# EDUCATIONAL MODULE ON SUSTAINABLE ADDITIVE MANUFACTURING (AM)

**Sustainable Additive Manufacturing: Laboratory Activity**

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# Purpose

To evaluate an additive manufacturing (AM) process, and to improve its sustainability performance by enabling informed energy and cost decision making during part design.

# Overview

A 3D solid model of a keychain will be designed using CAD (computer-aided design) and fabricated using fused deposition modeling (FDM) over the course of a two-part lab module. The energy and cost of manufacturing the keychain will be calculated using the process models discussed in lecture. The keychain will be redesigned to reduce energy use and cost. The laboratory module is divided into two lab activities. The first activity involves the design of an initial keychain model, and analysis and redesign for reduced time, energy, and cost. The second lab activity involves the fabrication of the redesigned keychain and verification of time, energy, and cost model results. You will perform an energy and cost comparison of the initial keychain model and a redesigned keychain model and reflect on your findings from the lab activities. Details about the two lab activities and final lab report are provided in the next section.

# Lab Activity for Week 1: Design and Redesign

Using CAD, a 3D model of a keychain will be developed, which is to be fabricated using an FDM machine. An example keychain design is shown in Figure 1. The dimensions are 40 mm x 15 mm x 5 mm. The ring hole is 2 mm x 2 mm x 2.5 mm. First, develop an initial solid model and calculate the process time, energy use, and cost as described below. Next, develop alternate designs that reduce energy use and cost. Finally, select a preferred design to be manufactured.



Figure : Example keychain design

As discussed in lecture, the energy used in an AM process for fabricating a product is dependent on the product design parameters and the process parameters. The product design parameters are obtained from the solid model and the tessellated model. The energy used during the process is represented as a function of process build time to fabricate the part and the post-processing time. The procedure to estimate the build time and the post-processing time are discussed in Appendix A. The procedure to estimate the process time, energy use, and the cost of the product by using the FDM process models is shown in Appendix B.

As alluded to above, the process energy use and cost can be reduced by changing the product design and process parameter values. The keychain design can be refined by adding or removing features from the existing solid model. Calculate the process time, energy use, and cost for fabricating the part using the FDM (Appendix B). Compare the initial and redesigned keychain model based on the calculated energy and cost values. Based on the analysis, select a design to be fabricated using FDM.

# Lab Activity for Week 2: Manufacturing the Part

An FDM machine (e.g., Fortus 400mc) is used for printing the part. A specifications sheet provided with the machine lists the different model and support materials that can be used in the machine, along with the different extruder/tool tips required for each model and support material. Process parameters (extrusion speed and layer thickness) are dependent on the tip chosen. In this activity, we will build the keychain exhibiting the best time, energy, and cost as identified in the design and redesign activity. Appendix A discusses the procedure to manufacture the part.

# Laboratory Report

Discuss your findings from Activities 1 and 2 above and explain how the energy and cost analysis contributed to your decision making. Your report must answer the following questions:

1. What was your initial design? How did the calculated shape complexity value for the initial design influence the total energy in making the part?
2. What changes did you make to the initial design? How did these changes affect the energy used to make the part?
3. Compare the two designs in terms of shape complexity, build time, post processing time, total energy and final cost. Are there tradeoffs to consider?
4. Discuss how the calculated energy use and cost influenced your design decisions during selection of your final design.

# Appendix A

Use the procedure below to obtain design and process parameter values for energy and cost calculation, and to print the designed part using the FDM machine.

1. Open the keychain design in a 3D modeling (CAD) software.
2. Analyze the part geometry and identify the following parameters:
   1. Identify the configuration of the part. The configuration is often represented as 2.5D or 3D.
   2. Identify the height of the part (Z).
   3. Identify the aspect ratio of the part. Alternatively, if the aspect ratio of the part is not available from the CAD model, its value can be calculated using Eq. 1, knowing the part height (Z) and smallest cross sectional size (Asmall).

(1)

* 1. Evaluate if the design contains small or long holes and channels are features. If so, identify the number of holes/channels in the design, and the related internal face area.
  2. Identify the outside surface area (SA) of the part.

The parameter identification procedure in Step 2 (a-e) are required to calculate the shape complexity index value (Sc). The shape complexity index value is a key variable which affects the post-processing time and, hence, the post-processing energy.

1. Save the keychain CAD file as an STL file extension type. Make note of the number of triangular facets into which the CAD file has been tessellated.
2. Load the saved tessellated model (.STL file) in RP-CAM software. Ensure that the dimensional units of the tessellated model are the same as that of the original CAD model.
3. Under menu, open machine settings and choose the correct machine (this step is necessary when more than one machine of the same technology is available).
4. Under material options, choose ABS as the model material and SR-30 as the support material.
5. Choose the correct extruder/tool tip used for printing ABS and SR-30 as specified on the FDM machine specification sheet.
6. Choose the layer thickness value for your build. Machine manufacturers provide the layer thickness values supported by the machine on the machine specifications sheet.
7. Open the support properties menu and specify the number of base layers to be printed. Typical values range from 5-10 base layers depending on the part to be printed. Also, select the thickness of support layer (this value is based on the tool tip selected).
8. Align the part on the virtual build plate in the software and choose finish. The job will be prepared and the track pattern for individual layers will be generated. Job information for the build will be generated and saved in the same location as the tessellated file by default, unless specified otherwise by the user.

Multiple jobs can be loaded onto a single build plate, provided there is available space. If printing multiples of the same part, the user can simply copy and paste the already prepared part and position it on the virtual build plate according to user requirements. Different parts can also be printed on the same build plate. To print different parts, each part will need to be prepared using the procedure explained above.

# Appendix B

The information below describes calculation of process time, energy, and cost for FDM.

# Total Process Time Calculation

The total process time is the sum of build time and post-processing time. The build time of the process is the total time required to build the part. In an FDM process, the build time can be represented as a function of the volume of part and the outside surface area of the part, as defined from regression analysis of previous experimental runs. FDM **build time** can be calculated using Eq. 2:

(2)

The **post-processing time** is the time required to remove any support material and base layers in the part washing station. It is found that post-processing time varies as a function of shape complexity and dimensional size. Based on various part design conditions, an index number can be calculated to represent the shape complexity (SC) of each part (Eq. 3). The index is given a value based on the four design criteria as follows:

1. Configuration: If the part design is 2.5D, SC1 = 0, and if the part design is 3D, SC1 = 1.
2. Aspect ratio: If the aspect ratio (Eq. 1) is < 10, SC2 = 0, else SC2 = 1.
3. Feature scale ratio: If triangle number (n)/volume is < 5000, SC3 = 0, else SC3 = 1.
4. Internal features: If part has long, small channels or holes, SC4 = 1, else SC4 = 0.

SC = SC1+SC2+SC3+SC4 (3)

The data required to calculate the shape complexity index is collected in Step 2 in Appendix A. Using the shape complexity index, the post-processing time (tpost) can be calculated by Eq. 4:

(4)

where tbase is the base time required to wash the part (dependent on operator’s skill level); Apart is the part outside surface area; Abase is the base outside surface area; Ni is the number of internal channels; and Ai is the internal face surface area of channels/holes. Also, K1, K2, K3 refer to the degree of difficulty in washing, as defined below:

If Sc ≥ 1, K1 = 1, else K1 = 0.

If Sc ≥ 2, K2 = 1, else K2 = 0.

If Sc ≥ 3, K3 = 1, else K3 = 0.

Thus, the total process time can be calculated Eq. 5:

(5)

# Process Energy Use Calculation

The energy consumed in the process (Eprocess) is the sum of build energy (Ebuild) and post-processing energy (Epost), as shown in Eqs. 6-8:

(6)

(7)

(8)

where, PFDM is the rated power of the FDM machine and Ppost is the rated power of the part washing station.

# Cost Calculation

The total cost of manufacturing the part is the sum of material cost (Cmaterial), energy cost in the form electricity use (Cenergy), and labor cost (Clabor). Material cost can be calculated as shown in Eq. 9:

(9)

where Cmodel is the model material cost and Csupport is the support material cost. The volume of model material and support material used can be obtained from the job report from Step 10 in Appendix A to calculate cost of model material (Eq. 10) and cost of support material (Eq. 11).

Cmodel (10)

Csupport (11)

where cmodel is the unit cost ($/kg) of model material, and csupport is the unit cost ($/kg) of support material. The total cost of energy (Cenergy) used in the form of electricity is calculated using Eq. 12, where celectricity is the unit cost ($/kWh) of electricity:

(12)

Similarly, total labor cost (Clabor) is given by Eq. 13, where noperator is the number of operators and W is operator hourly wage.

(13)

Thus, total product manufacturing cost (Cproduct) is given by Eq. 14.

(14)