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PARTICLE TECHNOLOGY EDUCATION IN THE 21ST CENTURY – Outcomes from the IFPRI sponsored workshop in Sheffield, April 2017

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Abstract

In April 2017, IFPRI sponsored a workshop at the University of Sheffield to assess the current state of global particle technology education and chart a course forward. There is clearly a demonstrated need for trained graduates at all levels across a broad spectrum of industries. A top down approach for curriculum is recommended and key high-level learning attributes for undergraduate education in particle science and engineering are proposed. The meeting participants identified a variety of barriers to particle technology education such as the crowded engineering curriculum and a perception that particle technology is both an art and an orphaned subject. Nevertheless, change is possible with better underlying science, new textbooks and software tools, examples of excellent programs and courses, and increasing demand from employers for skills in the area, as compared to 25 years ago. Suggestions for how to do this are reported. It will take persistence and cooperation between both academia and industry to achieve a significantly higher percentage of engineers trained in particle science and engineering. This education will benefit society in solving the world's current and future technological grand challenges.

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1. Introduction

Most practicing engineers in the petrochemical, biopharmaceutical, materials, energy, and consumer products industries who work in R&D, manufacturing, technical services, and technical sales and marketing will confront particulate processing sometime during their careers, and many of us spend our careers designing, making, and manipulating particles. We typically teach ourselves particle technology on the job – because education in particle technology was missing from our undergraduate and graduate engineering curricula. Often, engineering departments provide no courses in particle technology or, at best offer a single survey course. In this paper, we will often use the term "particle science and engineering" to describe the field for reasons that will be made clear below, and this can be read as a synonym for "particle technology", "particle engineering/design" and "solids processing".

We believe that the scientific advances made in the discipline over the last twenty years provide an opportunity to develop a modern particle science and engineering curriculum and re-energize particle science and engineering education. Recent progress in areas like granular dynamics, colloidal and suspension rheology, multi-scale modeling and simulation, and dynamic imaging of multiphase systems have facilitated the transition of particle technology from art to science. To take advantage of this, we need to develop a modern framework that defines the discipline and provides the structure for the development of new courses, textbooks, and educational programs that are attractive to prospective students and prepare them well for industrial practice.

In April 2017, the International Fine Particle Research Institute (IFPRI) sponsored a workshop at the University of Sheffield intended to assemble this framework, with a focus on undergraduate (first-degree) engineering education. The workshop brought together academic and industry experts in Particle Technology from Europe, North America, and the Asia-Pacific (See Table 1) to consider four major questions:

- What does industry need from particle technology education?
- What is the current state of particle technology education?

- What is the framework for a modern particle technology education?
- What are the barriers and opportunities for implementing particle technology into undergraduate engineering curricula?

The primary aim of this workshop was to deliver a list of high-level attributes of a modern Particle Science and Engineering curriculum with a secondary aim to identify how programs to deliver such goals could be developed and implemented.

Top down curriculum design is analogous to reverse engineering the manufacture of a particulate product (see Figure 1). For a particulate product, reverse engineering starts with defining the key product attributes, working down to a product structure that delivers such attributes, and then to a process design to deliver this structured product. To establish the syllabus for a particle science and engineering program, first we must define the attributes required in the graduate engineer or scientist, then work down to program and module learning goals and onto the correct learning environment and assessment to deliver these goals. The structure and outcomes of the workshop were based on this paradigm.

This paper summarizes the discussion and conclusions from the workshop, proposes key high-level learning attributes for undergraduate education in Particle Science and Engineering, and presents some ideas for implementing them into engineering undergraduate education.

2. Industrial Needs for Graduate Attributes in Particle Science and Engineering

This section of the workshop was introduced by three experienced industry practitioners representing three different industry sectors: Gavin Reynolds (Astra Zeneca), Karl Jacob (The Dow Chemical Company) and Marty Murtagh (Corning). Each was asked to challenge the group with the skills base needed for engineers and technologists within their companies. Break out groups were then asked to define a series of graduate attributes from a university degree appropriate for a new graduate.

In a reflection of the challenge for an effective particle science and engineering curriculum, each speaker presented quite different perspectives. Gavin Reynolds emphasized the need for graduate skills in three areas related to particulate products:

1. Characterization
    a. Particulate and bulk properties of powders
    b. Particulate product performance
2. Modelling
    a. Properties of mixtures of materials
    b. Product performance
3. Measurement, modelling and control
    a. Using in-line measurement to control particulate processes

He neatly captured the required engineering capabilities (in Pharma) in a single statement as *to understand, develop, scale-up, transfer and optimise any particulate process, with constrained material usage* and noted that "To be effective at this takes a lot longer for those without a strong particle technology background".

Marty Murtagh emphasised the need to understand powder rheology and mechanics and clearly differentiated that from fluid flow and rheology. He presented a strong case for the underlying science base in physics and chemistry including surface science and interfaces, colloid science, mechanics and so on. He viewed particulate processes from a material science paradigm: process-structure-function. Within unit operations, particles are created, transformed, mixed, and segregated. Flow modelling tools (CFD, DEM) are powerful for understanding these transformations.

Karl Jacob presented a list of 15 core concepts that all engineers need to understand to be successful in industrial particle technology process design and troubleshooting (see Table 2). He presented this as a wish-list of skills that all first-year new engineering hires possessed at Dow. Karl's list emphasizes the importance of powder handling and flow in industrial applications (bulk solids handling and underlying science, fluid-particle interactions, fluidisation, two phase flow and transport, segregation and particle packing). He emphasized that what appears as a line on a process flow sheet is a pipe if the material is a fluid, but a challenging unit operation that can shut down your plant if the material is a powder or slurry.

Bringing together the input from the invited experts and workshop participants, we summarise a high-level list of graduate attributes suitable for any engineering program in particle science and engineering:

First-degree students will understand particles and powders at the same level they do fluids. They are able to synthesize, analyse, scale-up, and optimize particulate processes and design particulate products. They demonstrate basic understanding required to:

1. *Characterize the properties of particles, powders, and structured products relevant to their manufacture and performance;*
2. *Relate the performance of particulate materials to their structure and chemistry*
3. *Design and analyze particle processing unit operations for particle formation; transportation; separation; reaction, heat and mass transfer; and delivery form manufacture;*
4. *Synthesize and analyze a flowsheet for manufacture of particulate products using simulation tools and models;*

Table 3 gives some specific examples of how these might be be broken down into to more detailed learning goals suitable for individual course (module, subject) design and development. This list is deliberately not exhaustive. While the programme levels attrbitues are universal, individual course goals will need to be targeted to local needs.

3. How well do current programs match with industry needs?

This section of the workshop was introduced by four academic participants who were asked to review the global status of instruction in particle technology education in their countries and region of the world. The speakers were Wolfgang Peukert (Friedrich-Alexander-University Erlangen-Nürnberg), Hidehiro Kamiya (University of Tokyo), Jonathan Seville (University of Birmingham, also representing IChemE), and Bert Diemer (University of Delaware). Other academic participants provided additional data in the breakout sessions.

There was a strong consensus among the industrial participants about the general absence of formal education in particle science and engineering and its impact on their companies. Karl Jacob observed that "particle technology is ubiquitous – it is not some sort of specialized field that only a few [engineers] will encounter." He went on to say, "without better knowledge in the field, I personally worry about how much money we are leaving on the table as a result of a lack of knowledge about solids processing technology." Marty Murtagh stated that at Corning, at least "one-third of technical staff deal with particles day-to-day; less than one percent have … training in particles and powder technology concepts."

Globally, teaching of particle science and engineering varies widely. In Germany and Japan, it is a compulsory component of first-degree chemical engineering education, and one or more courses may be dedicated to the subject. In the UK, Australia, and New Zealand, accreditation of chemical engineering programs explicitly requires inclusion of elements of particle science and engineering. The extent of instruction, however, varies significantly. In the US, it is an orphan subject, with elements included in specialized chemical engineering, materials science, applied physics, and civil and mechanical engineering courses. A handful (ca. 15-20) of institutions now offer a particle technology course as either a standalone elective or as part of an elective sequence.

The consensus of this workshop about the status of particle science and engineering education has too many similarities with the status at the 1993 NSF workshop on Particle Science and Technology in 1993 [1]. At that time, Germany, Japan, and the UK were felt to be strongest in teaching of particle technology. In the rest of the world, especially the US, the subject was essentially absent from engineering curricula. Progress over the last twenty years in advancing the topic and integrating it into undergraduate and graduate education has been incremental, with some regions moving forward and others moving backward. Overall, participants felt that the concepts promoted by Davies, Nelson, and Jacob [2] remain valid today.

Given the state of formal education in particle science and engineering, it is unsurprising that it was the overwhelming consensus of the workshop participants that teaching of particle science and engineering at the first-degree level does not meet the needs of industry. In all but a few countries, engineering departments do not recognize particle science and engineering as a core competency and therefore do not include it in core courses. New graduates don't learn the fundamentals of particle properties, transformations, and unit operations and are unprepared to analyze or design particulate systems. They lack "language" – the engineering fundamentals and understanding of particle properties and characterization – to ask the right questions about the products and processes that they are analyzing. The high-level graduate attributes listed in section 2 above are not being addressed. For example, one of us was asked by a newly hired engineer to help with the design of a bag house. The engineer stated, "I don't even know where to begin." We would not expect such a comment with respect to fluid flow, heat exchange or distillation in chemical engineering.

At the postgraduate level in all countries, elements of particle science and engineering are most commonly taught in specialized courses such as colloid science, soft-matter physics, fluidization, biochemical separations, etc. The existence of these courses depends on research interests of specific faculty. A small number of universities offer masters or doctoral programs in particle technology or closely affiliated disciplines (e.g. pharmaceutical engineering). Some workshop participants felt that post-graduate preparation is better, perhaps sufficient for industry needs, however this was not a consensus view.

Table 4 summarizes an analysis of the mismatch between industry needs and the level of graduate skills in particle technology by workshop participants.

However, there are some positive examples of innovation and good practice that have developed in the last decade. A small number of engineering departments are experimenting with different approaches to including particle technology in their first- and advanced-degree programs. For example, the Chemical Engineering Department at the University of Sheffield has reinvented its undergraduate curriculum in chemical engineering to reflect the diversity of roles and industries in which their graduates are employed. The traditional unit operations laboratory has been replaced by an experimental investigation module in which student teams use statistical methods to design experiments and analyze their data. Experiments are performed on state-of-the-art integrated pilot plant equipment used in modern pharmaceutical and specialty chemicals manufacture: a GEA Consigma 25 continuous tablet manufacturing plant incorporating ten powder process unit operations, a NiTech COBRA continuous crystallizer and an AWL carousel filter drier (figure 2). A new core third year module, The Science of Formulated Products, covers key particle formation and processes operations such as hoppers and crystallizers but with a strong underpinning of key science related to characterization, particle and powder mechanics and product performance models. An elective stream in pharmaceutical engineering and formulated products provides a quarter of the cohort with a deeper education in the field.

The Department of Chemical and Biomolecular Engineering at the University of Delaware has taken a different approach. They have developed a comprehensive Master of Engineering program consisting of seven full semester courses covering particle science fundamentals (four courses), unit operations, particle product design, and an industrial internship. The structure of the program parallels that of chemical engineering degree program. The Masters program is offered to U. Delaware first-degree students as a “4+1” program, providing an efficient option for students to obtain comprehensive education in chemical and particle engineering.

The program at Purdue University shows the power of interdepartmental cooperation in particle technology. The departments of Chemical Engineering, Mechanical Engineering, Agricultural and Biological Engineering, Materials Engineering and the School of Pharmacy collaborated to create a palette of courses at both the undergraduate and graduate levels which show the true breadth of the field. The courses address both particle technology fundamentals which are common to all disciplines as well as discipline-specific emphasis on specific topics (for example, tablet compaction in industrial pharmacy). Additional benefits from the interdepartmental cooperation include increased class size, co-advised grad students and a significant base of graduates employed in the field of particle technology.

4. Barriers and opportunities to implementing instruction in particle science and engineering

The final sessions of the workshop were aimed at understanding the barriers to implementing particle engineering instruction into existing engineering curricula and developing an action plan to address these. It is clear from similarity between the conclusions of the NSF Workshop in 1993 and this workshop's assessment of the current state that particle engineering remains a niche topic to which most students have no exposure. The consensus of the workshop is that the lack of progress in making particle engineering mainstream is due to:

- Particle engineering is not included as a core element of chemical engineering in many countries, especially the USA.
- Particle technology is not viewed as interesting. It is seen as old fashioned art or empirical technology, rather than exciting, cutting edge engineering science.
- Particle engineering is an orphan subject. No major engineering discipline claims it.
- Inclusion of particle engineering requires expansion of an already crowded curriculum or displacement of core topics which are believed to be more important, or simply surviving by inertia.
- A critical mass of instructors does not exist to teach the subject. Since it is an orphan subject, engineering departments feel no responsibility to teach it, and faculty feel no responsibility to learn to teach it.

These five barriers are symptoms of a more fundamental issue: the importance of particle science and engineering is not recognized by key stakeholders – students, faculty, government, and industry. There is no "pull" for inclusion of particle engineering in the curriculum. Industry doesn't demand literacy in particle science in hiring. Students don't understand why they need particle engineering literacy. Faculty don't teach topics that they see no need for.

This means that a critical step in implementing particle science and engineering into the chemical engineering curriculum is to educate students and faculty on the fundamental and ubiquitous role that particles play in chemical and biomolecular processes. There are two elements to this. The first is retrospective: update and expand the Merrow report of 1993 [3] to illustrate quantitatively the economic impact of particle processing in the economy.

The second is prospective: to make the case that particle design and processing are key elements of cutting-edge research and development and are essential to addressing the grand challenges of climate change, sustainable growth, and global health. In addition, highlighting examples of cutting-edge research based on design and manipulation of particles (e.g. non-local granular rheology, nanoparticulate therapeutics, metal-oxide framework adsorbents for CO_2 capture) will demonstrate the relevance of particle engineering now and in the future. A successful marketing campaign for particle science and engineering should make the case for considering particle engineering as part of the core discipline.

The name "Particle Technology" is by itself an impediment to acceptance into the core discipline. The word "technology" implies a specific industrial application rather than a broadly applicable discipline, and it is widely believed to be empirical and old fashioned. Workshop participants agreed that we should rebrand the topic as "particle science and engineering" or "particle engineering" to emphasize its fundamental nature, breadth of application, and scientific basis. It is also critical to teach particle science and engineering as a discipline – a unified set of skills and analytical tools – rather than as a list of applications.

To address the curriculum crowding problem, particle engineering topics should be included in existing core courses. This was called "stealth introduction" by several us at the workshop, but on reflection it should be more public and deliberate. If one ignores the traditional emphasis on fluid-phase systems, many of the key topics listed in Table 2 and Table 3 fit quite naturally into standard chemical engineering courses. Examples of how this could be done are shown in Table 5.

Finally, the critical mass problem can be addressed by building a global network for particle engineering instruction. This would provide a means of creating and sharing course content and delivering instruction. Particle engineering expertise, both academic and industrial, can be leveraged to educate students globally rather than locally.

There are several reasons why we are in a much better position to take advantage of these opportunities now that we were 25 years ago:

1. Quantitative particulate science and engineering is significantly advanced in the past 25 years [4]. Some of the many examples include regime maps for design of major unit operations such as wet granulation; maturation of discrete element modeling as a rigorous and quantitative technique; and better, more fundamental models for performance of particulate products including strength, disintegration and dissolution.
2. With this new engineering science, new textbooks are available to support teaching and learning at core undergraduate and masters level e.g. [5] [6] [7].
3. Robust software tools are now commercially available for simulating particulate processes similar to the way flowsheet simulations tools and CFD simulations have been available and accessible for two to three decades. These include gFormulate (PSE) and SolidSim (ASPEN) for process simulation, and DEM for particle scale simulations from a range of vendors as well as open access.
4. Industry sectors in which high value particulate products are manufactured are now major employers of engineers, particularly chemical engineers. They are demanding different skill sets from the graduates they employ.
5. New undergraduate and masters level programs, such as those highlighted in section 3, provide a good template for other to use, as do many programs in Germany and Japan.

5. Concluding remarks

The particle technology community cannot stand still and accept the status quo in educating future generations of engineers in particle science and engineering lest we continue to repeat the woes outlined by Merrow thirty plus years ago. The workshop underscored the industrial need for trained engineers across functions from basic research to engineering to manufacturing to product use. This is not restricted to a small number of PhD particle technologists who will develop new particle-based products, but it includes most personnel in engineering and manufacturing. In some cases, companies have responded by the formation of their own particle technology laboratories which have had a measure of longevity – they assist in both new product development and process design/improvement.

However, this is only the tip of the iceberg – there are far more companies that do not embrace particle science and solve their particle technology challenges one-at-a-time without the benefit of understanding the engineering fundamentals because they must in order to produce their particulate products (this was also highlighted by Merrow [3]). This leads us to ask the following rhetorical questions: 1) how much is the processing of bulk solids/particulate goods compromised because of the lack knowledge in the field; and 2) how many good ideas for new products or line extensions are discarded because the particle technology hurdle it too high?

So what can industry do? We should work closely with universities in our regions to embed particle science and engineering in core curriculum through volunteering on department and program advisory boards, providing expertise to teach classes where local faculty do not have the expertise, and mentoring design groups and research projects in the relevant areas. We should emphasize the importance of skills in particle science and engineering and back this up in our hiring practices.

What can academics do? We need a change in mind set, not a survey course. Particulate products are an exciting and continuously growing part of the life of graduate engineers. We should work hard to embed particle science and engineering context and examples in core engineering subjects (see Table 5 examples). We should move the emphasis in underlying science towards multiphase systems, surfaces and interfaces, mechanics and material science. We should work closely with industry partners to provide case studies and, most importantly, data sets to help make these changes happen. We should make good use of new textbooks and simulation tools in teaching and leverage partnerships with technology companies in so doing. Where appropriate, specialist elective streams and Masters programs provide the opportunity for advanced courses and we need to learn from the pedagogically strong, if somewhat isolated, programs that have been developed in the last ten years in the USA and UK, and mine the reach seam of particle science and engineering education in counties such as Germany and Japan.

We, the particle technology community, cannot stand idly by. It will take the combined efforts of academia, industry and professional organizations such as IFPRI to continue to push individual academic institutions, government funding agencies, engineering societies such as IChemE, AIChE, and ASME, and education accreditation bodies to support major initiatives in particle technology education. It is very pleasing that as a follow up action from the workshop, IFPRI has formed an Education and Outreach Committee to catalyze and provide leadership in this national and international agenda. It is easy to accept the status quo; however, if we educate the engineers of tomorrow, they will be better prepared to take on the global (particle) challenges such as resource conservation, food, and human health.

5. Acknowledgments

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7. Figures and Tables

Table 1: Participants at the IFPRI Workshop on Particle Technology Education for the 21st Century

Name	Institution or Company	Country
Cuitino, Alberto	Rutgers U.	USA
Dave, Raj	NJIT	USA
Diemer, Bert	U. Delaware	USA
Ghadiri, Mojtaba	U. Leeds	UK
Hrenya, Christine	U. Colorado	USA
Kamiya, Hidehiro	Tokyo U. A&T	Japan
Litster, Jim	U. Sheffield	UK
Michaels, Jim	U. Delaware	USA
Muller, Frans	U. Leeds	UK
Ocone, Raffaella	Heriot Watt U.	UK
Ooi, Jin	U. Edinburgh	UK
Peukert, Wolfgang	U. Erlangen	Germany
Pitt, Martin	Sheffield U.	UK
Poletto, Massimo	U. Salerno	Italy
Pratsinis, Sotiris	ETH	Switzerland
Salman, Agba	U. Sheffield	UK
Selomulya, Cordelia	U. Monash	Australia
Seville, Jonathan	U. Surrey	UK
Smith, Rachel	U. Sheffield	UK
Sun, Jin	U. Edinburgh	UK
Wassgren, Carl	Purdue U.	USA
Wu, Charley	U. Surrey	UK
Bonsall, Judith	Unilever	UK
Francqui, Filip	Granultools	France
Hendrickson, Willie	Aveka	USA
Hipkins, Kathryn	Hosakawa Micron	UK
Hoffman, Jeff	Paul O Abbe	USA
Hu, Kan-Nian	Vertex	USA
Jacob, Karl	Dow Chemical Co.	USA
Koynov, Athanas	Merck & Co.	USA
Lubda, Dieter	Merck KGaA	Germany
Maarschalk, Kees	Corbion	Netherlands
Martindejuan, Luis	Proctor & Gamble	UK
Mitchell, Niall	Process Systems Enterprise	UK
Muller, Hubert	Evonik	Germany
Murtagh, Marty	Corning	USA
Pasha, Massih	Chemours	USA
Reynolds, Gavin	Astra Zeneca	UK

Table 2: Karl Jacob’s wish list of key concepts in solid processing understood by all engineering new hires

Key Concept	Importance of this concept
Sampling techniques	Sampling and sample division are key for gathering the correct information about a particle technology process
Fundamental single particle calculations	Terminal velocity, particle drag, equivalent diameters, etc. are used broadly across all of solids processing
Particle size distributions	Engineers need both a conceptual and numerical framework for the description of the size of particles
Packing of particles	Important for packaging of bulk solids, agglomerate design
Interparticle forces	Need to understand why particles stick or do not stick together – key for agglomeration, caking, particle adhesion, etc.
Ergun equation and its variants	Essential to understanding how pressure drop across beds of solids changes as a function of key variables, such as voidage
Particle technology dimensionless numbers	Re_p, Ar, Fr, Bi, etc. - engineers need to appreciate what they mean and how they impact process operation
Jannsen Equation	Essential for hopper design, tabletting, reactor design
Drying	Drying is used extensively in the process industries – many misconceptions about psychrometry and vacuum drying exist
Saltation	Fundamental concept for successful slurry and pneumatic conveying
Fluidization fundamentals	Important not just for fluidized beds but conveying, hopper design, agglomeration, etc. Includes concepts like minimum fluidization velocity, pressure drop, bed densities

Hopper flow	Improperly designed hoppers cause a myriad of production issues
Particle coating calculations	Particle coating is key for manipulation of particle properties
Grade efficiency	Provides engineers with a method for quantifying separator efficiency
Grinding circuits	Allows maximum production of right sized particles through the use of a size reduction device with a separator

Table 3: Examples of subject level learning outcomes matched to programme level graduate attributes

Graduate attribute (program level)	Example learning outcomes (subject level). The student will ...	Blooms taxonomy Level
Characterize the properties of powders, particles and structured products relevant to their manufacture and performance	• Know the definitions of important particle properties. • Know the definitions on particle property distributions and properties of the distributions. • Manipulate raw particle size distribution data to get frequency and cumulative distributions, calculate distributions means and other properties • Distinguish between correct and biased sampling techniques • Do basic sampling statistics calculations • Use particle characterization and sampling for real engineering problem solving	Knowledge Knowledge Application Comprehension Application Analysis
Design and analyze particulate materials, relating performance to structure and chemistry	• Be able to list a series of particulate products from several industry sectors(eg. Foods, agricultural chemicals, consumer goods) and the attributes important for their performance • Use micromechanical models to estimate the strength of an agglomerate given its structure and properties of the primary particles. • Given a required dissolution profile, of a particular product determine suitable properties of (a) primary particles, or (b) agglomerates, to achieve specification.	Comprehension Application synthesis
Design and analyse particle processing unit operations for particle formation; transformation; delivery form manufacture; transportation; separation; reaction, heat and mass transfer	• State the flow regimes for gas-solid and liquid-solid contacting and discuss the advantages/disadvantages of each regime for fluid-solid contacting. • Calculate the terminal settling velocity and minimum fluidization velocity for any particle-fluid system. • Use bulk solids properties from a shear cell to design mass flow hoppers using Jenike's design method;	Comprehension Application Analysis

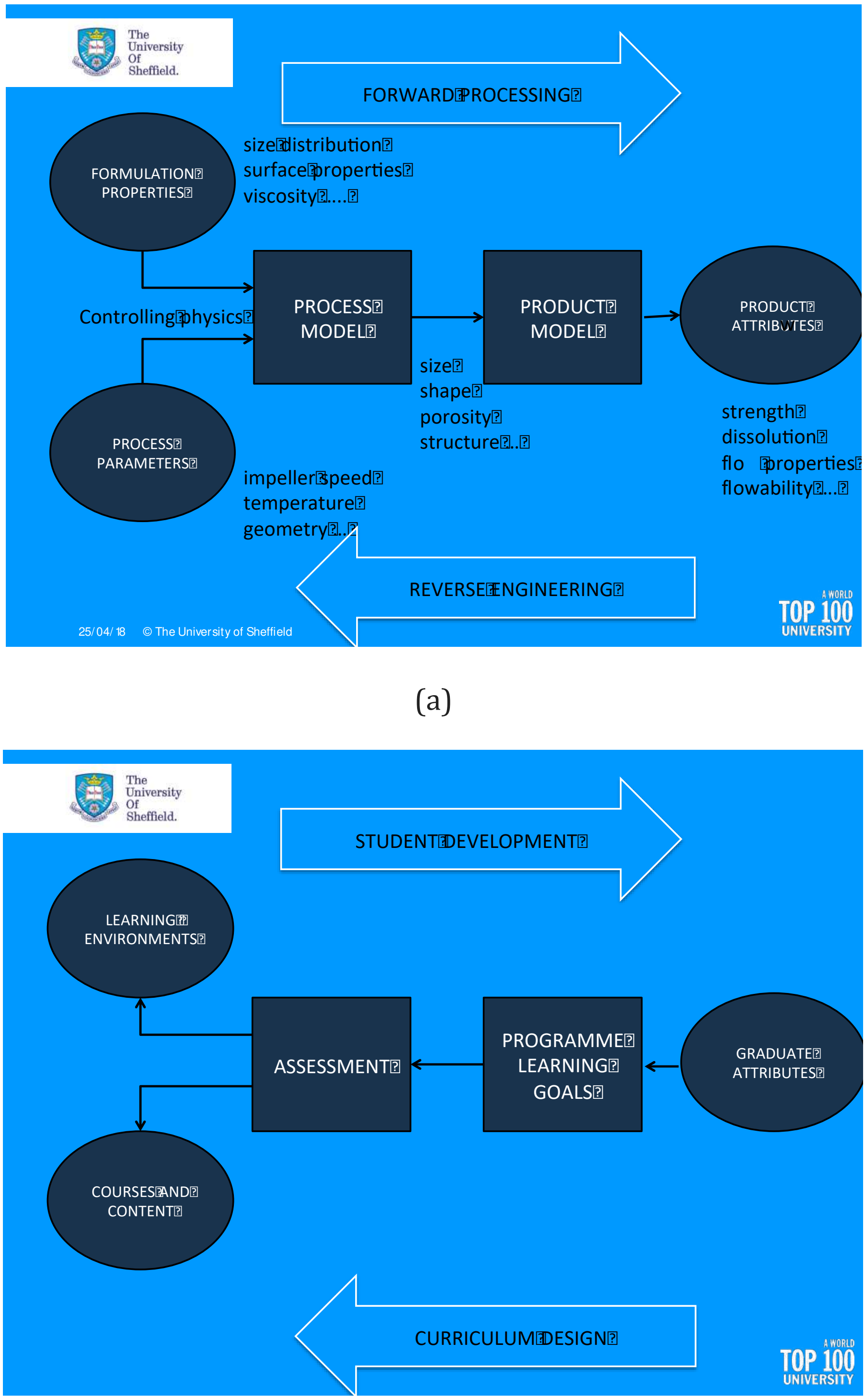
	• Know the mechanisms for cake washing and dewatering. Be able to predict the final moisture content of a filter cake and know the effect of process parameters on moisture content. • Use correlations and settling velocity calculations to calculate cut size, grade efficiency and pressure drop for cyclones, centrifuges and gravity classifiers. • Use crystallizer mass, energy and population balances to address simple problems related to crystallizer design and operation problems. • For a given set of conditions, calculate the dimensionless groups that control growth and consolidation in wet granulation, and use the appropriate growth regime map to predict good conditions for granule growth.	Applicaiton Synthesis Application Analysis
Synthesize and analyze a flowsheet for manufacture of particulate products using simulation tools and models	• Use the population balance to solve design and operating problems in crystallization, granulation, grinding, spray drying and aerosol processes. • Use flowsheeting tools to synthesize and compare different flowsheets for multiple unit operations, e.g. open loop grinding compared to closed loop with product size classification.	Analysis Synthesis, evaluation

Table 4: Analysis of the mismatch between industry needs and the level of graduate skills in particle technology by workshop participants

Desired Attribute	**Skill Level (1-10 scale)**
Understand key elements of particle safety	1
Understands basics of particle characterization	1
Understands individual particle properties	3
Understands bulk powder properties	1
Understands difference between particles and continuous phases	3
Understands that process impacts particle properties	3
Understands that particle properties impact processing	3
Introduced to common particle unit operations	3
Introduced to modeling of particulate systems	1

Table 5: Examples of integration of particle science into standard chemical engineering curriculum

Course	**Topic**	**Particle application**
Thermodynamics	• Phase equilibrium	• Solubility; absorption and adsorption
Fluid mechanics	• Stress, strain, viscosity • Hydrostatics • Drag; Stoke's law • Pipe flow	• Stress ratio • Jansen stress; incipient yield; Mohr analysis • Settling; fluid-particle separations • Fluidization; pneumatic conveying; slurry transport
Kinetics and Reaction Engineering	• Batch & continuous reactors: rate=f(concentration) • Catalysis	• Batch & continuous crystallizers: rate=f(supersaturation) • Particle size, surface area, porosity
Transport Phenomena	• Diffusion • Transport coefficients and analogies • Simultaneous heat and mass transport	• Brownian motion • Transport to a sphere (stagnant; correlations) • Drying; coating
Process Analysis and Design	• Staged separations	• Mill & granulator circuits



(a)

(b)

Figure 1:. Reverse Engineering of (a) a particulate product, and (b) a particle technology curriculum

Figure 2: Powder Processing Pilot Plant used in the core undergradaute chemical engineering module “Experimental Investigation” at University of Sheffield.