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

3  
4                     **James D. Litster<sup>1</sup>, James N. Michaels<sup>2</sup>, Karl V. Jacob<sup>3</sup>**

5  
6                                     **Abstract**

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

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## 21 **1. Introduction**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

96 Karl Jacob presented a list of 15 core concepts that all engineers need to understand to be  
97 successful in industrial particle technology process design and troubleshooting (see Table  
98 2). He presented this as a wish-list of skills that all first-year new engineering hires  
99 possessed at Dow. Karl’s list emphasizes the importance of powder handling and flow in  
100 industrial applications (bulk solids handling and underlying science, fluid-particle  
101 interactions, fluidisation, two phase flow and transport, segregation and particle packing).  
102 He emphasized that what appears as a line on a process flow sheet is a pipe if the material is

103 a fluid, but a challenging unit operation that can shut down your plant if the material is a  
104 powder or slurry.

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

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

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

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

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

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

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

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

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

155 Given the state of formal education in particle science and engineering, it is unsurprising that  
156 it was the overwhelming consensus of the workshop participants that teaching of particle  
157 science and engineering at the first-degree level does not meet the needs of industry. In all

158 but a few countries, engineering departments do not recognize particle science and  
159 engineering as a core competency and therefore do not include it in core courses. New  
160 graduates don't learn the fundamentals of particle properties, transformations, and unit  
161 operations and are unprepared to analyze or design particulate systems. They lack  
162 "language" – the engineering fundamentals and understanding of particle properties and  
163 characterization – to ask the right questions about the products and processes that they are  
164 analyzing. The high-level graduate attributes listed in section 2 above are not being  
165 addressed. For example, one of us was asked by a newly hired engineer to help with the  
166 design of a bag house. The engineer stated, "I don't even know where to begin." We would  
167 not expect such a comment with respect to fluid flow, heat exchange or distillation in  
168 chemical engineering.

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

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

178 However, there are some positive examples of innovation and good practice that have  
179 developed in the last decade. A small number of engineering departments are experimenting  
180 with different approaches to including particle technology in their first- and advanced-  
181 degree programs. For example, the Chemical Engineering Department at the University of  
182 Sheffield has reinvented its undergraduate curriculum in chemical engineering to reflect the  
183 diversity of roles and industries in which their graduates are employed. The traditional unit  
184 operations laboratory has been replaced by an experimental investigation module in which  
185 student teams use statistical methods to design experiments and analyze their data.  
186 Experiments are performed on state-of-the-art integrated pilot plant equipment used in

187 modern pharmaceutical and specialty chemicals manufacture: a GEA Consigma 25  
188 continuous tablet manufacturing plant incorporating ten powder process unit operations, a  
189 NiTech COBRA continuous crystallizer and an AWL carousel filter drier (figure 2). A new  
190 core third year module, The Science of Formulated Products, covers key particle formation  
191 and processes operations such as hoppers and crystallizers but with a strong underpinning  
192 of key science related to characterization, particle and powder mechanics and product  
193 performance models. An elective stream in pharmaceutical engineering and formulated  
194 products provides a quarter of the cohort with a deeper education in the field.

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

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

#### 212 **4. Barriers and opportunities to implementing instruction in particle science and** 213 **engineering**

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

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

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

238 This means that a critical step in implementing particle science and engineering into the  
239 chemical engineering curriculum is to educate students and faculty on the fundamental and  
240 ubiquitous role that particles play in chemical and biomolecular processes. There are two  
241 elements to this. The first is retrospective: update and expand the Merrow report of 1993  
242 [3] to illustrate quantitatively the economic impact of particle processing in the economy.

243 The second is prospective: to make the case that particle design and processing are key  
244 elements of cutting-edge research and development and are essential to addressing the  
245 grand challenges of climate change, sustainable growth, and global health. In addition,  
246 highlighting examples of cutting-edge research based on design and manipulation of  
247 particles (e.g. non-local granular rheology, nanoparticulate therapeutics, metal-oxide  
248 framework adsorbents for CO<sub>2</sub> capture) will demonstrate the relevance of particle  
249 engineering now and in the future. A successful marketing campaign for particle science and  
250 engineering should make the case for considering particle engineering as part of the core  
251 discipline.

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

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

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

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

- 271 1. Quantitative particulate science and engineering is significantly advanced in the past  
272 25 years [4]. Some of the many examples include regime maps for design of major  
273 unit operations such as wet granulation; maturation of discrete element modeling as  
274 a rigorous and quantitative technique; and better, more fundamental models for  
275 performance of particulate products including strength, disintegration and  
276 dissolution.
- 277 2. With this new engineering science, new textbooks are available to support teaching  
278 and learning at core undergraduate and masters level e.g. [5] [6] [7].
- 279 3. Robust software tools are now commercially available for simulating particulate  
280 processes similar to the way flowsheet simulations tools and CFD simulations have  
281 been available and accessible for two to three decades. These include gFormulate  
282 (PSE) and SolidSim (ASPEN) for process simulation, and DEM for particle scale  
283 simulations from a range of vendors as well as open access.
- 284 4. Industry sectors in which high value particulate products are manufactured are now  
285 major employers of engineers, particularly chemical engineers. They are demanding  
286 different skill sets from the graduates they employ.
- 287 5. New undergraduate and masters level programs, such as those highlighted in section  
288 3, provide a good template for other to use, as do many programs in Germany and  
289 Japan.

## 290 **5. Concluding remarks**

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

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

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

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

327 We, the particle technology community, cannot stand idly by. It will take the combined  
328 efforts of academia, industry and professional organizations such as IFPRI to continue to

329 push individual academic institutions, government funding agencies, engineering societies  
330 such as IChemE, AIChE, and ASME, and education accreditation bodies to support major  
331 initiatives in particle technology education. It is very pleasing that as a follow up action from  
332 the workshop, IFPRI has formed an Education and Outreach Committee to catalyze and  
333 provide leadership in this national and international agenda. It is easy to accept the status  
334 quo; however, if we educate the engineers of tomorrow, they will be better prepared to take  
335 on the global (particle) challenges such as resource conservation, food, and human health.

## 336 5. Acknowledgments

337 The authors appreciate financial support of the workshop by the International Fine Particle  
338 Research Institute, Vertex Pharmaceuticals Inc., AstraZeneca, Merck KGaA, and the  
339 Chemours Company.

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341

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343

344 **7. Figures and Tables**

345 Table 1: Participants at the IFPRI Workshop on Particle Technology Education for the 21st  
 346 Century  
 347

<b>Name</b>	<b>Institution or Company</b>	<b>Country</b>
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

<b>Key Concept</b>	<b>Importance of this concept</b>
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, tableting, 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

<b>Graduate attribute (program level)</b>	<b>Example learning outcomes (subject level). The student will ...</b>	<b>Blooms taxonomy Level</b>
Characterize the properties of powders, particles and structured products relevant to their manufacture and performance	<ul style="list-style-type: none"> <li>• Know the definitions of important particle properties.</li> <li>• Know the definitions on particle property distributions and properties of the distributions.</li> <li>• Manipulate raw particle size distribution data to get frequency and cumulative distributions, calculate distributions means and other properties</li> <li>• Distinguish between correct and biased sampling techniques</li> <li>• Do basic sampling statistics calculations</li> <li>• Use particle characterization and sampling for real engineering problem solving</li> </ul>	Knowledge Knowledge Application  Comprehension Application Analysis
Design and analyze particulate materials, relating performance to structure and chemistry	<ul style="list-style-type: none"> <li>• 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</li> <li>• Use micromechanical models to estimate the strength of an agglomerate given its structure and properties of the primary particles.</li> <li>• Given a required dissolution profile, of a particular product determine suitable properties of (a) primary particles, or (b) agglomerates, to achieve specification.</li> </ul>	Comprehension  Application  synthesis
Design and analyse particle processing unit operations for particle formation; transformation; delivery form manufacture; transportation; separation; reaction, heat and mass transfer	<ul style="list-style-type: none"> <li>• State the flow regimes for gas-solid and liquid-solid contacting and discuss the advantages/disadvantages of each regime for fluid-solid contacting.</li> <li>• Calculate the terminal settling velocity and minimum fluidization velocity for any particle-fluid system.</li> <li>• Use bulk solids properties from a shear cell to design mass flow hoppers using Jenike’s design method;</li> </ul>	Comprehension  Application  Analysis

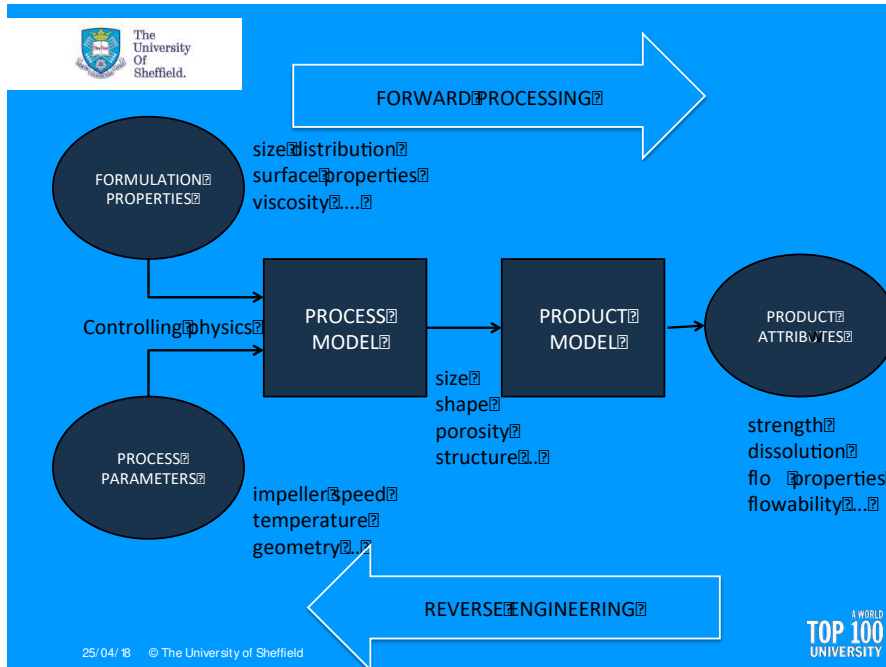
	<ul style="list-style-type: none"> <li>• Know the mechanisms for cake washing and dewatering. Be able to predict the final moisture content of a filter cake and know the effect of process parameters on moisture content.</li> <li>• Use correlations and settling velocity calculations to calculate cut size, grade efficiency and pressure drop for cyclones, centrifuges and gravity classifiers.</li> <li>• Use crystallizer mass, energy and population balances to address simple problems related to crystallizer design and operation problems.</li> <li>• 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.</li> </ul>	<p>Applicaiton</p> <p>Synthesis</p> <p>Application</p> <p>Analysis</p>
<p>Synthesize and analyze a flowsheet for manufacture of particulate products using simulation tools and models</p>	<ul style="list-style-type: none"> <li>• Use the population balance to solve design and operating problems in crystallization, granulation, grinding, spray drying and aerosol processes.</li> <li>• 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.</li> </ul>	<p>Analysis</p> <p>Synthesis, evaluation</p>

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

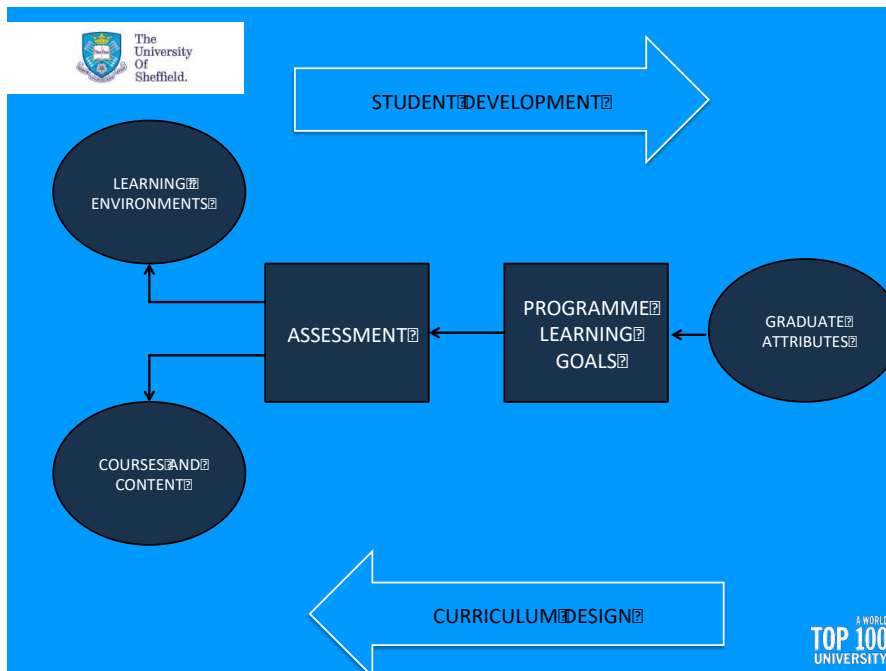
<b>Desired Attribute</b>	<b>Skill Level (1-10 scale)</b>
Understand key elements of particle safety	1
Understands basics of particle characterization	1
Understands individual particle properties	3
Understands bulk powder properties	1
Understands difference between particles and continuous phases	3
Understands 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

<b>Course</b>	<b>Topic</b>	<b>Particle application</b>
Thermodynamics	<ul style="list-style-type: none"> <li>• Phase equilibrium</li> </ul>	<ul style="list-style-type: none"> <li>• Solubility; absorption and adsorption</li> </ul>
Fluid mechanics	<ul style="list-style-type: none"> <li>• Stress, strain, viscosity</li> <li>• Hydrostatics</li> <li>• Drag; Stoke's law</li> <li>• Pipe flow</li> </ul>	<ul style="list-style-type: none"> <li>• Stress ratio</li> <li>• Jansen stress; incipient yield; Mohr analysis</li> <li>• Settling; fluid-particle separations</li> <li>• Fluidization; pneumatic conveying; slurry transport</li> </ul>
Kinetics and Reaction Engineering	<ul style="list-style-type: none"> <li>• Batch &amp; continuous reactors: rate=f(concentration)</li> <li>• Catalysis</li> </ul>	<ul style="list-style-type: none"> <li>• Batch &amp; continuous crystallizers: rate=f(supersaturation)</li> <li>• Particle size, surface area, porosity</li> </ul>
Transport Phenomena	<ul style="list-style-type: none"> <li>• Diffusion</li> <li>• Transport coefficients and analogies</li> <li>• Simultaneous heat and mass transport</li> </ul>	<ul style="list-style-type: none"> <li>• Brownian motion</li> <li>• Transport to a sphere (stagnant; correlations)</li> <li>• Drying; coating</li> </ul>
Process Analysis and Design	<ul style="list-style-type: none"> <li>• Staged separations</li> </ul>	<ul style="list-style-type: none"> <li>• Mill &amp; granulator circuits</li> </ul>



(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 undergraduate chemical engineering module “Experimental Investigation” at University of Sheffield.

