the product under controlled conditions.
8. Customer product tests and trial sell to obtain relevant feedback.
9. Trial production in a batch.
10. Pre-commercial business analysis.
11. Production start-up to undertake full-scale production.
12. Market launch for the defined marketplace

Additional considerations in product design are [Ulrich et al., 2000]:

1. *Trade-offs*: A difficult part of product development is recognising and understanding trade-offs to maximise overall outcomes.

2. *Dynamics*: As technologies and customer expectations evolve rapidly, products must be developed for the future and not only per current expectations.
3. *Timing*: For products to be successful, quick and efficient decisions are essential as customer expectations may change dynamically and additional costs may result due to time delay.
4. *Economics*: Often large investments of scarce resources (eg, people and capital) are needed. New products should not only appeal to customers but also be as inexpensive as possible within the company.

**Product Design within Curriculum**

In a recent redesign of our curriculum, two senior year courses are offered on product design:

- Product Formulation and Design
- Design Practice 2 – Products and Value Chains.

The first course module provides students with a working knowledge of the types of discrete systems available, the ways in which particulate systems can be characterized and their applications in industry. These aspects form the foundation for an introduction of the modelling techniques used for discrete systems. Many products such as particulate systems (eg, powders), as well as polymeric (eg, emulsions) and biological systems (eg, cells) emerge from processing steps as discrete entities. The course provides an introduction to the basic concepts in discrete systems necessary for a chemical engineer to be able to formulate and design discrete products having desired properties.

The second course is based on the recognition that chemical engineers are involved in the creation of products and processes, the manipulation of complex systems, and the management of technical operations. The course is project-driven and helps develop an appreciation of the practical application of concepts and tools to solve problems in the process, product and service sectors. The case studies cover a range of design scenarios: the domain of particulate products, entrepreneurial ventures and product value chains. The scales include: molecular to macro-systems levels, underpinned by considerations of management. The learning outcomes of the course include:

- Developing a strategy for taking a product development idea from concept to commercial artefact, with appreciation of economic arguments, underlying uncertainties and trade-offs inherent in the development.
- Applying design and analysis tools for synthesis of particulate products leading to manufacture of a preferred product at pilot scale – and demonstrating this in project mode
- Developing a strategy for design and analysis of extended business enterprises, with a focus on value chain optimisation.

The senior year courses culminate in the final year courses of Design and Thesis. For both these courses open-ended problems in process and/or product design are tackled. We describe below the conduct of a recent Thesis Project which focuses on product design as a goal for Industry and learning outcome in a University course.

**Product Engineering: A Case Study**

Applied product engineering was carried out in collaboration with a leading Industry Partner as part of the Major Industrial Project Placement Scheme (MIPPS). In our Department, MIPPS (for undergraduates), replaces the first semester of final year for the outstanding students (1st class honours potential) with a 6- month full time research in industry. The undertaking involves working on a significant project selected and supervised by the industrial sponsor. Additional supervision is provided by an academic staff. Self-study and report submission on case studies are conducted to replace otherwise required courses of the semester. This allows selected students to complete their degree in the normal four years time, and make the Scheme unique in Australian Engineering education.

The Scheme is self-funding, allowing scholarships to the students, a fee to the academics, and a token contribution to the Department. During the five years of its operation, significant industrial problems have been solved, so that it is rated highly by industry, attracting sponsorships than can be met by the number of qualified students available. The students work full time in industry at the sponsor's premises, on a project selected by, and under the control of the company. Department staff assist with the problem definition and solution.

For this project, a specific product engineering work was executed from the market research, product and process development through to product release during the six-month period. The experience shows that the typical problems faced by industry for product design within the limited time available can be accommodated within the current undergraduate program successfully. The coordinated team-work between the industry and academic partners and the student is a key ingredient for such an undertaking to succeed.

Inadequate market analysis is the major reason why products fail, which is followed by product problems or defects. It is therefore important that these areas are accurately ascertained. Quality Function Deployment (QFD) is a tool for bringing the voice of the customer into product development from conceptual design through to manufacturing. QFD was born out of Total Quality Control (TQC) activities in Japan during the 1960s. It begins with a matrix that links customer desires to product engineering requirements, along with competitive benchmarking information, and further matrices can be used to ultimately link this to design of the manufacturing system.

The use of analytical techniques in conjunction with QFD (e.g., simulation, design of experiments, regression, mathematical target setting, and analytic hierarchy process) were helpful in improving cross-functional integration and better decision-making processes. QFD is motivated by two issues: (a) how to design a new product that meets customer needs, and (b) the desire to provide QC process charts (control plan) to manufacturing [Cohen, 1995].

QFD includes a set of matrices that relate inputs to outputs. In phase 1, Product Planning Matrix of QFD, often qualitative customer requirements are translated into design independent, measurable, quality characteristics of the product. The quality characteristics are prioritized from the customer's perspective and target values (or preliminary specifications) for the desired level of performance based on competitive bench-marking. After the selection of a design concept, Phase 2 examines the relationship between the quality characteristics and the various components or parts of the design.

The result of Phase 2 is a prioritization of the component parts of the design in terms of their ability to meet the desired quality characteristic performance level. The important few components are then deployed to Phase 3 that explores the relationship between the part and the manufacturing processes, identifies the manufacturing operations that control the component target value. In Phase 4, the key manufacturing processes and associated parameters are translated into work instructions, control and reaction plans, and training requirements necessary to ensure that the quality of key parts and processes is maintained.

Ideally, these four phases combined provide a traceable link from the shop floor back to customer requirements that provides workers insight into how their job function impacts customer satisfaction.

The project was developed, as part of the company's product growth initiative in the anti-graffiti market within the Thesis goals of the University. The steps followed in our quest for a product is given in *Figure 1*. The key considerations to reach our objectives are as follows:

- Determination of market potential: Examination of market size and potential; interview "lead consumers" in the anti-graffiti market; interview consumers; develop product specifications from market research.
- Comparison of company products with existing anti-graffiti products: Functional testing of existing products to test product specification compliance; cost assessment of existing and proposed products.
- Design of proposed products: Investigate 'user-friendly' solvent alternatives and surfactants; analyse types of 'graffiti' that must be removed; design graffiti remover product; compatibility analysis of graffiti remover and different types of graffiti.
- Development of a cost effective production process: Cost analyses for determining the most effective process; design and build a rig for manufacturing.
- Product design is an iterative procedure which adds significantly to the time of the overall process. Therefore careful analysis at all levels of the process is essential.

Initial investigation of the anti-graffiti market determined its size and structure. The market size was of anti-graffiti protection, prevention and removal was determined to be $200 - $350 million in Australia. Further analysis and breakdown of these costs determined that the future market for anti-graffiti products is in the order of $20-50 million within Australia and highly significant for the global market.

***Graffiti Types and their Removal***

The aim of graffiti removal is to remove graffiti without changing or ruining the original surface. There are two possible ways to remove graffiti either manually or mechanically. Manual removal methods would include wiping, scraping scouring. Mechanical methods include pressurised water, pressurised grit blasting or abrading. The main disadvantage of mechanical cleaning is that the abrasive action of these cleaning methods may damage a porous surface with the stripping of the graffiti affected area rather than the removal from the surface.

The public sector graffiti protocol test [Geason et al, 1990] defines the following types of graffiti: black enamel spray paint, black leather dye, black marker pen, blue marker pen, red marker pen, crayon, whiteboard marker and red automotive spray paint. Their removal can be carried out using:

*Solvent based graffiti removal liquids* based on chlorinated hydrocarbons: (a) monoglycol ethers and glycol acetates; (b) diglycol ethers; (c) polar and miscellaneous solvents. Generally groups 1 and 2 have low occupational exposure limits associated with them and therefore should only be used in highly ventilated areas. Group 3 due to low vapour pressures are less likely to present any exposure risks and are therefore less dangerous in use.

*Solvent based graffiti removal gels*, which consist of solvents combined with a thickening agent. These solvents will fall in to the above mentioned five groups. The advantages of using gels are that they adhere to the vertical surface giving a prolonged exposure time, solvent evaporation can be retarded, they can be controllably applied avoiding over consumption. Due to the higher viscosity of gels compared to liquids the diffusion of the solvent into the graffiti may take longer.

Anti-Graffiti Coatings are of types that range from permanent single clear coat lacquers to three or four pigmented systems to wax based sacrificial coatings. These coatings are categorised as follows:

1. *Clear coatings* that range in their gloss and number of coats necessary. The durability of these coatings varies. Other types of coating in this category are the water-borne acrylic lacquers, whose graffiti resistance is limited due to poorer chemical resistance.
2. *Pigmented coatings* serve dual purpose: prepares a new surface over a previously damaged surface and protects against graffiti after application.
3. *Sacrificial coatings* are two types of sacrificial coatings: solvent-based silicone/wax or water-based polysaccharide coatings. Unlike wax/silicone coatings these polysaccharides have the advantage of being able to be touched up immediately.

The candidate products were selected for final testing, based on the technical requirements and customer expectations determined through QFD after scaling of responses. A sample of the interview matrix and our scaling approach for market research for the various functionalities of the products are shown in Tables 1 and 2, respectively. A summary of the QFD for the customer expectations are shown in Table 3. We find that the performance and cost effectiveness factors rate high in the QFD.

**Table 1:** Interview matrix

| Interviewee type | Number of people Interviewed |
|---|---|
| Council Members | 12 |
| Graffiti Specialists | 3 |
| End Consumers | 15 |

**Table 2:** Scaling for market research for the various functionalities of the products

| Customer Expectation | Scale |
|---|---|
| Feature is undesirable | 1 |
| Feature is not important | 2 |
| Feature would be nice, but is not necessary | 3 |
| Feature is highly desirable | 4 |
| Feature is critical | 5 |

**Table 3:** Customer Expectations for the Graffiti Remover

| Expectation | Scale |
|---|---|
| Removes all paints | 5 |
| Removes all dyes | 5 |
| Cost effectiveness | 5 |
| Non-Hazardous | 4 |
| Ease of application | 4 |
| Biodegradable | 4 |
| Fast Working | 4 |
| No-Residue | 3 |
| Rinse off with water | 3 |

| | |
|---|---|
| Non-Flammable | 2 |

Consistent with market research, the following chemical attributes were identified for the product: (a) able to remove paint, (b) able to remove dye, (c) durable, (d) safe and non-hazardous, (e) biodegradable. The relevant physical attributes identified were: (a) aesthetics: both before and after removal, (b) applicable to both protected and non-protected substrates, (c) protection of porous surfaces (eg, masonry, bricks, sandstone), (d) protection of non-porous surfaces, (e) applicable to both horizontal and vertical surfaces (unaffected by gravity). The economic viability was analysed based on: (a) product competitiveness in the marketplace, (b) economic viability of the industry.

Based on the QFD results, technical analysis for a range of materials having the desired functionalities were screened. In particular diffusion and solubility parameters from databases were examined. Hansen solubility parameters, based on the dispersion component, the polarity component and the hydrogen bonding component, were identified for a range of graffiti removal material for their technical assessment. The diffusion coefficients were evaluated for the selected systems to assess their effectiveness in penetrating into the graffiti. Three products were identified for possible introduction into the anti-graffiti market, namely, a two-component polyurethane clear paint based on available teflon technology, a water-borne fluoro-chemical traditionally used as a transparent protective layer for water and oil repellency and functionalized esters.

Initial tests were carried out samples prepared according to the testing protocol developed. After screening the products and determining the final mix of products, production processes were evaluated for the graffiti remover gel and liquid. A sample of the QFD matrix developed is shown in Table 4.

**Table 4:** Weighted decision matrix for the graffiti remover

| | | **Liquid Prototype 1** | | **Liquid Prototype 2** | | **Liquid Prototype 3** | |
|---|---|---|---|---|---|---|---|
| **Selection Criteria** | **Weights** | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score |
| Cost | 20% | **3** | 0.6 | 1 | 0.2 | 3 | 0.6 |
| Paint removal | 15% | **3** | 0.45 | 4 | 0.6 | 2 | 0.3 |
| Dye removal | 15% | **3** | 0.45 | 2 | 0.3 | 4 | 0.6 |
| Non-Hazardous | 15% | 5 | 0.75 | 5 | 0.75 | **3** | 0.45 |
| Solvent strength | 15% | **3** | 0.45 | 5 | 0.75 | 3 | 0.45 |
| Biodegradable | 10% | 3 | 0.3 | **3** | 0.3 | 3 | 0.3 |
| Non-flammable | 10% | 3 | 0.3 | **3** | 0.3 | 3 | 0.3 |
| **Total** | **100%** | | **3.3** | | **3.2** | | **3.0** |
| **Develop further?** | | | **YES** | | **NO** | | **NO** |

Following the final selection of the product to be marketed based on the QFD matrices, significant technical innovations were undertaken for cost reduction, raw material sourcing and production design. These considerations led to the implementation of an environmentally friendly and socially responsible policy, achieving a smaller environmental footprint. The main production system included a material preparation and design of a batch production process. Complications due to high viscosity of gels and conglomeration of the additives and thickening agents were overcome through further innovations. These allowed for the production of graffiti removers having the desired characteristics. The production began at the final stages of the thesis tenure, followed by immediate marketing. Products met with market success as product inventory was negligible at steady state.

## Conclusions

This work examined the educational and technical development aspects in product design. The steps towards product engineering were analysed and implemented for a specific case as part of a student project in collaboration with industry. The market size is significantly large enough to warrant product design and development. The QFD method was employed for evaluating customer expectations and performance measures of the product. Plausible solutions were developed initially from both an internal and external analytical approach. The solvency of the products was assessed by estimating the Hansen solubility and diffusion coefficients. After selecting the product range, appropriate processes were designed. Reduced costs were aligned with the policy of reducing environmental impact. Optimal solutions were chosen for further development and translation into an anti-graffiti product range. It was a primary focus to assess customer expectations and incorporate them into the product range to maximise efficient use of resources. Benchmarking of the proposed graffiti protection system against products already within the anti-graffiti market proved that both had a viable product range with significant cost and graffiti protection advantage.

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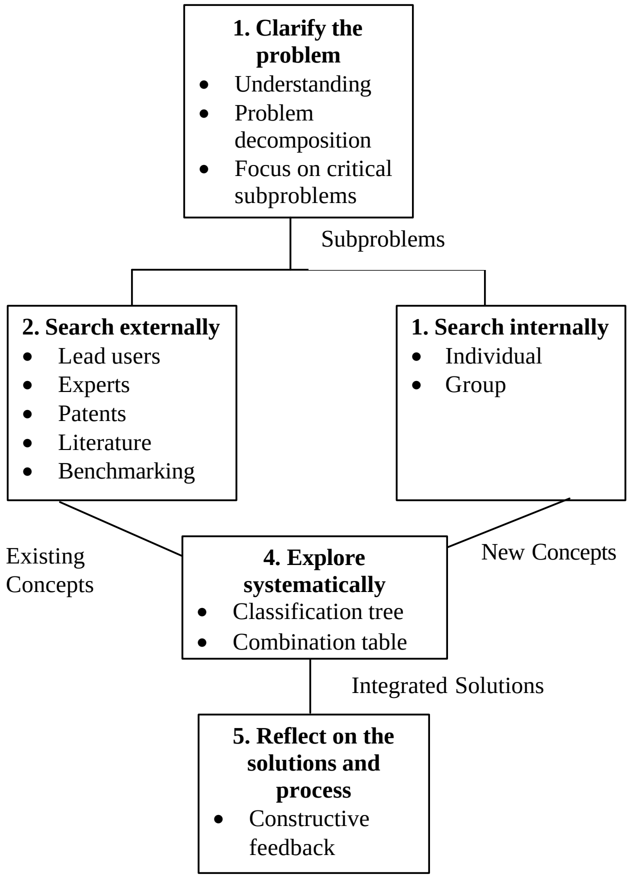


**Figure 1**. Road-map for product design.

**Biography**

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Vince Gomes is the director of Teaching and Learning and a faculty member of Chemical Engineering Department at the University of Sydney. He received the bachelor's degree from IIT and the master's and PhD degrees in Chemical Engineering from McGill University. His primary areas of interest are in educational methods and assessment, curriculum design and problem-based learning.