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WIP PAPER: Integration of Mechanical Properties of Materials in an Undergraduate Course on Manufacturing Processes for both Mechanical and Industrial Engineering Students

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Abstract:

At the University of Puerto Rico's Mayagüez campus in the Department of Mechanical Engineering, a course on Manufacturing Processes (INME 4055) is offered. The course is compulsory for the Mechanical Engineering (ME) and the Industrial Engineering (IE) undergraduates. This paper outlines the pros and cons, the promises and challenges, in communicating with students from two different programs with two different educational preparations taking the same Manufacturing Processes course. ME students take a course on Mechanics of Materials as a prerequisite for this course, whereas their IE peers do not. The promise is the peer-learning that emerges as a function of group assignments. For example, when ME and IE students are mixed together in small groups of 3 to 4 students per group, the ME students tutor and prepare their IE partners in both written reports and their oral presentations. However, in individual tests, the IE students struggle because they do not grasp foundational concepts and do not have the practice that their ME peers have through the pre-requisite class. As such, IE students work at a a slower pace and bump up against time constraints during testing. This WIP paper suggests several ways of addressing this educational challenge in service of the students and their instructors.

Key words: elasticity, plasticity, bulk forming, machining, casting, welding

Introduction and Historical Antecedent:

At the University of Puerto Rico's Mayagüez campus, Mechanical Engineering is one of the two founding departments, each over a century old. In fact, the campus is still called by its initial name, College of Agriculture and Mechanical Art (Colegio de Agricultura y Artes Mecánicas: CAAM as abbreviated in Spanish). Currently the Mechanical Engineering Department is very strong in student enrollment, diversity of programs, and graduate studies. Even today, the Mechanical Engineering department demands the highest grade point average (GPA) from incoming high school graduates. Among all the departments of the Faculty of Engineering, namely, Civil, Electrical, Chemical, Mechanical and Industrial, graduates from Mechanical Engineering departments are still at highest demand in Puerto Rico's local industries, including mainland U.S.

The Mechanical Engineering undergraduate program is concentrated in five areas, such as, Thermo-fluidics, Machine design, Manufacturing and Materials, Aerospace Engineering and Bio-engineering. While thermo-fluidics and aerospace go hand in hand with each other, the joint materials and manufacturing section relates more to machine design. Bio-engineering includes biomaterials and their manufacturing processes whereas the conventional manufacturing processes in the macroscale level give a general introduction to the processes that are often used in the metalworking industries. This general introductory course is offered to the fourth year undergraduate students in both Mechanical Engineering (ME) and

Industrial Engineering (IE) in their Bachelor's Degree programs; and *the course is compulsory for both the programs [1].* This paper addresses this joint venture of ME and IE undergraduate students in a compulsory course on some of the fundamental ideas of the mechanics of materials and their direct applications in several basic manufacturing processes extensively used in the manufacturing/metalworking industries.

A brief overview at the course syllabus:

The prerequisites for this course include:

Microstructures for metals and polymers;

Mechanical properties of materials;

Phase diagrams for steel and other alloys;

Some basic inorganic chemical reactions;

Some basic relations relating forces, stresses and strains.

The *specific objectives* of the course are to facilitate exploring the basic concepts of the mechanics of materials and to apply them in the manufacturing processes commonly used in metalworking industries; and offer some design criteria for these manufacturing processes.

The class lectures are divided as follows:

1. A brief review of metals, alloys, ceramics, polymers, and composites used in manufacturing processes.
2. Quality control including tolerances on basic dimensions, surface finish, and texture of the final product.
3. Processes of casting, molding, and their design considerations on the geometry of the final product.
4. Materials forming: Basic concepts of elasticity and plasticity and their applications in materials forming processes, such as, rolling, extrusion, forging, drawing, hydroforming and electro-magnetic forming.
5. Materials removal processes: Basic concepts of flow and fracture, and their applications in machining, grinding, electric discharge machining (EDM), electrochemical machining (ECM) and chemical mechanical planarization (CMP) processes.
6. Materials union processes: Welding, soldering and other permanent and temporary assembly (joining) processes like fastening with nuts and bolts, riveting, etc.
7. Production automation: Computerized numerical control (CNC), flexible manufacturing systems (FMS), basic group technology (GT), coding and classification of parts.

See detailed syllabus in Appendix A

A brief analysis of the syllabus:

Understanding the mechanics of materials is of utmost importance in a course on Manufacturing Processes. As such, the first few lectures are delivered on the mechanics of materials, covering the basics of elasticity and plasticity, ending in fracture mechanics. Hooke's Law is explained in the elastic region, and Ludwick's law in the plastic region. For the ductile materials used extensively in the metalworking industries, the yield criteria, the instability criteria, and the fracture criteria are emphasized. The behavior of the brittle materials, such as the ceramics, cast iron, glass, several composites, etc. that are used in the manufacturing industries are also introduced [2].

During the lecture sessions of the particular manufacturing processes, like casting, materials forming, materials removal, materials addition, the fundamentals of the mechanics of materials are applied to each of the processes mentioned here. For understanding the manufacturing processes common in the metalworking industries, the mechanics of materials is as important as statics and dynamics, called in a common combined term as *Rational Mechanics*, originally stemming from its Latin root.

In the section dealing with Materials Forming, the Volume Constancy Law is introduced because it is applied to the analysis of some of the most industrial mass production processes, such as, rolling, forging, wire and cup drawing, extrusion, etc. as conventional processes as well as hydroforming, electromagnetic forming and explosive forming as nontraditional processes. In materials removal processes where the volume is lost, such as in machining, grinding, sand blasting and chemical mechanical planarization (CMP), the basic concepts of fracture mechanics are introduced before embarking on the individual processes, because chips and burrs have to be physically separated from the work material in order to produce the final part or component. In materials addition processes where the volume is gained, such as the permanent assembly processes, such as welding, soldering and the other forms of joining methods, the applications of the behavior of materials are illustrated in each process.

Furthermore, many of the aforementioned processes are carried out as *hot working* where the working temperature is above the recrystallization temperature of the work material. Some of the fundamental concepts of thermodynamics and heat transfer are introduced here in to understand the thermal effects on the governing parameters in each individual manufacturing process mentioned above. For example, how the temperature and the "strain rate" affect the work material during a process needs to be addressed clearly in a class lecture before analyzing the process parameters for the minimum cost or for the minimum process cycle time in a situation of mass production in the industries. With this understanding the mechanics of materials, students have the foundational understanding necessary for further learning in course on Manufacturing Processes.

Instructor's Dilemma and Students' Confusion:

In a lecture hall where the undergraduate students from Mechanical Engineering (ME) and Industrial Engineering (IE) are assembled for a joint class, the instructor faces a situation similar to what we call *'mixed media flow'* in fluid mechanics. Whereas each fluid medium has its own individual properties and functional characteristics, the common goal is the *flow*. Similarly, before coming to attend this course on Manufacturing Processes in the fourth year, the ME and the IE students have very different academic and professional preparations and aspirations over the preceding three years. Nevertheless, the common goal is to comprehend and apply the basic concepts of flow and fracture of deformable materials in manufacturing processes that are common in the metalworking industries today. For example, the IE students take several beginner's courses on statistics and on the theory of probability. The ME students, on the other hand, take a course on mechanics of materials and another on materials science; and both of the courses focus on the deterministic methods in dealing with the mechanics and the science of materials rather than applying any statistical tools. In the area of thermo-fluidics (one course in fluid mechanics, three in thermodynamics and one on heat transfer) the ME students do not use any *statistical* *thermodynamics*, originally introduced by Max Planck and further advanced by Erwin Schrödinger [3] and many other physics gurus during the first half of the twentieth century.

The instructor, being conscious of the time constraints, starts with the stress-strain diagram, then proceeds with the yield criterion of von Mises and the Ludwick's Law, the volume constancy, the instability and fracture criteria of the material, assuming that all the students have some background in the general area of the mechanics of materials, at least, the definitions of the terms used. The IE students do not keep up with their ME counterparts for not having enough background in the deterministic laws of the mechanical behavior of materials. The instructor, again, due to the time limits, does not fully cover the statistical quality control of the final products in batch production, an area that the IE students are more competent in as compared with their ME peers.

Thus, many IE students get bored, and even frustrated, in a class when the instructor is talking most of the time about Stress, Strain and Strength – the SSS of manufacture-able materials. What about the statistical quality control of such workpiece materials in mass production? What about introducing the concepts of clean manufacturing, lean manufacturing, green manufacturing, etc. in class lectures? The honest answer is that we simply don't have enough time to cover so many aspects of manufacturing processes and systems in a single course.

Near the end of the semester we offer a few lectures on the topics that interest the IE students: Group Technology (GT), Flexible Manufacturing Systems (FMS) and Computer Integrated Manufacturing (CIM). But this is only a very quick overview, a cosmetic facelift and not deep learning.

Some Viable Solutions:

Many decades ago when the term "manufacturing processes" was almost nonexistent or in its embryonic state, most of the Mechanical Engineering schools used to offer two courses: Production Engineering I and Production Engineering II for the undergraduates. The word 'Production Engineering' was synonymous with the term 'Manufacturing Engineering 'of today. While Production Engineering I used to cover all the "hardware" of industrial manufacturing processes, Production Engineering II dealt with the softer sides of manufacturing what we call today as "Manufacturing Systems". Manufacturing systems include statistical tools in quality control where the IE students not only feel comfortable but can also contribute significantly to the class. The same is true in the areas of Group Technology (GT), Flexible Manufacturing Systems (FMS), Coding and Classification Systems, Manufacturing Cells, Time and Motion Study, etc.

Today there are several standard textbooks for this undergraduate course on Manufacturing Processes; the two most widely used are by Professor Groover [4] and by Professor Kalpakjian [5]. Interestingly indeed, Prof. Groover is an Industrial Engineer and Prof. Kalpakjian is a Mechanical Engineer; and their books are very similar. The chapters are very similar, almost parallel in dealing with the hard side of the manufacturing processes – the materials and the machines for any particular process. Only in the last couple of chapters of each book are the topics of the manufacturing systems briefly illustrated, and not enough for a full one semester for IE undergraduates. Thus, there is no dichotomy, no conflicting duality in the process of instruction. It is only the question of bifurcating interest and preparation among the IE and the ME students, and the time constraints for satisfying both the groups!

One viable solution is to offer two different courses, one for the ME and the other for the IE undergraduates. Manufacturing Processes, similar to Production Engineering I of the old school can be taught in the ME Department and Manufacturing Systems, similar to Production Engineering II, can be offered in the IE Department. Such bifurcations are very common and have been routinely accepted in engineering curricula: Thermodynamics for Chemical Engineers, Strength of Materials for Civil Engineers or Machinery Vibrations for Mechanical Engineers. This way both the instructor and the students are happier!

Nevertheless, this change to two courses instead of one increases credit hours for the department faculty and hence, the cost increases in the departmental budget. Therefore, we are looking for other solutions that will place a burden on the budget. One such solution is to divide the students in the class into small groups of three to four students per group such that each group has at least one IE student. Some of the assignments should be given in the form of working in groups where the ME students can do peer tutoring to their IE partners within each group. This seems to be a very good and viable solution since we don't need to reschedule the class hours nor the lecture rooms. Besides, the students will learn how to work in a group in a "real world" industrial environment instead of working alone.

Similar systems of dividing a large class into small groups for tutorial sessions (after the main lecture is delivered by the professor) had been established in German engineering schools many decades ago. The professor gives the general lecture on a particular topic, mainly its theoretical constructs, in a large lecture hall, maybe with over hundred students in the hall. Such lectures are called *'Vorlesungen'* in German. Then the class is divided into many small groups, called *'Übungen'*, where the Graduate Students who are Teaching Assistants (*Wissenschaftlicher Mitarbeiter,* translated literally in English: 'Scientific Coworker') help the small groups in solving particular tutorial problems, such as the numerical examples on a particular topic covered in the main lecture. Another suggestion is to offer a few 'back up' lectures on the basic terms of elasticity and plasticity for the IE students in parallel sessions. This will involve a bit more work for the instructor but the IE students will feel more comfortable and less confused when the chapters on the individual manufacturing process like rolling, machining and casting will start. This can be implemented with no extra cost if the instructor agrees to offer a few more hours of lecture *ad honorem.*

Another way of bridging the gap is to design in the instructional learning joint oral presentations by the ME and IE students. A typical group consists of two ME and one IE student. The group in its presentation talks about a particular topic from an industrial perspective. Many students in the class have previous industrial internship experience. Relating such experiences of a real life manufacturing scenario opens up an environment of group dynamics, particularly during the question–answer session after each talk. We tried this method in the Fall 2019-20 semester, and it appears that the IE students are feeling more comfortable in the class in their interaction with their ME peers as well as with the instructor. Some student comments are given in Appendix B.

Closing Remarks:

Combining students of different background preparations under one course is difficult, not only in engineering and physical sciences (i.e. engineering physics, analytical chemistry, materials science, etc.) but also in many other disciplines. It may be even more complex in socio-humanistic courses where the students of behavioral sciences (i.e. psychology, sociology, anthropology, etc.) join with their counterparts from life sciences, such as, biology, physiology, kinesiology, etc., due to some common, overlapping interests in interdisciplinary research.

The conflict between the Mechanical Engineering (ME) and the Industrial Engineering (IE) preparatory background stems from focusing on deterministic and probabilistic preparations. The IE undergraduate program introduces several courses on statistics whereas ME has none. On the other hand, the ME undergraduate program offers two compulsory courses: Mechanics of Materials and Materials Science, as prerequisites for this very basic course on Manufacturing Processes.

The goal is to make all the students of ME and IE undergraduate programs feel prepared and comfortable in the class lectures. And there is no easy, quick-fix engineering solution! A similar scenario exists in a general course on Vibration. In chemical engineering, vibrations are generated from the chemical reactions in the reaction towers; in civil engineering, there are seismic vibrations; in mechanical engineering, there are machinery vibrations arising in the machine tools like lathe, milling machine, grinder, etc. Vibrations produce 'chatter marks' on the machined parts. In a common course on Vibration, where to start and where to end?

An optimal solution in such interdisciplinary courses is to prepare the students with some basic analytical "tools" that can be used as fundamentals – a common platform of operations – for different but allied disciplines. A basic course on vibration can start with a simple second order differential equation for a 'spring-mass' vibrating system, and explain therefrom overdamped, underdamped and critically damped vibrations. Later, this basic model can be modified for particular applications in civil, mechanical and chemical Engineering. In a basic course on Manufacturing Processes this common platform is mechanics of materials: phenomenological and structural plasticity. Some statistics can be introduced in structural plasticity for the IE students whereas the other part is essentially deterministic. In group assignments, including written reports and their oral presentations, both the ME and the IE students are expected to benefit from each other. This will also alleviate the boredom of conventional tests and exams.

References:

1. Course syllabus; Manufacturing Processes; Updated for the ABET visit in November 2019; Mechanical Engineering Undergraduate program, University of Puerto Rico. (See Appendix A).
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5. Kalpakjian, S, and Schmid, S. R.; Manufacturing Processes for Engineering Materials (5th Edition); Prentice Hall (New Jersey); 2008; Chapters 2, 5, 6, 8-10, 12, 15.

APPENDIX A: Course Syllabus of Manufacturing Processes (INME 4055)

Course Title: Manufacturing Processes; number of credits: 3; Contact Period: Three hours of lecture/week.

Textbook: Groover, M. P.; Fundamentals of Modern Manufacturing Materials, Processes and Systems (5th edition); 2015; Wiley.

Course Description: Different manufacturing processes and machine tools; influence of the method of fabrication upon the properties of materials; computer numerical control (CNC) of machine tools and operations; use of plastics. Group Technology (GT), Flexible Manufacturing System (FMS); coding and classification system.

Prerequisites and co-requisites: INGE 4001 or INME 4107

Course Objectives:

Upon successful completion, students will be able to:

-Distinguish between different types of casting and differentiate between their outputs;

-Identify, formulate and solve bulk deformation processes like forging, rolling, extrusion, drawing, etc.

-Identify, formulate and solve machining operations of turning, milling, drilling, grinding, etc.

- Relate the common mechanisms of tool wear to desirable cutting tool material properties;

-Examine a design/drawing of a component and describe a feasible sequence of manufacturing processes.

Instructional Strategies:

Lectures in the class, home assignments (individual and in groups), oral presentations.

Thematic outline and timeframe (in hours of lecture):

Introduction to manufacturing (2); Review of materials science (3); Statistical process control (2); Process capability (2); Casting (2); Solidification and structures (2); Heat transfer on molds (2); Fluid flow (2); Review of mechanics of materials: elasticity, plasticity and fracture mechanics (4); Bulk deformation: rolling, forging, extrusion, drawing, hydro-form, electromagnetic forming, etc. (8); Materials removal processes: machining, grinding, EDM. ECM, Chemical mechanical planarization (CMP), etc. (8); Computer numerical control (CNC) of machine tools and operations(3); Group technology, flexible manufacturing, coding (2); partial tests (3); **Total classroom contact period: 45 hours per semester.**

Evaluation Strategies:

Take home assignments, written reports and their oral presentations (in group), written tests in the class (individual), final exam (individual). NOTE: There is a range of “weight /percentage” for each evaluation. Usually each instructor decides over the percentage as long as it is within the range.

APPENDIX B: Opinion of some of the Industrial Engineering (IE) students in the class:

Excerpts from an opinion survey of students in this joint ME and IE class are given here.

- Most of the concepts that are taught in the class are new to industrial engineers since we focus on other aspects of the mass manufacturing industry, such as, optimization, automation and cost analysis of the different processes involved. The dynamics of the class is a huge plus to integrate us, the industrial engineering students.

- In my experience, I feel that I can now design better manufacturing layouts, generate more automation ideas, incorporate better safety requirements and even grow a desire to study mechanical engineering in the future after coursing the Manufacturing Processes class. Also, some students may correlate the importance of the topics with IE applications on their own, but some may need more guidance with a more IE focused class of manufacturing processes.

- At first glance I thought the class of manufacturing processes would be unnecessary for us, the industrial engineers. After the first couple of classes I realized that there is a lot to learn from how different processes affect materials and the importance of how these materials are treated and manipulated. I have to make notice of how the professor has made an attempt to show the different opportunities for all engineers in having students showcase their experience at a CO-OP or Internship in the industry.

- The manufacturing class INME 4055 is a class that applies for all engineers to be able to be related with manufacturing processes and understand how materials work, with a focus in safety, design and all processes available to perform any kind of work for a raw material. It would be important to have a space in the course to perform cost management analysis for the raw material, for the elaboration process, for maintenance. It would be interesting to perform statistical analysis, design, planning, operations management, simulations and problem solving.

- We were completely lost when the professor was mentioning all the concepts he was going to teach us in the semester. But thanks to the professor's easy to understand teaching, we survived. Impressively, the professor explained the concepts with real life problems that made it incredibly easy to understand. He introduced the volunteered opportunity of presenting a CO-OP/Internship experience that the student was a part of. This was an interesting new teaching tool that we never experienced before. At first, we were a bit skeptical about it, but after experiencing the presentations first hand, it brought a whole new perspective about what we were learning in the class.