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From thought to thing: using the fused deposition modeling and 3D printing processes for undergraduate design projects

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ABSTRACT
This paper describes the processes used to integrate two additive manufacturing (AM) processes into various engineering courses, which contain a design element, at the University of Windsor. The 3D printing (3DP) and fused deposition modeling (FDM) AM processes are used to fabricate components. There are unique design and post processing opportunities and issues associated with these processes, which are described in detail. Sophisticated projects can be fabricated and tested by personnel with limited technical skill sets, as the process planning is uncomplicated, and minimal supervision is required while the part is being built. A selection of student projects is presented to highlight the opportunities that can be realized, and to discuss the post processing challenges.

KEYWORDS
Fused deposition modeling; 3D printing; functional prototypes; design process; practicum

1. 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 [6]. 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. Performance indicators, curriculum maps, and assessment schedules are being developed to assess the learning outcomes [6,7], [12,13], [31]. This approach complements the CDIO curriculum (Conceiving – Designing – Implementing – Operating) model for developing systems and products. Team based projects focus on design-build-test tasks, integrating theoretical problem solving with practical issues [8,9]. The discussion for this paper targets developing physical functional prototypes to allow student teams to experience the CDIO challenges for a variety of industry sponsored or entrepreneurial undergraduate design projects. The process flow, and lessons learned are presented in section 2.0, sample student projects in section 3, and the summary and conclusions in section 4.

Students experience unique challenges throughout the design process, as they are required to apply academic knowledge to open-ended problems that 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 and should not be underestimated [23]. This requires more than technical knowledge [26] to understand and solve the problems. Judgment skills related to tools and methods to be used for a given project as well project management (time and resource management) also need to be developed. Idea generation techniques, conceptual sketches, and crude physical mockups can be utilized to help with the problem definition, and provide a basis for a variety of concept designs to be explored in more detail (Figure 1).

The conceptual designs need to be fleshed out, and detail designs generated prior to realizing the final design solution. To evaluate and refine the design, it must be implemented at some level and tested (Figure 2). Typically, students do not have an appreciation of process planning concerns, fixture design, and other manufacturing and assembly issues. Comprehension of product realization challenges and decision making related to the necessary skill levels, time, costs, and available resources should be learned throughout a program of

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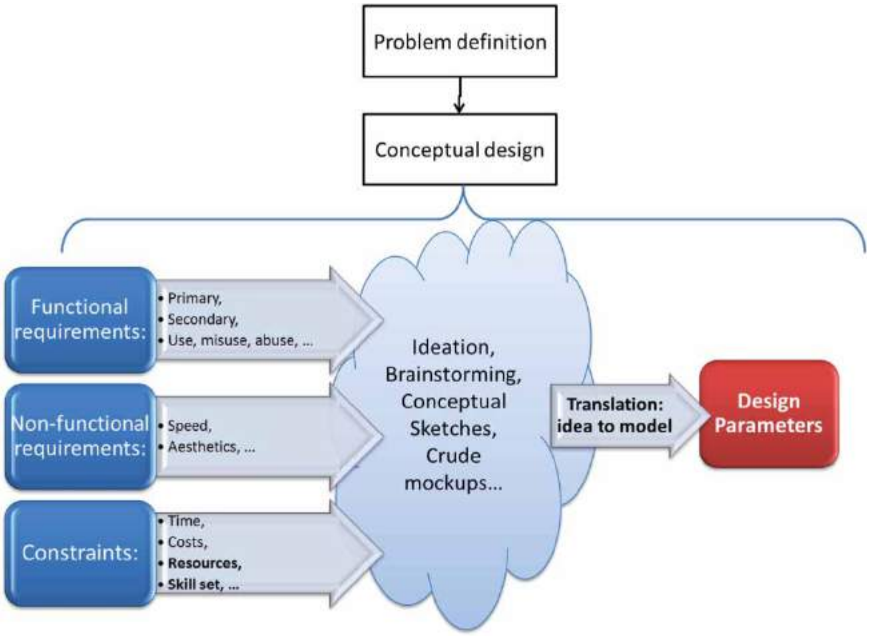


Figure 1. Problem definition and conceptual design elements.

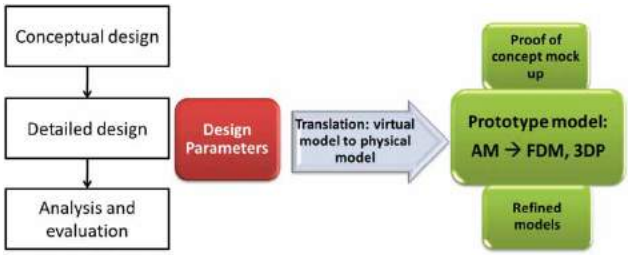


Figure 2. Physical realization of the virtual mode.

study, but this may not be a target focus for a particular course. The student may engage in design activities, and perform complex simulations to achieve desired performance characteristics, but develop solutions that have impractical or non-functional geometry from a fabrication and assembly perspective. Using additive manufacturing (AM) methods expands the opportunities for students to realize their designs without delving deeply into the manufacturing domain. Students experience 'fit and finish' issues, have exposure to time and material resource constraints, and depending on the project, are able to assess the goodness of their designs during the implementation and operation stages.

With AM processes, a three-dimensional (3D) part is built by layering two-dimensional (2D) cross sections successively to create the final solid. Similar to printing a document, there are minimal user interactions, and the detailed process planning is transparent to the user. 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). Many interchangeable terms are used to describe the AM process family. One of the most common pseudonyms is 3D printing due to the simplicity related to selecting the build options. For these projects, a 3D Systems Z450 3D printer (3DP) [37] and a Stratasys Fortus 400 MC fused deposition modeling (FDM) [29] machine are used to fabricate components. 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.

For the 3DP process, powder is rolled across the previous layer, or build platform, and binder is then deposited on top in the regions where the solid material is to be, forming each cross-sectional layer. The build table is indexed in Z by the layer thickness, and the process repeated to create the final part or assembly. No support material is required for overhanging geometry as the powder acts as a build platform. Modifying the input file allows the designs to generate colored models. In order to accomplish this, standard color print heads are integrated within the process. There is a curing time after the component is built, and the surrounding powder must be gently removed after the curing time. The final part is fragile; hence, an impregnation post processing operation is required. Applying a coating layer not only strengthens the part, but it also brightens the colors.

For the FDM process, thermoplastic material is extruded through a nozzle to create the layers, as is the support material if it is required. The support material is

Table 1. 3DP and FDM process characteristics summary.

AM Process	Build Envelope	Material	Color	Support Removal	Post Processes
3DP	20.3 × 25.4 × 20.3 cm	Plaster	Yes	No	Cure time Brushing debris Impregnation
FDM	40.6 × 35.6 × 40.6 cm	ABS plastic	Single color material	Yes	Support material removal Sanding or surface smoothing, as required

extruded through a separate nozzle. The build and support material (if required) is deposited per layer, the base table indexed in Z by the layer thickness, and the process repeated. The support material is brittle or dissolvable and is designed to facilitate its removal. The type of support material is dependent on the machine, and the build material. After the part is built and the support material removed, the part surfaces may need to be smoothed, depending on the final application. Both processes have enclosed build chambers. The main characteristics of the 3DP and FDM processes are summarized in Table 1.

2. Process flow

The general build process flow and the process milestones are presented in Figure 3, and explained in detail in the next subsections. The general process flow consists of reviewing the 3D computer aided design (CAD) model for build related issues, developing a build plan for a time/materials quote, building the part, and the final testing. The main milestones presented in Figure 3 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.

2.1. CAD model review: 3D model

To start the fabrication process, a 'valid' CAD model is required as the input. There are two conditions to be met: (i) The boundary surfaces must enclose a finite volume, and (ii) non-manifold geometry (zero–thickness surfaces or more than two surfaces meeting along a common edge or point) is not allowed. The model must be 'water tight', and can be developed using solid modeling or surface modeling tools. There cannot be gaps, overlapping surfaces, duplicate surfaces, or discontinuities in the model. These problems can be avoided when using solid modeling systems, as by definition, solid models have a closed volume, but care must be taken not to introduce non-manifold geometry. Free form complex surfaces are challenging to model with solid modeling tools. Consequently, there are applications where surface modeling tools are more effective (i.e., reverse engineering a forearm for a specialty cast – section 3.2). Importing graphics via converting raster to vector data can be particularly problematic as small line, arc, or spline segments may be created. It is recommended that this imported geometry be used as a template and the graphic designs be remodeled to reduce the geometric entities, and to ensure continuity.

Unlike machining, where internal fillets will occur as a result of the cutting tool nose radius, all fillets must be incorporated in the 3D CAD model. Fabricating thin walls, small features, closely positioned features, and features with thick wall – thin wall junctions can be problematic. 3DP parts are fragile, and can break easily prior to impregnating the part with an infiltrate, and small, thin features can be damaged when removing support material from FDM parts. FDM parts with thick wall – thin

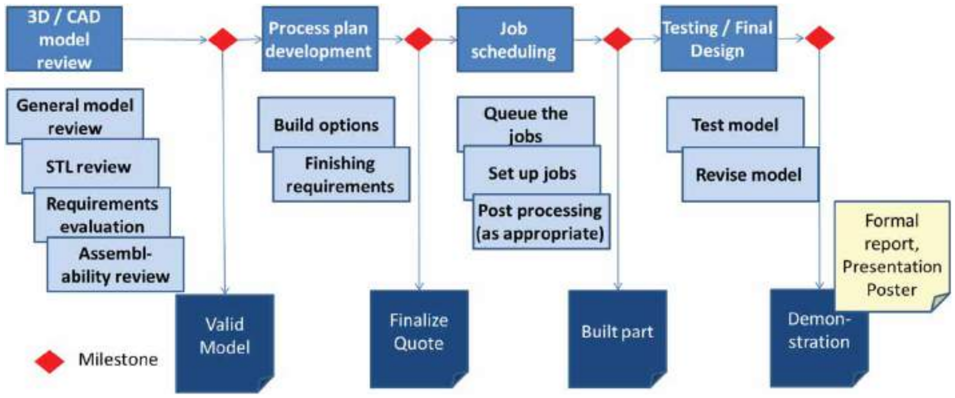


Figure 3. The build process flow and milestones for realizing components using the 3DP and FDM processes.

wall junctions can deform or warp [27]. Large components need to be sectioned, and an assembly strategy needs to be determined. The limits for AM processes must be determined individually. The model can consist of an assembly; however, the assembly must contain gaps between components to avoid subcomponents being joined during the build process.

A general 3D model review should be performed to evaluate potential build and performance problems. Many students inadvertently include non-manifold or have stray geometry in their files. Creating three dimensional fillet blends also have represented a challenge; hence, assistance with advanced geometric modeling may be necessary. It is recommended to convert the model into an IGES file, import the IGES file into another CAD system, and create a 'body' solid. This conversion process has been successfully used to identify several general surface geometry issues quickly. A detailed assessment needs to be performed to highlight filleting, thin walls, small features, segmentation and assemblability, and so forth. This should be done prior to creating the project files to prevent downstream implementation issues.

2.2. *CAD model review: considering anisotropic properties*

Anisotropic strength properties have been reported by many researchers for the FDM process [1,4,15,23,34], but limited data (mainly on tensile strength) is available for the 3DP process [14,16–18,25,28,33,36]. Experiments have been done for a variety of build options for both the FDM and 3DP process to establish base line information for design projects. Tensile and compression test samples are designed and built in various orientations (Figure 4). Selected results are presented here to illustrate the impact of the fabrication options on the tensile and compressive strength.

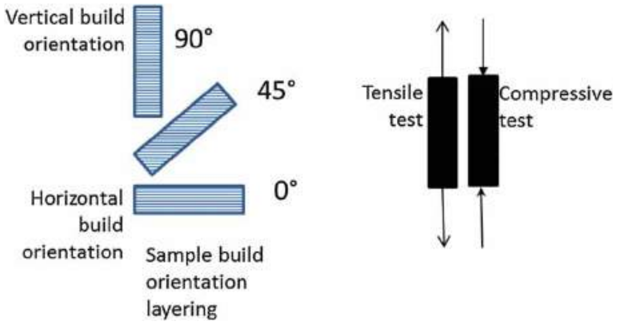


Figure 4. Test sample build orientations showing the build layering within the test sample.

The FDM process allows users to build in solid, sparse (shell), or double sparse modes, and users can orient the component to adjust the raster travel path fill pattern (Figure 5). The strength, material usage, and build time is significantly impacted by these various settings. The mechanical characteristics for solid and sparse fill modes for ABS (acrylonitrile butadiene styrene) are illustrated for selected build orientations, and raster fill strategies (Figure 6). Note: for the test samples, the sparse fill strategy utilized approximately 30% of the material compared to the solid option; consequently, the force per unit volume is reported here.

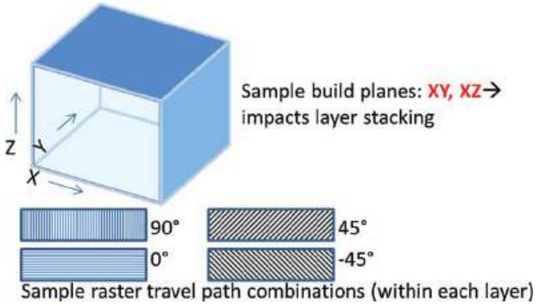


Figure 5. Raster deposition patterns for the FDM process, and build plane nomenclature.

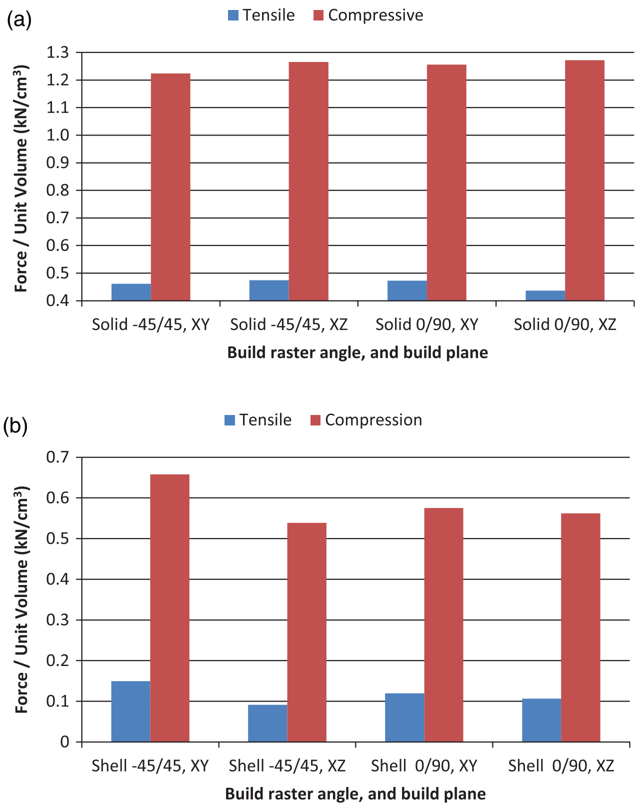


Figure 6. The force per unit volume material for (a) solid specimens, and (b) shell specimens (ABS).

It can be seen that the FDM test samples exhibit significantly stronger compressive strength characteristics as compared to the tensile strength. The 0°/90° XZ build orientation has the weakest tensile strength and the 45°/-45° XZ build orientation has the weakest compression strength. The solid specimens exhibited a tensile strength four times greater than the sparse tensile specimens (on average); whereas, the solid compressive specimens are 2.2 times stronger than the sparse filled specimens.

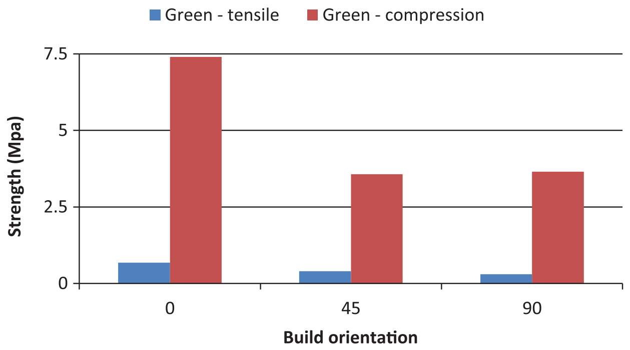
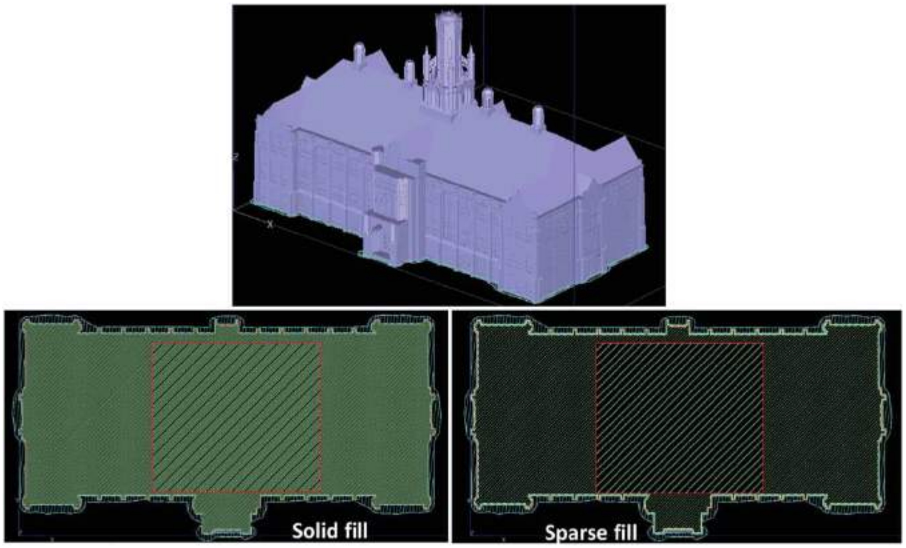


Figure 7. Experimental tensile and compressive strength results for cured 'green' test samples.
Note: the observed strength is much higher in compression than tension [10].

For the 3DP process, tests were done for cured green components with no infiltrate, and various post processing scenarios (Tables 4 – 7 in the Appendix). The cured green components are stronger in compression than in tension when experimentally testing the strength characteristics (Figure 7), but are not strong overall. The build orientation affects the mechanical characteristics. Care must be taken removing the part / assembly from the build chamber prior to any post processing tasks.

These anisotropic strength characteristics need to be taken into consideration in context with respect to the design challenge being addressed. For a large display model (Figure 8), the sparse fill mode is appropriate. Strength is not a functional characteristic, and the time and materials savings are significant using this build mode. For functional FDM components, ribs may need to be incorporated, or walls thickened to prevent the fabrication strategy influencing the performance results. For an 'intermediate' strength application, design changes may need to be incorporated within the original model (i.e. create a 'shelled' model with a 6 mm wall thickness), and build the component using the build solid mode.

If a 3DP component must have thin walls or delicate overhanging features, a 'fixture' or cradle to surround the part should be designed, with a gap (~ 2 mm) between the fixture and the part. Incorporating a fixture will protect the part from being damaged when it is removed from the build chamber, as it has been shown that the 'green' parts are very fragile. Once the part or assembly is removed from the build chamfer, and some loose powder removed, then the part must be carefully removed from the protective fixture.



	Solid	Sparse or Shell
Time	139 hr 42 min	76 hr 51 min
Model cm^3	4752.601 cm^3	1386.716 cm^3
Support cm^3	239.661 cm^3	239.669 cm^3

Figure 8. Scale model (350 × 180 × 220 mm) of the University of Windsor's iconic Dillon Hall, the solid and sparse fill strategies, and their impact on time and material.
Note: the support material usage.

To conclude, the strength characteristics related to AM processes are still not well understood. 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.

2.3. CAD model review: creating the STL file

For many AM processes, the CAD model must be converted into an STL (Stereolithography Tessellation Language) file. The STL format represents three-dimensional models as a set of triangular facets. There is no connectivity or topological information. When converting a CAD model into the STL format, conversion issues may occur such as duplicate, intersecting, or flipped triangles. There may be holes in the model, stray geometry, or a loss of resolution (Figure 9). Other problems may be related to the CAD model, such as fillets that have reversed surface normals. These problems may not be readily evident until they are highlighted when creating the build file. STL repair tools are available, but the goal should be to have the CAD model be the master model to accommodate required design changes highlighted during the testing phase; hence, the original model should be updated. The original equipment manufacturer (OEM) process planning software typically provides the slice height where the fault occurs. Therefore, the problem regions can be readily targeted. The amount of the tessellation for curvilinear geometry is determined by a chordal tolerance (also called the chord height or facet deviation), which is applied to the original surface or solid model when saving it to the STL format. Care must be taken to ensure the resulting faces are smooth, and there are gaps between components for assembly models.

2.4. Process planning development: build requirements evaluation

There are limited process planning options, but the slice thickness and build orientation influence the component strength and surface finish, as well as the material usage, and the build time. Thin walls (less than 1.5 mm), closely spaced and small features need to be carefully scrutinized, as there may be unexpected end results (Figure 10 – FDM process).

For the FDM process, surfaces where the support material contacts the build material are significantly rougher; hence, if surface smoothness is a concern, the orientation that minimizes the build-support material contact area should be determined.

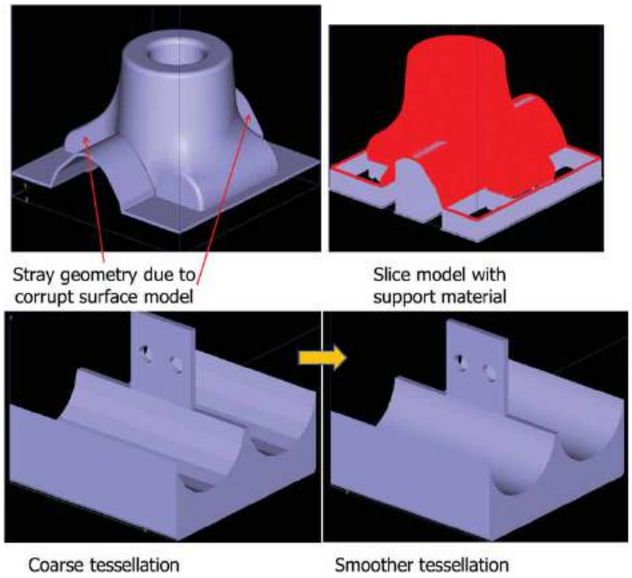


Figure 9. Problematic surface model causing stray geometry and coarse tessellation and in the STL file.

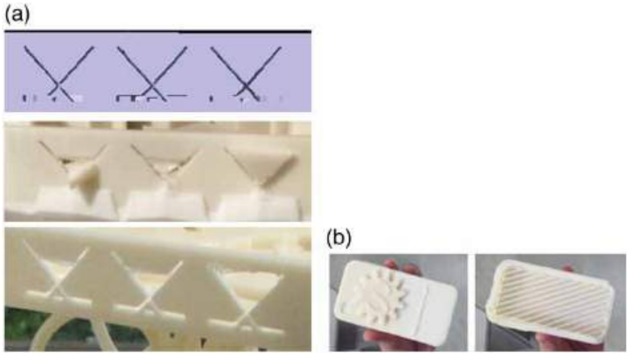


Figure 10. (a) Problems with thin walls, closely spaced small features: top – model, center – built component with support material, bottom – final part, (b) cell phone cover build orientation chosen to result in the best surface finish.

Large components need to be segmented, and assembly features added as appropriate. Design for assembly strategies should be considered. However, for the FDM process, the build time is a function of the boundary perimeter as well as the component volume (Figure 11).

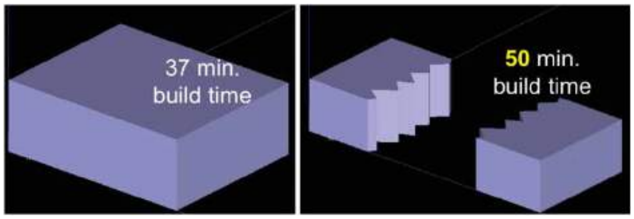


Figure 11. Build time for a cube and the cube with a partition.

Figure 12. Four module colored scale model of University of Windsor's Centre of Engineering Innovation.

Once the build settings are determined, a time and material estimate from the OEM software can be used to provide information for the final quotes and job queuing. The build time for large, complex components will be long, so a job scheduling plan for a classroom setting needs to be determined; however, minimal human interaction is required while the components are being built.

For the 3DP process, the part accuracy depends on several factors, but the primary contributing factors are the 'bleed compensation' settings and the orientation of parts in the build chamber. When the binder is printed on powder, it will tend to spread slightly, causing surface of the part to migrate outward. To compensate for this growth or "bleeding", the bleed compensation has to be ON to introduce a build offset within the travel parts to shave off a small amount of thickness from the surfaces. It is important to rotate the mating surfaces for an assembly to the same orientation to ensure the part will mate properly as there can be dimensional variations due to the build orientation.

For the 3DP components, colors can be added to STL model via the OEM software (Figure 12), and these colors will be printed out on the boundaries. To incorporate multiple colors for the FDM process (on a per layer basis), the build material spool needs to be changed when the build process is paused.

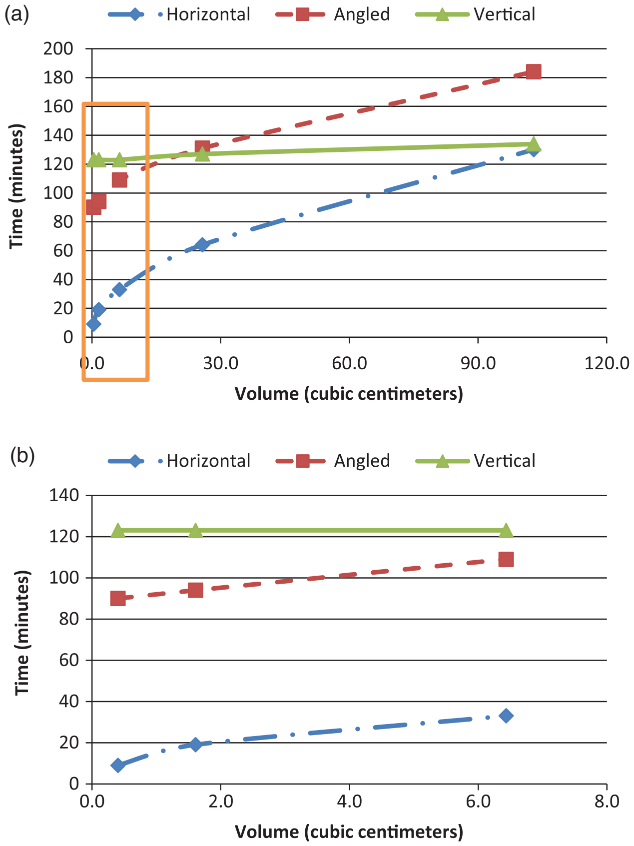


Figure 13. (a) The build time for a 5.1 cm length cylinder for various cylinder diameters and orientations [19]; (b) expanded graph for the points within the rectangle.

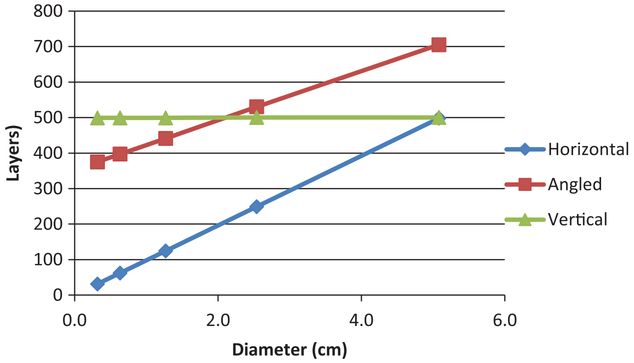
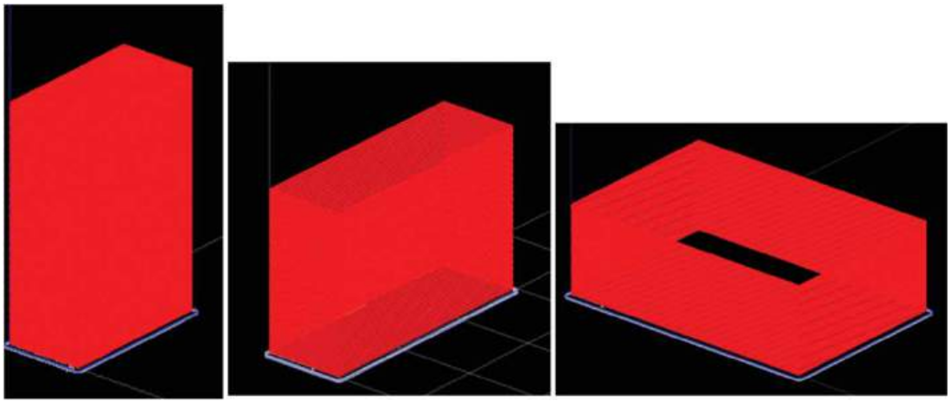


Figure 14. The associated number of layers for the various diameters and build orientations shown in Figure 13 [19].

2.5. Process planning development: layer thickness and build orientation impact

The component build time is a function of the model size, slice thickness, and build orientation. However, the 3DP build time is strongly influenced by the number of layers, as each cycle requires dispersing the material, and packing it via a roller prior to dispensing the binder. For a constant length cylinder, the build time increases minimally (Figure 13) for larger diameters when the cylinder is built with a vertical orientation, as the number of layers remains constant (Figure 14). For cylinders built in the horizontal and angle orientations, the build time is sensitive to the diameter variations as this impacted the number of build layers.

To evaluate the FDM process in order to compare build times with respect to orientation without



Height dim. →	z= 75 mm	z= 50 mm	z= 25 mm
Time	2h 56 m	2h 52 m	2h 41 m
Build (cm3)	85.4	85.9	86.2
Support (cm3)	0.3	0.5	0.8
Height dim. →	z= 150 mm	z= 100 mm	z= 50 mm
Time	19 h 54 m	19 h 37 m	19 h 3 m
Build (cm3)	675.5	677.1	681.7
Support (cm3)	1.0	1.5	2.9

Figure 15. The build time and material requirements for a block using the Fortus 400 machine, Insight software, and 0.18 mm slice height to fabricate a solid part using basic supports.

introducing support material requirements, a 25 × 50 × 75 mm and a 50 × 100 × 150 mm block is built in different orientations, and the build time results are shown in Figure 15. Figure 16 illustrates the impact of slice thickness and orientation for the 25 × 50 × 75 mm block for z = 75 and z = 25 in the upright positions. It can be seen that that orientation has a minor impact on the build time. The slice thickness has the greatest impact on the build time. Introducing support material introduces two sources of additional fabrication time: (i) the time to deposit the material, and (ii) the time to switch between the build and support feeding systems. The surface finish is rougher for thicker layers, and this requirement needs to be balanced with the build time. Researchers have engaged in many optimization approaches to resolve material usage, time, and surface finish [2,3,21,24,30]; however, there is no commercial implementation to date, and limited research has been conducted while considering strength criteria as part of the optimization solution [35].

Unique job queuing strategies can be employed for these additive manufacturing processes. For the 3DP process, multiple components can be stacked in the build envelope, and nesting the components to batch build several components is a viable solution to minimize the layer-powder preparation time impact (Figure 17). It must be ensured that there is clearance between components.

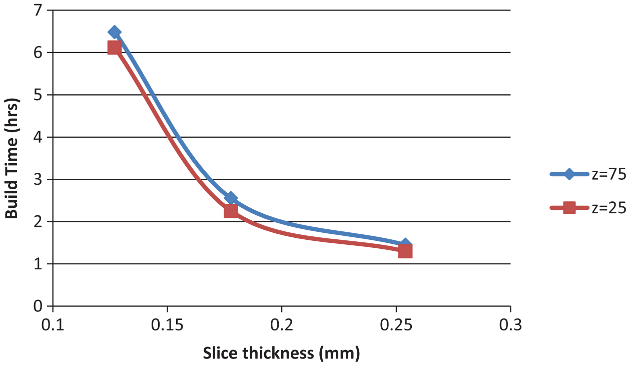


Figure 16. The impact of build orientation and slice thickness.

2.6. Job scheduling: post processing

The parts manufactured using the 3DP and FDM processes need significant post processing. Time must be allocated for this in project plans, and materials, and facilities are required to support these tasks. For the 3DP process, the post processing consists of the following:

- Cure time in the build chamber, which is 1–2 hours depending on the part size,
- Shaking or vacuuming the loose build material around the part, and carefully removing the part from the build chamber,

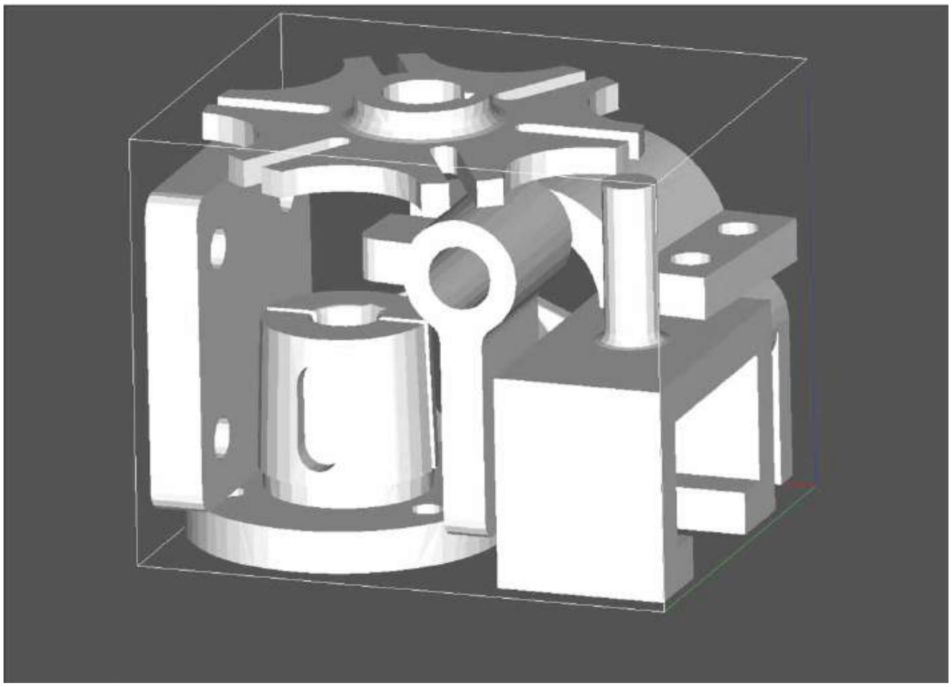


Figure 17. Eight models positioned within the 3DP build envelope.

- Brushing or dusting off loose debris using nylon-bristle brushes, riffler files, and fine grit sandpaper,
- Air drying to ensure the part is dry prior to coating it with a resin / infiltrate. If low humidity is not possible, a convection oven can be used. Note: convection drying at 165 degrees F / 70 degrees C will cut the drying time in half.
- Impregnating the part with an infiltrate. Ensure that the working area is prepared with wax paper, plastic sheet, paper towels, and students are wearing gloves, safety goggles, and a lab coat. There must be proper ventilation in the post processing area. Depending on the impregnation material, i.e., resin, fumes are released that can irritate the eyes and lungs.
- Cure time for the impregnated part to dry. Place the component on a fixture with contact points that are spread widely apart, and have minimal surface contact area.

Care must be taken to handle the parts cautiously, as the green parts are fragile, and edges will chip away easily. Some infiltrates set quickly; therefore, small practice pieces should be fabricated for training to expose the students to these problems and develop their techniques. Common infiltrate types and special instructions are presented in Table 2.

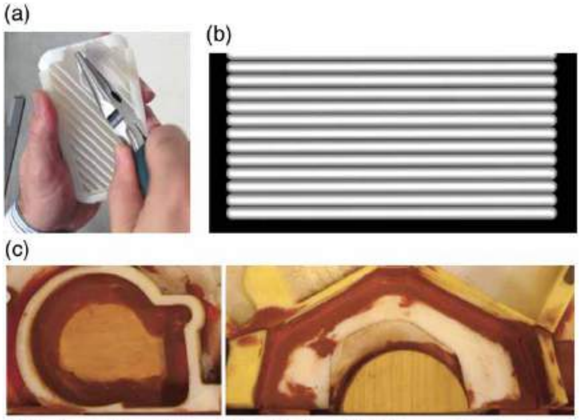
Table 2. Summary of OEM recommended infiltrate materials and special instructions for each.

Infiltrate type	Product name	Special instructions
Cyanoacrylate	HyperBond®	Use with adequate ventilation Vapors irritate mucous membranes Avoid skin and eye contact
Epoxy	Z-Bond®	Eye, skin, and respiratory irritant Avoid breathing vapors Use with ventilation Wear suitable personal protective equipment
Polyurethane glue	Elmer's®	May irritate eyes, and skin Use rubber gloves to avoid sticking / irritation Dangerous fumes when mixing with other products
Epsom salt	100% natural mineral	

A set of infiltrate materials was tested, to determine the performance characteristics related to strength, time, materials, and safety [19]. This is summarized in Tables 4–6, in the Appendix. No one post processing solution is optimal. Note that the Epsom salt infiltrate weakened the compressive strength. Although this infiltrate substance is recommended by the OEM, experiments indicate that the compressive strength is weakened, and no statistically significant strength improvements are noted when performing tensile test experiments.

The FDM built parts have less post processing steps, but the post processing for this process can also be time consuming:

- Support material removal (using needle nose pliers (Figure 18), tweezers, needles), or time allocated in



Putty is used to add a fillet between the FDM built module and the back plate.

Small internal fillets smoothed out with putty

Figure 18. (a) Removing support material, (b) layering, and resultant surface, (c) pattern modules mounted on a back plate for sand casting core boxes, where a fillet and smooth blending could not be achieved without hand work.

a soak tank if dissolvable support material is being used;
- Rough sanding (rough grit paper), and
- Precision sanding (fine grit sand paper, riffler files).

It is recommended that as much dissolvable support material be manually removed prior to immersing the component in the soak tank to minimize the soak time. Stray support material may remain, requiring the use of files and sand paper to remove the excess support material. The part may distort or warp. Additional post processing may be required. Fillers such as Bondo® [5] or putty (Figure 18(c)) can be used. If the part is built with the thickest layer setting (0.33 mm) to reduce build time, the surfaces will be rough as the unit normal vector approaches (0, 0, 1); subsequently, filling the rough surface valleys, drying the filler material, and sanding may be necessary, depending on the final application. Small fillets may not be as smooth as required. When interfacing modules being built by two different processes, it may not be feasible to model and fabricate the blending without introducing a manual post processing step. Handwork will be required to address these situations.

3. Sample projects

3.1. Manufacturing process design course (06-91-321)

The Industrial Engineering Manufacturing Process Design course at the University of Windsor is taught in the 3rd year. Selected learning outcomes are:

- Identify the manufacturing processes and materials employed to manufacture a component,
- Recognize basic physical and mechanical properties associated with materials transformed by the manufacturing process,
- Compare and contrast manufacturing processes with respect to feasibility, costs, skills and infrastructure requirements, and
- Explain advantages and disadvantages, similarities and differences between forming, molding, removal, additive and joining processes.

Traditionally for their final projects, students dissected small assemblies, and reported on the manufacturing processes. To expose the students to manufacturing and design for manufacturing challenges, teams (which have 5–6 team members randomly selected at the beginning of the term), are given the project statement: “You have been given the responsibility to fabricate a scale model of a T Rex skeleton. The individual 2D ‘bones’ need to be fabricated, and assembled. You need to consider how to assemble the skeleton in conjunction with making the individual components.” Each group has the same skeleton data, scaled differently. No group can copy another group’s designs directly, but they can discuss and collaborate on technique. It is expected that the students explore several manufacturing process options, and include lessons learned in their final reports. Some sample project guidelines are:

- You must use multiple manufacturing processes;
- Design related calculations must be done to support your design decision making ;
- You must create molds with minimal silicone usage;
- You must calculate the amount of resin and molding material required, and this includes pre-determining the ratios for the materials;
- A minimum 2 joining methods must be utilized;
- The ‘bone’ thickness can vary between 3–8 mm;
- You can ‘design for X’ and modify the geometry for joining or to provide economies of scale advantages or to facilitate the manufacturing and/or assembly processes.

Sample project materials include silicone molding materials, quick set resins, and mold making materials. The students have to create a Bill of Materials, identify every part, and discuss the manufacturing and assembly steps to be employed, and their reasoning, as shown in Table 3. This information is submitted as part of an interim update to ensure that the students are making progress, and to determine the feasibility of their approaches. If an AM process is to be used for a final

Table 3. Sample task list and Bill of Materials for the dinosaur project.

	Mfg Process		Assembly Process							
Part no.s	Process & Steps	Materials List	Process & Steps	Materials List	DfX	Who	How	When	Why	Comment

Figure 19. (a) T-Rex head bones built using the FDM process, (b) silicone material being poured into a mold with FDM bone patterns, and (c) molded parts (colored parts were made from resin and a color additive, highlighted head, ribs, and backbones are FDM built parts.

part, or a mold element, this needs to be stated, along with key information (preliminary process planning using the OEM software). This is to help the students' progress with their projects, but also help with scheduling and job queuing.

The 'head' parts for one team were built using the FDM process, as well as some ribs to be molded (Figure 19). As the students had to explore multiple processes, the T-Rex projects shown in Figure 20 consist of a variety of processes. As the students had to report on the time, materials, costs, the required design and fabrication challenges and solutions for a variety of manufacturing processes and assembly strategies, at the completion of these projects, the students understood the advantages

Figure 20. Two sample Manufacturing Process Design projects [11].

and disadvantages of many processes, including the FDM process.

3.2. *Individualized 'body contact' entrepreneurial projects*

The Industrial Engineering Manufacturing senior design or capstone course at the University of Windsor is taught in the 4th year, and students are challenged to solve open-ended engineering design problems while considering issues related to performance, cost, and societal impact. Selected learning outcomes are:

- Apply a design process appropriate to the engineering problem at hand, including unstructured creativity as part of a structured design problem.
- Generate and evaluate design concepts after gaining a sound understanding of the problem background (functional requirements, business issues, societal impact) and existing design concepts.
- Employ creative design techniques, fundamental analysis related to the functional requirements, design parameters, and stakeholder expectations, and develop a proof-of-concept prototype.

The students develop operational (who, where, etc.), performance (water and corrosion resistance, strength requirements), shape and other related engineering specifications after the problem is defined. Once the requirements are established, then design solutions are proposed.

Two entrepreneurial projects based on developing solutions for personalized sports equipment / casts and bike seats (Figure 21) enabled students to learn about reverse engineering, 3D modeling of organic shapes, and using the FDM process to realize functional prototypes. One project targeted addressing bulky medical casts and braces along with uncomfortable and ill-fitting sports equipment. The other project targeted leisure cyclists, focusing on developing a bike seat to enable them to ride their bicycle for long periods of time with minimal discomfort. The reverse engineering was performed using a Xbox Kinect as a scanner, and various software tools used to manipulate the point cloud and mesh (i.e., ReconstructMe©, Meshlab©, and Rhinoceros 5V©). A student's forearm and a 'soft' clay mold placed on a support to emulate a bike seat were used as the models.

For the bike seat project, the test cyclist would sit on a stationary bicycle for several minutes to ensure the mold would conform to a valid pedaling shape. Cross sections from strategic points were analysed to create curves, and subsequently a parametric loft solid model. A personalized seat was designed from this information. The final bike seat solid models included support ribs, and

Figure 21. Personalized sports equipment / casts project mesh, 3D model, and FDM model, and bike seat clay mold, scanned mesh, model and FDM variants. For the arm cast, the parting line and key anthropometric regions are identified. The pressure points are highlighted for the bike seat. The first version was uncomfortable; however, the final version met the design requirements. Once the base design and parametric model was established, the implement, operate cycle, redesign, etc. cycle for this was very short.

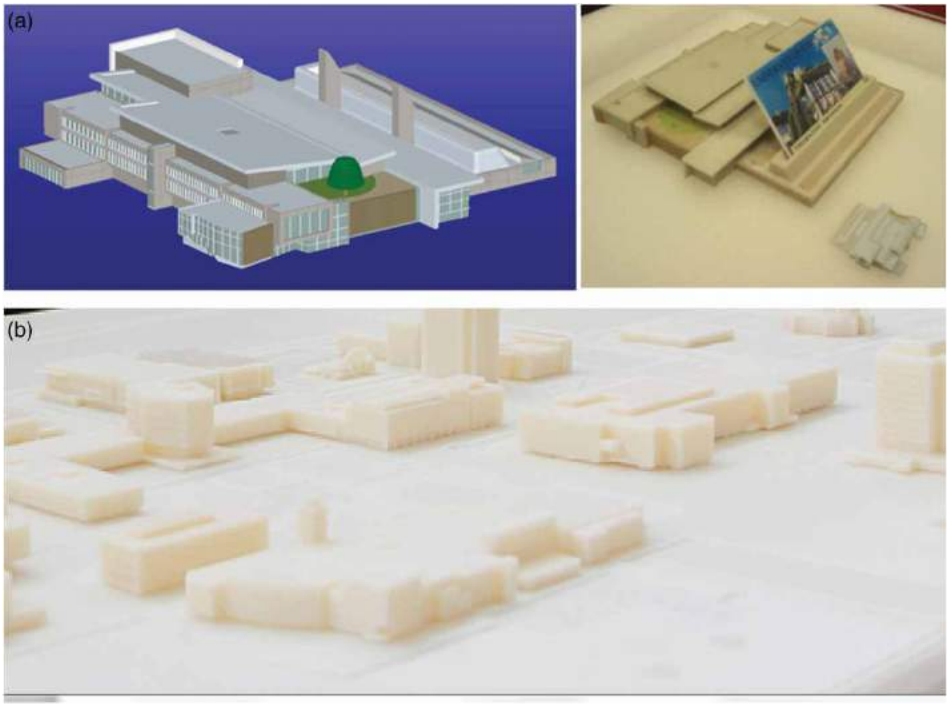


Figure 22. (a) Building based card holder, and key chain dongle, (b) section of the campus scale map [10].

mounting features on the underside. Seats were built, and tested, and the designs improved based on the user feedback. Three design iterations occurred in this project to determine the best designs.

For the arm cast, the point cloud data from the forearm was transformed into a surface model, which was converted to a sheet solid, and then thickened. This model would be very difficult to manufacture using conventional methods.

3.3. Architectural projects

A variety of architectural projects has been executed by 4th year capstone teams [32], but also with 1st year students. These projects focused on modeling and fabricating buildings. Architectural drawings were used for the Centre for Engineering Innovation scale model, and reverse engineered building information from digital photographs was used for the other building projects. The photographs can be used to extract the geometry using proportionality analysis, and for the colors, as the color mixing and saturation can be determined, and used for the 3DP color palette.

These architectural projects are used as displays; hence, the functional requirements focus on aesthetics. Challenges with the building project illustrated in Figure 12 focused on determining the proper wall thicknesses, the levels of detail to be included, and developing a realistic color palette for the siding and features. The project was extended to create card holders, and a model to be set in resin for key chains (Figure 22 (a)).

For the first year Technical Communications course, student teams were tasked to create a scale 3D map of the campus. This course focuses on exposing students to engineering standards, reinforcing engineering graphic standards presented to them in previous course work, as well as written and oral communications. The students had to develop interface standards for the modules, determine the scale of the project, methods to represent the roadways, sidewalks, and key features for the buildings. Each team had several students, and eight teams worked together on this project. Many had limited design and no manufacturing experience. The students faced challenges related to developing their standards, creating valid models, and developing an assembly strategy. Once valid 3D models were created, the models and base plate modules were fabricated using the FDM process. No checking was done via an independent review for connectivity or constant scaling, as these problem types needed to be experienced by the students for them to realize the consequences of their decision making. One building was not scaled properly, which was corrected shortly afterwards. Using an additive manufacturing based project in the Technical Communications course enabled students to experience a ‘super group’ design environment typical for large projects (Figure 22 (b)), and realize the impact of their design decisions.

3.4. *Rapid tooling project*

Many 4th year mechanical engineering projects have dealt with designing and fabricating cast components. The strut illustrated in Figure 23 is approximately 200 × 200 mm square, and 170 mm in height. The design features for this part consist of variable radii, deep external pockets, and even wall thickness throughout the pattern to minimize material usage and warpage of the component. The ribs, fillets and pockets are designed to maximize the strength to weight ratio and no 'design for machining' strategies are incorporated. In lieu of machining a set of struts, they were sand cast employing a cope and drag casting pattern set. The pattern was fabricated using the FDM process. There were two design-build cycles. Draft was incorporated in the model, but insufficient draft was introduced in the first model version in the internal 'chimney. The pattern could not be extracted from sand in the mold. On the second model version, the thickness slice thickness was selected to reduce build time. This also introduced pattern extraction issues; hence, the pattern was sanded to a smooth surface.

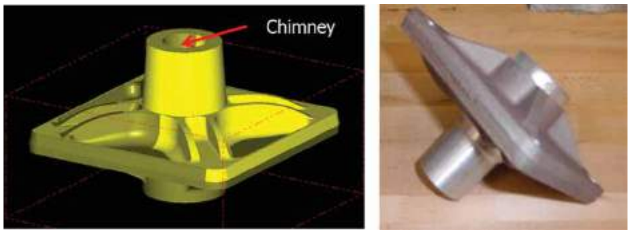


Figure 23. Strut CAD model, and final casting.

This component has much complexity, and would require multiple set ups for a 3 axis machine in order to allow small end mill tools reach the recessed fillets. Incorporating 'design for machining' strategies would reduce the number of required setups, but the weight of the component would increase approximately 15%. Using the FDM process allowed the students to optimize the functional design, and allowed the students to readily fabricate an adapted design to enable them to complete their project.

4. Summary and 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, and practical 'operate' issues can be highlighted with the FDM or 3DP fabricated parts. The effort associated with the implementation element of a CDIO cycle is reduced (Figure 24). However, the 3D CAD model and design requirements still need to be reviewed for manufacturing related issues, although the element related to process design / process planning is less complicated than that associated traditional fabrication and assembly processes (a checklist is summarized in Table 8).

A selection of projects is presented here. Another reverse engineering – 3DP architectural project is described in Urbanic *et al.* [33], and the design and fabrication of a low cost, simple, configurable pill dispensing machine is described in Jabr *et al.* [20]. In both these projects, complex sophisticated designs are realized for a low cost, and minimal human effort.

As students typically need to have their components built during the same time period, reviewing task lists and bills of materials in an interim report allows for appropriate job queuing. Although these processes require minimal supervision, the fabrication time may be days for complex parts. Some support is required to load and unload the parts, add the materials, and monitor the part fabrication. Proper training is required for the support staff, and machine maintenance must be performed on a timely basis.

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.

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 (section 2.6). 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

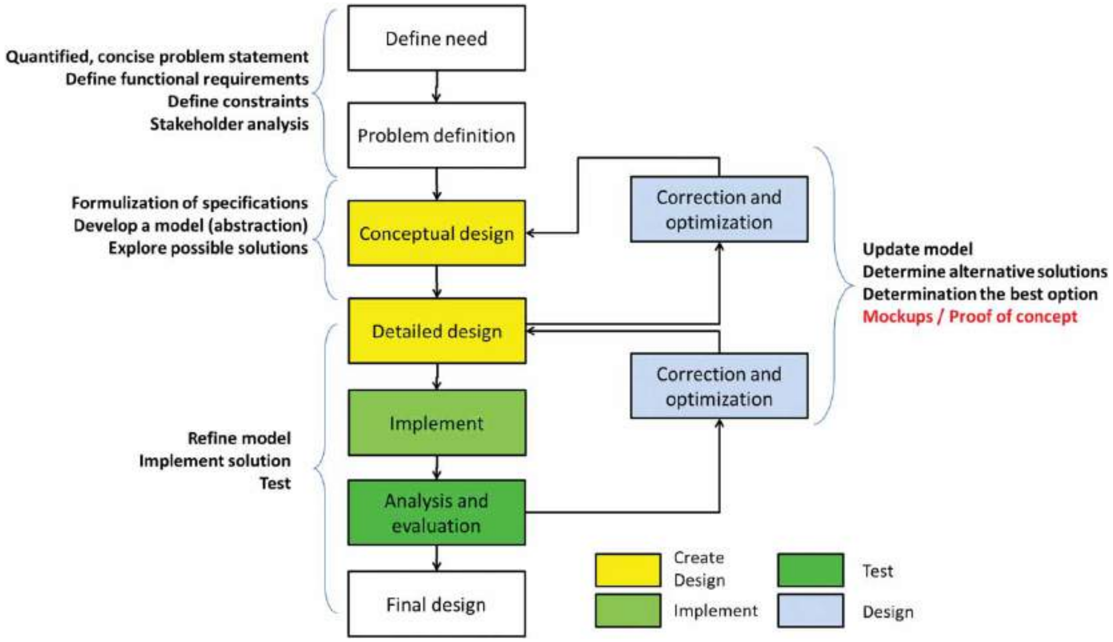


Figure 24. Classic design process, illustrating complementary CDIO perspectives. AM technologies allow for more emphasis on the ***CD & O*** elements, while providing students' insight with the ***I*** element.

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. The Z450 3DP used in this work has been problematic, and difficulty was experienced troubleshooting the actual problems. This has resulted in lost uptime, and external support costs.

To conclude, these processes have significantly improved the quality of the designs and the design experiences for our undergraduate students. AM processes can be embedded in a variety of courses to support learning outcomes. However, as with any other manufacturing process, there are unique fabrication issues, which need to be understood in order for the AM processes to be effectively leveraged.

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Appendix

Table 4. Infiltrates tested, and their codes that are used in Table 6 [19].

Type of Infiltrate	Infiltrate Code	Comment	Application Duration (s)	Curing	Mixing (minutes)
Control	C	No infiltrate			
Cyanoacrylate	B		30	10 min.	
Polyurethane Glue	P1		60	6 hours	
Polyurethane Glue	P2	2 hour oven cure	60	2 hours oven + 6 hours	
Epoxy	R1	*	30	1 hour	10
Epoxy	R2	*	60	1 hour	10
Epsom Salt Mixture	S1	Salt Solution 1**	5	3 days	5
Epsom Salt Mixture / Cyanoacrylate	Sb	Salt Solution 1**	5/30	3 days	5
Epsom Salt Mixture	S2	Salt Solution 2***	5	3 days	5
Salt Water / Cyanoacrylate	S2b	Salt Solution 2***	5/30	3 days	5

*Resin mixture 100:37 hardener by weight.
**Salt Solution 1 (210:334) salt per water by weight.
***Salt Solution 2 (105:334) salt per water by weight.

Table 5. Numerical / qualitative values, which correlate to the color coding employed in Table 7.

RANK 1-5, 1=best	Physical Strength (Mpa)			Absorption Depth (mm)	Time			Materials		
	Tensile	Compressive	Flexural		Application (sec)	Cure	Extra (Mixing, safety setup)	Build Needed (High - Low)	Binder used (High -Low)	Infiltrate cost
1	7	29.6	15	4.62	28	10mins	Nothing	Min.	Min.	Nothing
2	5.25	22.2	12	3.78	51	1 hr	Gloves			Commonly available, low cost
3	3.5	14.8	9	2.94	74	8hrs	Gloves, smock			Store
4	1.75	7.4	6	2.10	97	1 day	PPE			Order, specialty
5	0	3	3	1.27	120	3 days	PPE and Mix	MAX	MAX	Rare, specialty order

Table 6. Safety ranking summary (personal protective equipment: PPE).

RANK 1-5, 1=best	Safety 1 = safest
1	Nothing
2	Gloves
3	Gloves, Smock
4	PPE
5	PPE, Hood

Table 7. Summary of OEM recommended infiltrate materials and their ranking, adapted from [19].

	Build Direction	Physical Strength			**Absorption Depth ***	Time			Materials			Safety
		Tensile	Compressive	Flexural		Application	Cure	Extra	Build Needed	Binder used	Infiltrate cost	
C	0	🟥	🟧	🟥	⬜	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	45	🟥	🟥	⬜	⬜	🟩	🟩	🟩	🟥	🟥	🟩	🟩
	90	🟥	🟥	⬜	⬜	🟩	🟩	🟩	🟥	🟥	🟩	🟩
B	0	🟨	🟢	🟨	🟩	🟢	🟩	🟨	🟩	🟩	🟧	🟧
	45	🟧	🟨	⬜	🟢	🟢	🟩	🟨	🟥	🟥	🟧	🟧
	90	🟧	🟨	⬜	🟩	🟢	🟩	🟨	🟥	🟥	🟧	🟧
P1	0	🟨	🟨	🟨	🟥	🟨	🟨	🟢	🟩	🟩	🟢	🟢
	45	🟧	🟧	⬜	🟥	🟨	🟨	🟢	🟥	🟥	🟢	🟢
	90	🟧	🟧	⬜	🟥	🟨	🟨	🟢	🟥	🟥	🟢	🟢
P2	0	🟧	🟧	🟨	🟥	🟨	🟨	🟢	🟩	🟩	🟢	🟢
	45	🟧	🟧	⬜	🟥	🟨	🟨	🟢	🟥	🟥	🟢	🟢
	90	🟧	🟧	⬜	🟥	🟨	🟨	🟢	🟥	🟥	🟢	🟢
R1	0	🟩	🟢	🟩	🟩	🟢	🟢	🟧	🟩	🟩	🟧	🟥
	45	🟩	🟧	⬜	🟨	🟢	🟢	🟧	🟥	🟥	🟧	🟥
	90	🟨	🟩	⬜	🟢	🟢	🟢	🟧	🟥	🟥	🟧	🟥
R2	0	🟨	🟢	🟩	🟩	🟨	🟢	🟧	🟩	🟩	🟧	🟥
	45	🟢	🟢	⬜	🟧	🟨	🟢	🟧	🟥	🟥	🟧	🟥
	90	🟨	🟩	⬜	🟩	🟨	🟢	🟧	🟥	🟥	🟧	🟥
S1	0	🟥	⬛	🟥	🟩	🟩	🟥	🟢	🟩	🟩	🟢	🟩
	45	🟥	⬛	⬜	🟩	🟩	🟥	🟢	🟥	🟥	🟢	🟩
	90	🟥	⬛	⬜	🟩	🟩	🟥	🟢	🟥	🟥	🟢	🟩
Sb	0	🟥	⬛	🟥	🟩	🟢	🟥	🟨	🟩	🟩	🟧	🟧
	45	🟥	⬛	⬜	🟩	🟢	🟥	🟨	🟥	🟥	🟧	🟧
	90	🟥	⬛	⬜	🟩	🟢	🟥	🟨	🟥	🟥	🟧	🟧
S2	0	🟥	🟧	🟧	🟩	🟩	🟥	🟢	🟩	🟩	🟢	🟩
	45	🟥	🟥	⬜	🟩	🟩	🟥	🟢	🟥	🟥	🟢	🟩
	90	🟥	🟥	⬜	🟩	🟩	🟥	🟢	🟥	🟥	🟢	🟩
S2b	0	🟧	🟧	🟧	🟩	🟢	🟥	🟨	🟩	🟩	🟧	🟧
	45	🟥	🟥	⬜	🟩	🟢	🟥	🟨	🟥	🟥	🟧	🟧
	90	🟥	🟥	⬜	🟩	🟢	🟥	🟨	🟥	🟥	🟧	🟧

Note: *Absorption depth represents the different test specimens and not the build orientation, (0 = Tensile, 45 = Compression & 90 = flexural).

Table 8. Check list.

Step	Comment
Basic CAD model validation	Ensure model is water tight
Geometry check	Check for the presence of all 3D fillets Review all thin walls, small features, closely positioned features Thick wall – thin wall junctions: can be problematic as the parts may curl or warp with the FDM process
Evaluate strength considerations (considering anisotropic properties)	Modify the model to suit (thicken walls, add ribs, hollow out sections, etc.)
Design for Manufacturing checks	Check minimum feature sizes. Large component segmentation – inclusion of assembly features Design a fixture / cradle for delicate 3DP parts
Process planning: Layer thickness and build orientation impact	Discuss surface finish, build time, material usage for each project to determine the most appropriate slice thickness, and build orientation. Develop a job queue.
Batch process build jobs	Schedule jobs with common build parameters to minimize idle time. Batch components as appropriate. Typically, designs are completed near the term end.
Post processing	Ensure students have the space, safety equipment, tools, and materials to perform these operations. Check lists need to be incorporated in interim project updates to ensure students are aware of time / manpower commitments