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Teaching Manufacturing Processes from an Innovation Perspective

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Abstract

The manufacturing innovation that underlies advanced products comes about through rational, reasoned design, motivating the need for a manufacturing engineering curriculum within higher education that teaches methodologies for designing manufacturing processes. As an alternative to conventional manufacturing process courses, the authors propose learning outcomes and methods for teaching process design and innovation. Proposed learning outcomes for new process design courses include describing key relationships and directionality between product and process design functions, determining whether a component can be made with a process, selecting process sequences for products based on cost and/or environmental impact, specifying new process designs when needed, and choosing between product/process alternatives. Examples of instructional materials and approaches that are being developed to help meet these outcomes are discussed.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

In industry, manufacturing and product design are inexorably linked in the transition of ideas to production for satisfying customer needs. The design of a product affects what processes can be used to realize it, and *vice versa* the development of new process capabilities (*e.g.*, additive manufacturing over the past three decades) can drive new product functionality and how designs are conceived. However, within the educational domain, Manufacturing and Design disciplines remain largely separated: there are Design courses and there are Manufacturing courses, typically scattered over a number of disciplines. With the exception of the occasional Design-for-Manufacturability (DFM) course and a few select integration programs (*e.g.*, Massachusetts Institute of Technology [MIT], Boston University, Ferris State University, Grand Valley State University), Design and Manufacturing courses are rarely taught as an integrated discipline (despite a large variety of research groups which integrate the two). One example of Design-Manufacturing integration is in the Mechanical Engineering undergraduate curriculum at the University of Michigan, which has a series of three required courses in Design and Manufacturing I, II, and III for sophomore, junior, and senior students [1]. Technical elective courses in manufacturing processes, systems, and data analytics are included in the curriculum. However, there is limited time to lecture on in-depth manufacturing topics. At the graduate level, Clemson's THINKER program (Technology-Human Integrated Knowledge, Education and Research) puts students in teams to design new types of manufacturing processes to better integrate the human element of the system [2]. Such an approach introduces design thinking concepts to manufacturing students, requiring more creative thinking rather than purely prescriptive instruction.

Educational materials for such alternative approaches are lacking. If properly developed, these would enable manufacturing instructors to teach in a way that allows students to viscerally understand the interplay of Design and Manufacturing disciplines. Such barriers to teaching these viewpoints need to be symbiotically addressed. Here, the terms *Design* and *Manufacturing* as used in academia and industry are first clarified to avoid confusion. In academia, "Design"

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typically refers to mechanical (or mechatronic) product design whereby a set of functional requirements is analyzed and realized in an output product or system, while the term "Manufacturing" typically refers to the discipline of manufacturing engineering (*i.e.*, how to produce quality products economically). In industry, the term "Design" is also used as a noun to describe the rendering of product component specifications or that part of a manufacturing enterprise that develops product designs. In a similar manner, the term "Manufacturing" often means the set of organizations or facilities through which a product is produced.

In this paper, the term "design" is used as a verb, referring to the activity uniquely performed by engineers to satisfy the needs of a customer. Design activities can include requirements definition, conceptual design and detailed design, involving quantitative analysis leading to specifications of an embodiment to satisfy customer needs. In this way, product development involves at least product design, the domain of the product engineer, as well as manufacturing process design (MPD) [3-7], the domain of the manufacturing engineer.

While manufacturing engineering as an academic discipline rightly borrows from both industrial engineering and mechanical engineering, the practice of MPD is a distinguishable design activity beyond a sum of the two disciplines. In 2018, a study was conducted at Oregon State University [8] to compare the curricula of all U.S. ABET-accredited manufacturing engineering programs that offer undergraduate degrees, with the topical categories prescribed by the Society of Manufacturing Engineers' (SME) Four Pillars of Manufacturing Knowledge [9]. According to the study, the topical area of "Process Design" was found to occupy the least number of required credits with a mean of less than one required credit per program and only 25% of programs requiring courses in process design. These findings suggest that while industry feels MPD is something that manufacturing engineers should know, few programs know how to teach it.

The importance of teaching MPD becomes clearer when viewed from the perspective of industrial practice. Manufacturing engineers are often used in industry to advance process improvement within existing manufacturing systems. Here, the authors argue that a greater potential lies upstream in the development of products, where manufacturing innovation, conceived and consummated within MPD, drives new sources of competitive advantage. In industry, new products, assemblies and systems need to be developed within the context of manufacturing – if it cannot be made at an appropriate scale, it cannot be economically sold. This perspective has driven the development of DFM practices that constrain designers with rules-of-thumb, best practices and other considerations such as tooling and fixturing clearances, surface effects, tolerances, ergonomics and environmental considerations. While DFM practices have been effective at driving down the cost and duration of product development as well as product costs, such a one-sided view of the Design-Manufacturing symbiosis ignores the opportunity for process innovation within MPD. In DFM, manufacturing is viewed as a fixed constraint instead of as an enabler of new functionalities for product design. In contrast, the authors believe that by removing manufacturing constraints via MPD, manufacturing engineers can help product designers to be more creative (even artistic), realizing new product features at acceptable costs based on the availability of new manufacturing process capabilities. In this paper, MPD is extended to include the enablement of product design through manufacturing process innovation otherwise known as Manufacturing-for-Design (MFD) [2].

In order to advance the concept of MFD within industry, a new Design-Manufacturing educational paradigm is needed. To be clear, the vision is not to replace DFM with MFD, but to consider both methodologies in concert, just as Design and Manufacturing work symbiotically as disciplines within industry [2]. Product designers need to see their manufacturing colleagues as process designers capable of removing manufacturing constraints, not just people who inform product design of such constraints. One way to help manifest these new perspectives is by changing the way engineers are educated about manufacturing processes.

In order to reform the academic teaching of manufacturing processes from an MFD perspective, several needs must be met. First, educators must learn to teach engineers how to use the wealth of manufacturing process information available to solve product development problems as process designers. Initially, this comprises the selection of manufacturing processes and equipment from among the large universe of existing manufacturing technology available through the supply chain, including how to evaluate the capability and economics of certain processes for producing certain product features (MPD/DFM). Next, they must learn how to teach these process designers to innovate new manufacturing process augmentations or designs (MFD) and evaluate when to modify existing product designs to fit manufacturing constraints versus when to develop new manufacturing capabilities. Finally, educators must make provisions for helping product designers think more creatively about how to leverage new manufacturing processes. Combining methods for designing processes with product design creativity will help demonstrate the opportunities available by extending manufacturing process capabilities beyond their current state, making MFD easier for students to grasp.

Below, this paper highlights a decade of efforts at Oregon State University [3-5], Clemson University [2, 10] and the University of Michigan [11, 12] to advance manufacturing engineering pedagogy and coursework towards these integrated MPD/DFM/MFD objectives. Section 2 discusses the manufacturing learning outcomes for teaching manufacturing process courses in this new way. Section 3 provides specific examples of methods currently used to get at these outcomes. Finally, in Section 4, reflections are provided on current gaps in manufacturing process educational materials necessary to fully realize the MPD/DFM/MFD vision.

2. Learning outcomes

The goal of a manufacturing processes course should be to teach *engineers* how to design manufacturing processes, creating value within a product life cycle through an understanding of product customer and product design needs in light of both current and potential future *manufacturing* *process capabilities*. "Engineers" denote people with an understanding of the process physics underlying how discrete materials are transformed and how material properties are affected and/or enhanced through manufacturing processes. For discrete-part manufacturing, this includes at a minimum an understanding of material structure-property relationships (*e.g*., structural, thermal and chemical performance), the thermodynamics of materials (*e.g*., during casting, molding and heat treatment processes), and the mechanical deformation of materials (*e.g*., forming, joining and machining processes), in addition to underlying rate-based phenomena such as fluid dynamics and heat transfer.

"Manufacturing process capability" is interpreted to mean the ability of a process to impart a new shape and/or set of properties to a workpiece without defect. Therefore, a key learning outcome of a manufacturing processes class is the ability to determine whether a process is *capable* of producing a particular feature (*i.e.*, geometry or property) in a specific material at a given production rate. This outcome is essential for realizing product features and, in the product creation stage, critical for guiding product design teams on the manufacturability of their design. Product design teams also need to know how to adapt geometries and material specifications to enable the development of value-added product features and functions for a particular process.

Building on this concept, another way to increase value in product development is by helping to select the best production process sequences to meet product, market, and societal requirements. For companies with existing manufacturing infrastructure, this can be rather straightforward in that process selection is limited to currently available production processes and facilities. However, for small entrepreneurial companies working to advance new technology to market without possessing significant manufacturing infrastructure, opportunities exist to look at the universe of manufacturing technologies available within the supply chain for developing a new product. In order to do this, manufacturing engineers must not only understand and predict what process capability exists, but also be able to estimate what the cost and environmental impact of the product will be, whether through equipment and facility investment or the supply chain. Cost estimation and life cycle analysis provide quantitative means for selecting processes and equipment, with the supply chain providing options for make-or-buy decisions during scale-up. The selection of proper manufacturing process sequences can lead to better product performance, lower product cost and higher profitability for the manufacturing enterprise.

Finally, the concept of process capability ascribed above is limited to the universe of existing manufacturing processes and process equipment available for implementing a given sequence. A potential source of significant competitive advantage can be found in the adaptation or design of new manufacturing processes and equipment necessary to implement new process capabilities. The manufacturing processes and systems for an innovative product will evolve based on changing production quantity requirements, materials, sizes and shapes of the part to be produced.

In summary, the remainder of this paper discusses the pedagogy for teaching process design within manufacturing process courses to meet the following five learning outcomes:

Learning Outcome 1. *Describe* the key relationships and directionality between Design and Manufacturing functions in industry

Learning Outcome 2. *Analyze the capability* of a given process to manufacture a given product design and suggest changes to the product design to avoid failure and minimize manufacturing variation (DFM analysis)

Learning Outcome 3. From the universe of known manufacturing processes, *select a process sequence* to produce a product design concept for a market based on the cost and/or environmental impact of the process

Learning Outcome 4. *Specify new process designs* for a product design requiring manufacturing capability or economics beyond the existing universe of processes (MFD analysis)

Learning Outcome 5. *Choose* from among product/process alternatives based on the cost and/or environmental impact of the products and processes

3. Pedagogy being used to address outcomes

3.1. Teaching Process-Product Tradeoffs on the Basis of Cost

The Manufacturing discipline is broadly characterized by tradeoffs between competing interests (*e.g*., make vs. buy, tolerance vs. cost or flexibility vs. economies of volume). Those educated in Manufacturing need to be able to consider such broad balances quantitatively through the lens of both designers and makers. To that end, efforts at Clemson University to address Learning Outcomes 1 through 3 at the graduate level have focused on cost-centered education. A graduate course on manufacturing processes starts out focused on cost estimation as the basis for studying process modelling and physics. In this manner, cost models help to direct the investigation into cycle time calculations, equipment selection and energy requirements needed to produce a product. This backdrop enables discussions of balancing process requirements with product cost, in a manner similar to discussions in product development within industry (*e.g.,* what is the cost of a particular flatness tolerance or surface finish requiring grinding versus the performance of the product).

Early in product development, manufacturing process selection is motivated primarily by cost, though not at the exclusion of other important considerations such as worker well-being, environmental stewardship and corporate strategy. Understanding the main components of product cost, their underlying assumptions, and the sensitivity of cost to market and environmental factors helps to guide manufacturing engineers in their decisions and recommendations.

Prior work by the authors has discussed cost estimation on the basis of greenfield production dedicated to a single product [13, 14]. Here, efforts are made to model the costs of shared production resources in a way to consider the effects of equipment setup and batch size on product cost. One such product cost (C) model is given in Eqn. (1), comprising five key cost elements:

- C_m, material cost (raw material sensitivity)
- C_l, labor cost (time and overhead sensitivities)
- C_t, tooling and consumable cost (consumable sensitivity)
- C_c, capital cost (capital recovery, maintenance and tax sensitivities), and
- C_e, energy and utility cost (sensitivity to environmental impact)

$$C = C_m + C_l + C_t + C_c + C_e \quad (1)$$

Such a framework enables clear discussion and quantitative analysis of the relationships between design and manufacturing decisions (Learning Outcome 1). Each cost element and its corresponding tradeoff discussion(s) is envisioned as follows.

3.1.1 Material Cost. This component represents the incoming material cost, and sensitivity to material pricing and price variability. This cost will also consider process waste and material reusability. For example, machining a component leaves chip waste behind, whereas forging it results in a lower amount of trim waste or casting it results in waste that can be reused. A simple expression of material cost is given in Eqn. (2), where m_p is the designed part mass, $c_{m,m}$ represents the mass-based material cost, $c_{s,m}$ the mass-based salvage value, and m_s the mass of scrap material. This relationship can be formulated to be volume-based and add process-specific details.

$$C_m = m_p c_{m,m} + m_s(c_{m,m} - c_{s,m}) \quad (2)$$

3.1.2 Labor Cost. This component represents the burdened direct human input to process operations, so encompasses sensitivity to prevailing wages, process time, and assumptions behind overhead cost (*e.g.*, facility services) as well as non-value adding functions (*e.g.*, accounting and human resources), healthcare and regulatory costs. Normally process energy is included in the labor burden rate. However, in this model, it is considered separately in order to illustrate the magnitude of energy use in relation to other costs. Labor cost is formulated in Eqn. (3), where L_o is the operator labor rate, L_s is the (more highly skilled) setup labor rate, t_{cyc} is the cycle time, t_s is the overall setup time, n is the batch size, and B is the burden rate to capture unaccounted overhead costs.

$$C_l = \left(L_o t_{cyc} + L_s \frac{t_s}{n}\right)(1 + B) \quad (3)$$

Note that an activity-based costing method is employed, where different labor classes are considered explicitly. This approach allows for further exploration of process decision sensitivity to cost-contributing factors normally rolled up in the burden rate such as setup frequency and can drive thinking in aligned areas such as setup time reduction.

3.1.3 Tooling Cost. This cost component accounts for consumables used in the process. It is simply represented in Eqn. (4), where $c_{t,t}$ is the cost per tool and n_t is the number of parts produced per tool.

$$C_t = \frac{c_{t,t}}{n_t} \quad (4)$$

This cost component is considered in tradeoffs of tool cost and life (*e.g.*, an inexpensive Al_2O_3 grinding wheel vs. a more expensive but longer lasting cubic boron nitride wheel), as well as process settings which affect the tool life along with other cost factors (*e.g.*, machining speed).

3.1.4 Capital Cost. This cost component contains terms representing depreciation (capital recovery), taxes and insurance, and annual maintenance cost. It is given in Eqn. (5), where c_{inv} represents the overall investment cost, $t_{o,ann}$ the annual operating hours, D the annual depreciation allowance, TI is the annual tax and insurance burden as a percent of investment, and M the annual maintenance budget as a percent of investment.

$$C_c = t_{cyc} \frac{c_{inv}}{t_{o,ann}} (D + TI + M) \quad (5)$$

Such consideration of the elements related to capital can help support decisions such as what equipment to purchase, depreciation strategy (*e.g.*, straight-line, sum of years digits), and even factory location in a tax-favorable setting.

3.1.5 Energy Cost. Finally, energy cost is explicitly considered as a component of manufacturing cost (whereas it is normally rolled up into the burden rate). This allows for a clear understanding of the magnitude of energy cost in relation to other cost components in a product. It is represented in Eqn. (6), where E_p is the energy required per part, $c_{e,e}$ is the specific cost of energy and η is an efficiency term.

$$C_e = \frac{E_p c_{e,e}}{\eta} \quad (6)$$

It should be clear that this representation can be applied to any, even multiple, energy forms, and overall can be used to support decisions regarding type(s) of power for a selected process type, types of processes selected, and even facility location based on prevailing utility cost and availability.

Application of these cost elements across alternative process sequences can be used to support process selection based on final product cost at the required market volume (Learning Outcome 3). In order to do so, instructors need to ensure that discussions of manufacturing processes cover certain data needed to calculate each cost element. Key data to provide and discuss in the course of manufacturing process lectures includes material utilization (raw material), equipment type (manual, single cycle automatic, automated), cycle time and load/unload time (labor and capital), energy requirements, and tooling cost, life, and setup time. In all of these calculations, more universal costs are needed for raw materials, labor burden, consumables, depreciation, taxes and insurance, maintenance and energy rates as well as the value of scrap. Equipment costs can be supported using budgetary quotes for standard equipment.

In the discussion above, each elemental cost is accumulated into a single value for an entire production sequence. To provide greater insight into the driver of manufacturing costs for a particular sequence, these costs can be broken out also by process step [3, 4]. Further, much of the data provided for cost estimation can be used for rudimentary life cycle analysis [14] using educational software like GRANTA EduPack. As described below in Section 3.2, this approach has been used successfully at Oregon State University to help students choose between process alternatives as part of DFM and Design-for-Sustainability case studies.

Experienced readers will realize the overly-simplistic nature of this cost estimation approach as a singular guiding strategy. Though it can be applied across a wide variety of process types, there are of course additional concerns to be considered during manufacturing process selection. These will affect the outcome of process selection, or at the very least elicit conversation around it. Such considerations include, but are not limited to, the following:

- Safety of personnel interacting with the process,
- Existing engineering expertise and operational/maintenance experience with certain processes or machine types,
- Power and utility requirements vs. those available,
- Availability and location of support functions,
- Environmental impact of selected processes,
- Spare part crib stores of particular brands,
- Corporate strategy for flexibility and agility, and
- Potential future products or product families for which production would need to be prepared.

Therefore, though cost minimization can be taught as an ideal method for process selection, any process discussion should elucidate these additional considerations and how they may affect decision making.

The graduate course based in cost-centered study of manufacturing process analysis has been taught at Clemson since 2007. Student feedback ratings on the effectiveness of this instruction method have averaged 4.49/5.00, compared with a rating of 4.15/5.00 for all other courses in the same level and discipline.

3.2. Evaluating Process Selection Skills through Case Studies

To satisfy Learning Outcomes 1 through 3, efforts at Oregon State University (OSU) have focused on teaching MPD [3, 4, 7]. To date, MPD has been constrained to the activity of specifying, evaluating and selecting a flow of process steps needed to produce a particular product at a required cost and production quantity. As a design methodology [15], the MPD process taught at OSU currently involves process definition, process specification, and process evaluation and selection. Process definition consists of understanding the concept of the product designer and the process requirements of the market, which are typically the product cost target at an annual production quantity, but could also include an environmental impact target. Process specification involves choosing a sequence of manufacturing process steps that are capable of manufacturing the product concept. Process evaluation involves assessing the cost and environmental impact of the process by selecting equipment and estimating product costs and environmental impacts.

While similar in content to design for manufacturing and assembly (DFMA) methods, the teaching of MPD methods is from a different viewpoint. DFMA has come to encompass not only that a component geometry can be produced for a given process, but also that the best manufacturing process has been selected to produce the geometry [15, 16]. In this manner, cost estimation provides product engineers an economic means to evaluate product designs [17, 18]. However, as mentioned above, DFMA puts the emphasis on manufacturing as a constraint. In order to realize manufacturing innovation, MPD methods are needed from the perspective of the manufacturing engineer for how new processes can be designed. As an example, in order for manufacturing engineers to design better processes, efforts are needed to break out manufacturing costs and understand cost drivers in developing new process strategies for reducing product costs. For now, MPD is being taught at OSU as being limited to the selection of manufacturing processes from the set of known production technologies. These efforts are the forerunner to teaching the design of new manufacturing processes capable of addressing gaps in current manufacturing processes (Section 3.4).

Table 1. Seven modules used to teach MPD to undergraduates.

Module	Description	Topics Covered
1	Manufacturing Process Design & Process Selection	Process Definition, Process Selection, Cost Estimation, Environmental Analysis
2	Material Property Enhancement	Metals, Alloys, Strain Hardening & Heat Treatment
3	Metal Casting	Sand Casting Venacular, Defects, Riser Design, Microstructure, Equipment, Casting Processes
4	Metal Forming	Forming Capability, Flow Stress, Temperature Effects, Bulk Forming, Sheet Metal Forming
5	Metal Joining	Joining Capability, Welding Processes, Defects, Welding Rate, Brazing, Soldering, Adhesives
6	Powder, Ceramic and Glass Processing	Punch & Die Processing, Interparticle Friction, Powder Characterization, Powder & Ceramic Processes, Glassworking
7	Polymer Processing	Polymers, Polymerization, Polymer Structure, Properties, Polymer Processes

At OSU, the primary course in which MPD is taught is a ten-week, four-credit-hour undergraduate-level course on Materials and Manufacturing Processes. The most recent offering of the course contained seven modules (Table 1) consisting of twenty 80-minute lectures and eight laboratories (Table 2). Assessment of student learning was performed with homework, laboratories, case studies and exams. Laboratories and homework were used to build student’s skills in process selection and evaluation on the basis of cost and environmental impact (laboratories 1 & 4). The first laboratory was dedicated to helping students develop spreadsheets capable of estimating the costs of products based on prior cost estimation work [13]. Beyond that, these cost estimation tools were used to estimate the cost of various parts using case studies associated with laboratories 2 and 3, culminating in a DFM case study assigned as part of the module 5 homework. Process requirements were provided in terms of cost targets, annual production quantities and critical tolerances. To make grading easier, typically, process alternatives were provided. In some cases, students were asked to determine cycle times, equipment selection or utility requirements for certain process steps based on the information provided or acquired through laboratory exercises. In all cases, additional information necessary to estimate cost, as described in Section 3.1, was provided including the cost of equipment, the cost of tooling and tool life among other factors [4].

Table 2. Laboratory and homework assignments used to complement undergraduate instruction in MPD.

Laboratory	Description	Laboratory activities and associated homework assignments involving MPD
1	Cost Estimation	Develop spreadsheets used to estimate product cost
2	Property Enhancement	Compare results of hardness and tensile tests across several alloys; Economic comparison of hardness and tensile testing
3	Metal Casting	Compare cooling curve results with phase diagrams; Cost estimation of a cast part
4	Life Cycle Analysis	Perform an environmental impact case study to learn how to use GRANTA EduPack EcoAudit capabilities
5	Metal Forming	Evaluate various capability analyses for sheet metal bending; Select between stamping and photochemical machining of a sheet metal part based on cost
6	Metal Welding	Study the effect of spot welding parameters on weld strength and local hardness; Select between spot welding and mechanical clinching for a sheet metal component
7	Powder Processing	Investigate the effects of particle shape on interparticle friction and component density
8	Polymer Injection Molding	Use Moldflow software to investigate the effect of parameters on material density and defects during polymer injection molding

As described, process selection skills were evaluated in the context of five case studies. The objective of the case studies was to enable the students to apply lecture materials and laboratory activities within an MPD framework. Four of the five case studies built on results from corresponding laboratories involving: 1) mechanical property characterization, 2) sand casting, 3) sheet metal bending and 4) spot welding. The first case study involved a cost comparison of using hardness testing versus tensile testing to evaluate the mechanical properties of metal alloys. A scenario for incoming inspection within a company was provided for evaluating which of these different methods was more economical. Building on this, the second case study asked students to use cost estimation skills and results from the casting laboratory to determine the cost of a cast ingot. The third case study did not correspond to laboratory activities but, rather, involved the use of GRANTA EduPack software to introduce the concept of life cycle analysis as another means for evaluating process designs. Students were asked to evaluate different approaches to polymer packaging using an eco-audit tool. The fourth case study involved the use of cost estimation as a means to evaluate two different ways to produce a sheet metal component. In this case, the students were provided a sheet metal part and asked to determine whether photochemical machining or stamping was a better technique based on part cost at the production rates of interest. The fifth case study involved the use of both cost estimation and life cycle analysis as a means to evaluate the sustainability of two different process designs. Students were provided a second sheet metal part (from industry) and asked to determine whether spot welding or clinching was a better technique based on both cost and environmental impact at the production rates of interest. Initially, these case studies were provided as stand-alone case studies. Feedback from students indicated that having separate homework, case studies and laboratory reports became confusing and difficult to manage. Consequently, case studies have been integrated within existing laboratories (first three) and homework assignments (last two).

MPD has been taught as part of the graduate education curriculum at OSU for more than seven years within a micromanufacturing course. One of the course learning outcomes has been to provide the background and skills necessary for developing MPDs in support of products with micrometer-scale dimensions. Students are introduced to the concepts, theory and practice surrounding micromanufacturing techniques available through shared facilities at the OSU Advanced Technology and Manufacturing Institute. In the course, microchannel process technology is used as a means to explore the intricacies of MPD. More details can be found elsewhere [3]. Student feedback ratings on the effectiveness of the course have averaged 5.6/6.0, compared with a rating of 4.6/6.0 for all other courses at the same level within the school.

In this manner the objective of these courses has been to teach students objective skills for selecting manufacturing processes and for evaluating the manufacturability and sustainability of mechanical products. The goal is to teach students to become process designers. MPD has provided a good structure through which manufacturing process course materials are being organized. The long-term goal is to organize lectures for different processes in a way to emphasize not only the process physics, but how an understanding of those physics can lead to capability analysis and essential information necessary in order to conduct a bottom-up cost estimation for a given product design. Reorganizing these courses in this way will lead to recasting Materials and Manufacturing Process courses as MPD courses, delivering similar content in a manner that teaches process design.

3.3. Flipping the Classroom in order to Evaluate the Assimilation of Process Design

The flipped classroom is an instructional pedagogy to employ asynchronous pre-recorded lecture videos and assignments prior to the class time and consequently enable various interactive, hands-on activities with students during the face-to-face in-class time [19]. The flipped classroom has been implemented in ME 481 Manufacturing Processes at the University of Michigan (U-M) and 2.008x Design and Manufacturing II at the Massachusetts Institute of Technology (MIT) with evidence of active, group-based learning opportunities as well as one-one-one consultation and problem solving for students [20]. Well-designed instructional techniques with physical or virtual break-out rooms for student teams can promote interactive discussion among students, teaching assistants and instructors in a flipped classroom setup.

The creative product and process design is a key discussion topic during the class time in ME481 at U-M. Table 3 lists the eleven manufacturing process lecture topics. During the class time, the discussion is centered on specific product and process innovations related to manufacturing processes. At the start of the discussion, the instructor first recaps and presents the background and supplemental information on specific manufacturing processes. Student teams are then grouped in physical or online breakout rooms to discuss and prepare response to questions related to the manufacturing process of the lecture. Afterwards, the whole class reconvenes and each team reports back. The instructor and teaching assistant summarize the discussion. Finally, after the discussion, homework is assigned for each lecture.

Table 3. Lectures and discussion of manufacturing process related product design during class time in flipped classroom.

Lecture	Manufacturing process	Product innovations and discussion during class time
1	Overview of manufacturing processes for national security and competitiveness	Surgical mask production and shortage during COVID-19
2 & 3	Work-materials and tool-materials	Tesla Model Y large die casting (Giga press) and structural battery
4	Machine tools	Hand scraping of the precision machine tool base
5	Programming of computer numerical control machines and industrial robots	Harmonic drive speed reducer and its manufacturing processes
6	Machining	Large telescope lens manufacturing and piezoelectric adaptive optics
7	IC, MEMS, and PCB manufacturing	Intel's dilemma: Integrated device manufacturer (IDM) vs fabless foundry
8	Plastic and composite manufacturing	Thermoplastic carbon fiber composite for aerospace
9	Metal forming	Ford F150 aluminum body-in-white for weight-reduction
10	Additive manufacturing	Why no part in the DJI drone is made by additive manufacturing
11	Joining	SpaceX Starship stainless steel structure welding

As an example, the production of surgical masks and reasons for shortages during COVID-19 was the topic of the discussion in Lecture 1 Overview of Manufacturing Processes for Competitiveness and National Security. The surgical mask design, nonwoven material, joining process and assembly machine were discussed. The homework assignment was to watch the testimony by Mike Bowen (Executive Vice President of Prestige Ameritech, a US-based surgical mask manufacturer) on the Coronavirus Pandemic Response in the US House Energy & Commerce Subcommittee on Health in C-SPAN. Students need to elaborate on weakness in US manufacturing to cause the shortage of personal protection equipment (PPE) and provide their solutions to prevent repeating the same problem in the next pandemic.

This pattern of class time discussion connecting product design and process innovation was repeated for the remaining ten lectures in Table 3. In Lectures 2 and 3 on work- and tool-materials, the Tesla Model Y large aluminum die casting, known as the Giga press, was the topic of discussion. The large die casting parts for the body-in-white were found to eliminate hundreds of robots in the assembly line. The impact of such design innovation in future electric vehicle design was the main topic of discussion during the class time. The homework assignment was on the aluminum alloys and tool materials for such a large die casting process. For Lecture 4 on machine tools, a hand scraping process for precision machine tools was discussed. Manufacturing processes of the harmonic drive speed reducer for robots was the product innovation discussed in Lecture 5 Industrial Robots. Student engagement critically depends on the selection of the class time discussion topic, which links product and process. The topics listed in Table 3 serve as a reference. The course instructors have the freedom to create and develop their own topics.

The first three learning outcomes were fulfilled in ME 481 offered in Fall 2020. For Learning Outcome 1, the relationship between Design and Manufacturing functions in industry is the center of discussion during class time. A key example is the SpaceX decision to use a stainless steel structure design for its Starship. This discussion in class focused on the availability of automatic stainless steel welding equipment and the way to implement quality control for such a large structure.

For Learning Outcome 2, the Lecture 6 discussion on large telescope mirror, lens machining and piezoelectric adaptive optics was used as an example. Three lens designs for very large size telescopes for astronomy research (*e.g.*, the Giant Magellan telescope, European Extremely Large Telescope, and Thirty-meter Telescope) were first presented to students. Challenges in the manufacturing of telescope mirrors, particularly the limitations of weight and size, and DFM changes to minimize manufacturing variation to the piezoelectric adaptive optics of thin segmented mirrors were discussed.

For Learning Outcome 3, the Lecture 8 on thermoplastic (vs. thermoset) carbon fiber composite for aerospace industry was a good example. Processes for thermoplastic tape layering and extrusion of continuous carbon fiber have been adopted in aerospace industry. Compared to traditional thermoset, thermoplastic materials (*e.g.*, polyether ether ketone [PEEK] and low-melt polyaryletherketone [LM-PAEK]) can be recycled and welded for a wide variety of lightweight structures. The selection of a process sequence to match to the product design and specific aerospace and environmental requirements meets the goal of Learning Outcome 3.

For Learning Outcome 4, the Lecture 9 on metal forming process designs to overcome technical challenges (such as warm forming) in high-volume production (900,000 vehicles per year) aluminum sheet forming of the Ford F150 pickup truck body-in-white was the topic of discussion. Impacts of this lightweight structure design on fleet fuel economy and the expansion of aluminum body-in-white to electric cars helped students to achieve the Learning Outcome 4.

ME481 is under continuous improvement and will be one of three pillar technical elective courses at the University of Michigan. Smart manufacturing and MFD are two topics to be incorporated across all lectures.

3.4. Collaborative Problem Solving for Innovating New Manufacturing Processes

The first two sections above covered the selection of manufacturing process sequences from existing manufacturing technology to realize a given product design in light of economics and environmental impact. In this section, plans at Clemson University are explored to address Learning Outcomes 4 and 5 using difficult-to-manufacture designs to seed ideas for evolving or even re-inventing aspects of manufacturing process capability through collaborative team approaches.

DFMA has been a popular mechanism for addressing manufacturing and assembly requirements and considerations early in the development process [21-24]. Typically, the DFMA approach includes using design guidelines and methods for estimating manufacturing costs with early stage, low levels of information [17, 18]. Alternatively, concurrent engineering teams can be developed to infuse manufacturing considerations by including stakeholders in the design process. With a concurrent engineering approach, team and collaboration factors can influence the performance, such as distribution, leadership and decision-making structure, cultural factors, or time pressures [25].

In [2] the authors reported a new paradigm termed *Manufacturing for Design*, whereby the onus of innovation shifts from the product engineer to the manufacturing engineer in terms of discovering or designing a method to manufacture the designed product. Some enabling technologies for this include additive manufacturing [26, 27] and smart flexible factories driven by Industry 4.0 technologies [28, 29]. This approach drives a collaborative approach in contrast with the "throw it over the wall" mentality that has resulted from a historical division of tasks for design and manufacturing functions.

MFD represents a framework whereby product design creativity is not quelled by manufacturing system limitations but rather used as a motive force of innovation to rethink manufacturing process approaches and assist in facilitating real innovation in manufacturing. This is not proposed as a replacement for DFMA, but an extension that can help question the manufacturing-based requirements during a product development process, particularly considering evolving artificial intelligence tools. It is clear that existing machines, planning systems and supply chains cannot be abandoned or reinvented, but one can instead consider an intermediate augmentation step to feasibly enhance existing capital infrastructure and information systems in order to realize new designs in new materials or to achieve new functional requirements and desires. The blending of DFMA and MFD strategies (a proposed DFMA/MFD approach) can lead to feasible evolution of manufacturing, and ultimately disruptive process innovation, defined as a rethinking of manufacturing rather than just improvement on existing solutions.

This approach is currently being applied in two parallel and interlaced programs at Clemson University and Greenville Technical College in Greenville, SC. Graduate THINKER students (comprising mechanical, electrical or automotive engineering and computer science fields) and Associate degree advanced mechatronic students work in teams to address product realization problems put forth from industry in the theme of human-technology interaction. Manufacturing systems are designed in one semester then prototyped in the subsequent semester. Team collaboration effectiveness in collaborative problem solving (CPS) is assessed by a Learning Sciences evaluation team which gives formative and summative feedback to the program [30].

4. Challenges and Recommendations

While a good deal of creativity has gone into the development of new methods for teaching manufacturing processes in the context of MPD, several challenges remain. First and foremost is the means to share classroom materials. To be useful, this has to include not only lecture materials, but also case study materials, assignments and examinations. A beginning strategy is to gather the best practices at each university, and to create a public domain digital repository of programmatic strategic overviews, course content, graphics, highlight and lecture videos, homework and exam problems for instructors (especially junior faculty) to draw from in developing MPD courses. Many figures and videos are copyrighted and cannot be freely distributed. Based on consultation with copyright experts at the U-M library, sharing coursework materials among instructors for a noncommercial instructional purpose is legal. The onus to secure the use of copyrighted materials within university courses will be up to individual instructors.

Second, to make it easier for new faculty to assimilate these new methods within their courses, efforts are needed to standardize content. For the learning outcomes discussed in Section 2, the authors offer a general structure of future courses for teaching MPD (DFMA/MFD) as shown in Table 4. To deliver this course content to students, efforts are needed to develop guidebooks and templates that overlay the repository of course materials, bringing them together in ways that facilitates instruction. Instead of a comprehensive textbook which covers the knowledge of all manufacturing processes, a cyber-based approach is needed that is flexible (for different teaching styles), adaptable (for different focuses in lecture), digital (no paper copy) and low-cost (for students). This is a challenge as well as a great opportunity for educational innovation in manufacturing process education. The goal is not to duplicate the vast amount of manufacturing process and DFMA materials available to educate students, rather to integrate materials from different publishers in a way to facilitate the teaching of MPD.

Table 4. Recommendations for future content required to teach MPD.

- The relationship between Product Design and Process Design
    - The Design-Manufacturing culture
    - Understanding and translating requirements into design specifications
    - Translating design specifications into manufacturing specifications
    - How teams of product designers work and how manufacturing can contribute
- Evaluating product designs (DFMA)
    - Questioning specifications
    - Feedback on product designs
- Process selection
    - Understanding available processes
        - Process physics
    - Cost estimation
        - Unit manufacturing processes, defining a set of standardized process steps
    - Make vs. buy analysis, Manufacturing as a service
    - Additional considerations (existing equipment, expertise, build country/environment, training, maintenance)
- Process integration (integrate processes together into a system)
    - Energy, material handling, data flow
- Design of new processes (MFD)
    - Formalized approach structure: Augmentation vs. Reinvention
    - Leveraging technology trends (past: programmable logic controllers, present: additive manufacturing, future: smart manufacturing and artificial intelligence)
    - Human side of manufacturing

Further, some new pedagogical materials may be needed, such as those needed to teach process selection and/or the design of new manufacturing processes. Additional modules will likely be needed including discussions on challenges across dimensional scales as well as modules on metrology and surface finishing. Of particular interest is the opportunity to integrate new methods for assessing the impact of manufacturing processes. This includes feature-based cost estimation techniques [31, 32] that have been embedded within design software (*e.g.* aPriori). Furthermore, opportunities exist to develop reusable life cycle inventory data models for conducting gate-to-gate and full life cycle assessments for assessing the environmental impact of MPDs based on unit manufacturing processes [33]. Finally, it would be helpful to develop additional industrial case study materials (across traditional and high-innovation industries) that could flow-through the materials as running examples to illustrate concepts, using cost estimation methods to explain the effects of selection and/or design decisions upon product cost at required market quantities. These case studies could be integrated with homework and laboratory assignments as needed. New generative design tools (*e.g.* within Autodesk Fusion) could become a critical learning resource for advancing these case studies.

A recommendation for learning material to support a broader understanding of the interrelationships of Design and Manufacturing is education in personal relationship success on teams. Engineering design is described as a complex social activity, the complexity of which is mitigated through the systematic sequencing of activities and the integration of many actors to ensure coverage of a shared view (*i.e.*, collaboration) [34]. Engineering design is the process through which collocated teams of project managers and discipline specialists engaged in individual tasks address a human need through an iteration of steps: problem definition, conceptual design, configuration and parametric sizing, and detailed design [15, 35, 36]. The individual silos and decoupled tasks in this approach often prevent creating a shared vision among the individual team members, especially across traditional Design and Manufacturing disciplines. A true collaborative design scenario means that the actors have a common objective through the sharing of resources, ideas, expertise, and responsibilities [37]. In this scenario, the team members, information, and resources may span geographic, organizational, digital, or temporal boundaries with design tasks performed in parallel or series.

At no other point in history has there been such a prevalence of interdependently designed, collective-centric work in organizations as today [38]. No longer are great accomplishments achieved by "lone wolves" operating in isolation; instead, they are reached through the combined, interdependent efforts of many, reaching outcomes beyond that of what could be accomplished by any one individual alone. This process of teaming is not singular, but instead comprises numerous sub-processes, both explicit and implicit, that become increasingly complex in the modern digital age. While prior research has largely focused upon the interplay of human-human teaming, there is a growing recognition of the critical need to understand how artificial agents can and will interface with human team members in terms of dynamics such as handoffs, sequencing, and coordination patterns, as well as meeting deadlines under time pressure. In any teaming case however, the clear understanding of human requirements should be considered in team and system design [39].

The former points about the need for good interpersonal communication and the important role of the need for interdependent teaming in manufacturing-based design highlight an explicit need to consider diversity and inclusion guidance in the development of a repository of knowledge. These teams are heterogeneous in many dimensions of diversity: gender, race, background, education, expertise, philosophy, communication style and more. The need for developing materials with an eye toward considering all team members' input and communicating effectively with people from a variety of persepctives, has never been more critical than in today's world.

Finally, assessment materials and guidance will be key for any educational program success, particularly as methods and procedures depart from the traditional. The assessment of Herro *et al.* [30] has highlighted the value of "ill-defined and ill-structured" (*i.e.* open-ended) problems representing modern design challenges to present to teams in order to elicit effective reliance on interpersonal relationships and team dynamics to bring forth creativity. They discovered four main themes driving effective instruction in collaborative problem solving:

- Choice of collaborative communication tools for sharing ideas and content (especially apparent during the COVID-19 situation),
- The importance of recognizing expertise when forming teams and deciding responsibilities,
- Building trust, and
- The importance of individual work outside of team settings in contributing to design success (again becoming especially apparent during COVID-19)

As new pedagogies are developed for teaching manufacturing process design, sound strategies for assessment will be necessary in order to ensure that educational methods are capable of preparing future manufacturing engineers.

5. Summary

The aim of the authors is to plan for educating a new generation of engineers who are knowledgeable of manufacturing processes and its relationship to engineered products. Such engineers will continue learning and innovating new product and process technologies becoming leaders in their industries. Students with such backgrounds can become excellent manufacturing engineers for designing new manufacturing technology in support of the production line. They also can be equally excellent product design engineers with an understanding of the limitations and potential breakthroughs available through MPD. As a result, the authors desire to instill a spirit of innovation within future students, educating them to become leaders of manufacturing enterprises providing impact throughout society. Integrated product and process design is a complex social activity requiring collaboration and teamwork. A vision to understand and strengthen these relationships can serve as the foundation for a new dimension of design-centered manufacturing education.

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