Title:
From Thought to Thing: Using the Fused Deposition Modeling and 3D Printing Processes for Undergraduate Design Projects

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Introduction:
Undergraduate engineering education balances engaging the students with mathematics, natural sciences, engineering science, engineering design, and complementary studies elements. 'Engineering design' integrates these core categories in order to develop products, processes and systems that target the functional requirements while considering realistic constraints – such as the economics, health, safety, environmental impact, and so forth. The students should be exposed to understanding the problem, the iterative nature of design, and creative problem solving in a variety of topics related to their discipline. Preparing graduates for engineering practice in industry is a principle objective. Towards this goal, educators are switching to outcome-based assessment to demonstrate that students have learned the required skills and knowledge. This approach complements the CDIO curriculum (Conceiving – Designing – Implementing – Operating) model [3] for developing systems and products. Team based projects focus on design-build-test tasks, integrating theoretical problem solving with practical issues actively.

The discussion for this paper targets developing physical functional prototypes within a variety of classroom settings. Students experience unique challenges throughout the design process, as they are required to apply academic knowledge to open-ended problems which do not have a single answer. Translating the 'needs' statements and the functional requirements into quantifiable elements and design parameters can be difficult for students [7]. More than technical knowledge is required to understand and solve the problems. Judgment skills related to tools and methods to be used for a given project and project management also need to be developed.

Conceptual designs need to be fleshed out, and detail designs generated prior to realizing a design. To evaluate and refine the design, it must be implemented at some level and tested (Figure 1). Typically, students do not have an appreciation of process planning issues, fixture design, and other manufacturing and assembly issues. Using additive manufacturing (AM) methods expands the opportunities for students to realize their designs as they are developing their academic and practicum skill sets, as the process knowledge requirements are minimal. The process options typically are limited to selecting the slice thickness and build orientation, which correlates to the 'draft, normal, and fine' print settings and the paper orientation (portrait or landscape).

The objective of this work is to highlight challenges and successes when using these technologies for undergraduate course work, and to show how these technologies can be incorporated in several courses. The general build process flow and the process milestones are presented in Figure 2.

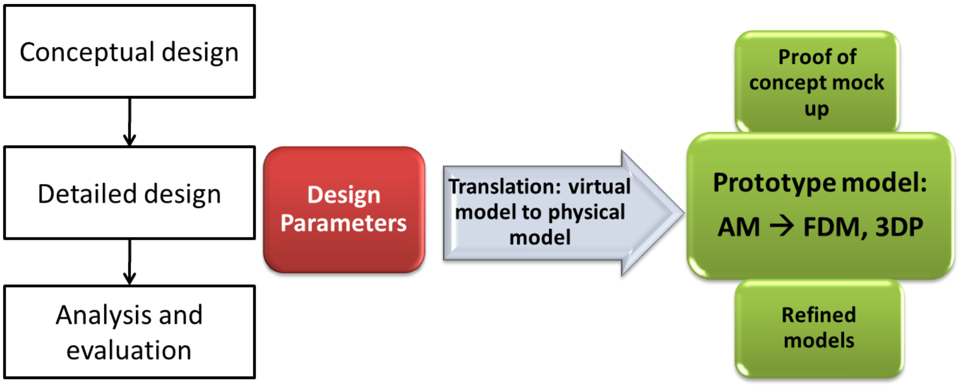

Fig. 1: Physical realization of the virtual mode.

The main milestones presented in Figure 2 are: (i) CAD 3D model review, (ii) process plan development, (iii) job scheduling, and (iv) testing / final design. The CAD model review focuses on ensuring the model is valid from a fabrication perspective. The process planning and job scheduling discussions focus on building limitations and the post process requirements.

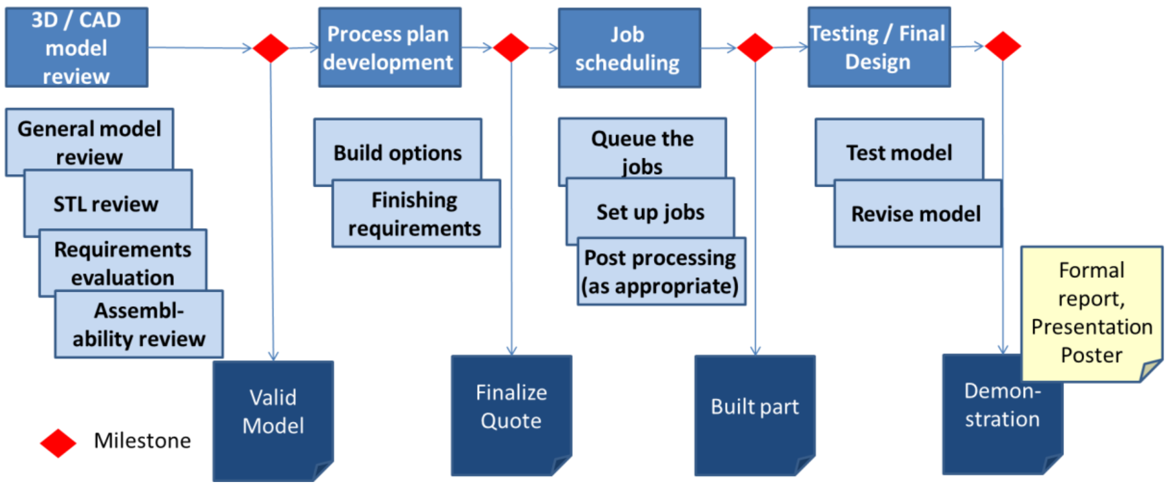

Fig. 2: The build process flow and milestones for realizing components using the 3DP and FDM processes.

<u>Main Ideas:</u>
The FDM and 3DP fabrication processes require minimal interactions to determine a process plan; however, there are many practical issues to consider throughout the design process. Although AM processes are touted as “done in one” fabrication solutions, there limitations and time – quality tradeoffs to be considered. The CAD model must be ‘water tight’, all fillets must be in the CAD model, or else internal sharp corners will be manufactured. Fabricating thin walls, small features, closely positioned features, and features with thick wall – thin wall junctions can be problematic. Large components need to be segmented, as the build envelopes for the FDM and 3DP fabrication processes are enclosed, and not expandable.

The FDM and 3D printing processes will fabricate a component with anisotropic properties [1, 2], [5, 6], [8], and the limits for all the available materials-process conditions are not well-defined. Therefore, base line testing needs to be done to establish design guidelines and fabrication rules. The final application strength requirements should be considered during the component design cycle and prior to selecting a fabrication strategy.

When developing a process plan, and queuing the build jobs, the slice thickness, location, and orientation within the build envelope are the main decision parameters. Although there are limited decision parameters, innovative job queuing strategies can be employed. For example, for the 3DP process, multiple components can be nested in the build envelope. This is a viable solution to minimize the layer-powder preparation time impact (Figure 3). It must be ensured that there is sufficient clearance between components.

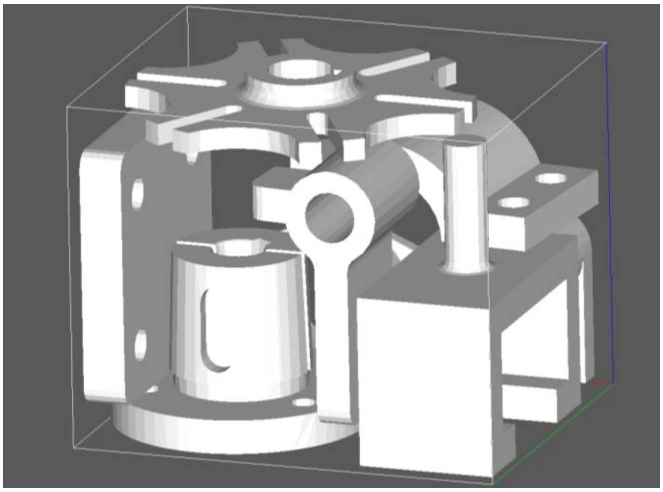

Fig. 3: Eight models positioned within the 3DP build envelope.

The post processing requirements for both the FDM and 3DP processes may be significant. Post processing issues need to be considered, as the final component may not have the strength, durability, or surface finish required without additional treatment or rework. This is AM process dependent. From a process layout perspective, there needs to be room for the machine(s), storage, and the post processing operations. For both the 3DP and FDM processes, the build area must include storage for consumables (3DP: powder, ink, binder, resin; FDM: build and support material, base plates, tips, etc.), machine maintenance tools (grease kit, brushes, spray bottles and shovels), and safety equipment (lab coats to be used while resin coating, neoprene gloves, and safety goggles (for 3DP resin applications) or safety glasses (FDM process)). The listed safety equipment is required for the post processing operations A post processing area with appropriate ventilation is required as the impregnation materials may irritate the lungs, and dust is generated with any sanding. The ZBond® 101 resin material is an extremely fast setting, low viscosity, general-purpose infiltration resin, and a work area to allow for spraying, dipping or painting the coating must be provided. The support material must be removed for the FDM parts. A work area to allow for physical material removal or an immersion tank for the dissolvable support material must be provided. Attention must be paid to machine maintenance.

Design and build projects have been introduced in a variety of courses, and they include architectural projects such as a 3D campus map consisting of sections for the 85-119 Technical Communications course (Figure 4), or the design and testing of an individualized bike seat (Figure 5).

Fig. 4: Section of the campus scale model [4].

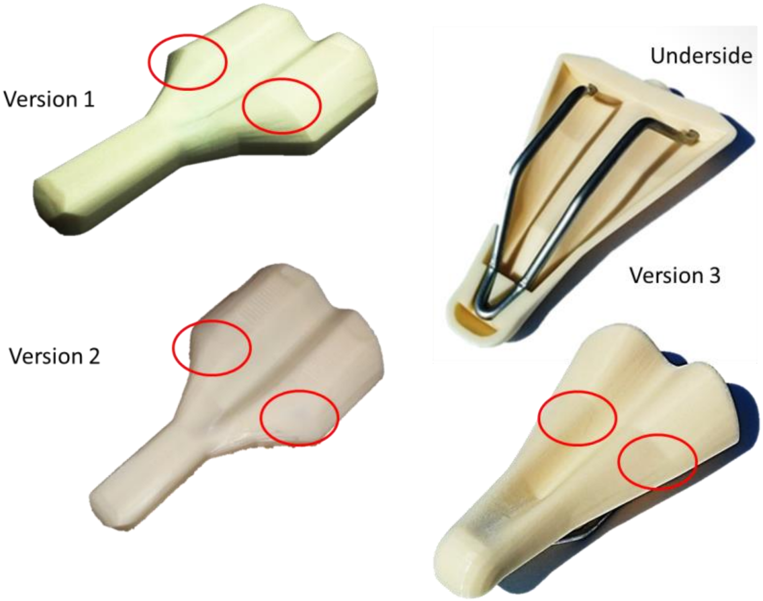

Fig. 4: Individualized bike seat design configurations: version 3 is the final design configuration.

Conclusions:

The use of the 3DP and FDM additive manufacturing processes has allowed students to realize sophisticated designs, and then test them as appropriate. Employing AM technologies has advanced their design experience, as this technology allows for a greater 'create – design' solution space, as the process planning efforts are significantly reduced using these technologies. There are practical modeling issues, and some 'design for manufacturing' issues to be considered.

Post processing issues need to be considered, as the final component may not have the strength, durability, or surface finish required without additional treatment or rework. This is AM process dependent. The post processing is time consuming for the 3DP and FDM additive manufacturing processes, but grinding, sand blasting, cleaning, and coating are typical post processing issues for several other processes, so the students will gain insight into standard final finishing related fabrication issues, but they are not overwhelmed by them. Care must be taken to provide space and the appropriate safety equipment, and to ensure that the students follow safe procedures.

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